Vacuum Dewatering of Elutriated Wastewater Sludge Conditioned with Lime Sludge

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VACUUM DEWATERING OF ELUTRIATED WASTEWATER
SLUDGE CONDITIONED WITH LIME SLUDGE

BY

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A thesis submitted in partial fulfillment of the requirements for the degree Master of Science, Major in Civil Engineering, South Dakota State University

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser   Date

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INTRODUCTION

One of the basic functions of a treatment plant, water or wastewater, is the removal of suspended solids from the water being treated. The settleable solids that are naturally present in the water and wastewater, or that are derived from the precipitation of non-settleable matter by chemical coagulation or biological flocculation, are removed from settling tanks as sludge (1-439).

Upon settling, the precipitants form a loosely structured mass, the bulk of the sludge volume being comprised of water. Consequently, because of the low solids content, a relatively large volume of sludge is produced. The amount of sludge produced as well as the constitution and composition of the sludge are a function of (a) the nature of the waters or wastewaters from which they originate and (b) the treatment process to which the waters are subjected (2-755).

It is generally conceded that wastewater sludges present a greater disposal problem than do sludges from water treatment plants. For instance, sludges from a lime softening process in a water purification plant concentrate to a much greater extent than raw or digested sludge from a wastewater treatment plant. Consequently, the reduced volume of sludge produced in the former facilitates the handling and disposal of the sludge. Equally important is that sewage sludges generally are of a putrescible nature, and frequently contain a significant concentration of pathogenic organisms.
Therefore, it can be readily seen that the disposal of sewage sludges presents a complex problem because of its hygienic, aesthetic, and economic significance.

Presently, there is a gamut of methods used to dispose of sludge solids, including: sludge lagooning, Zimmerman combustion, atomized suspension, incineration, sludge barging, landfill, and use as a fertilizer or fertilizer base (3-110). Prior to its ultimate disposal by many of the above mentioned procedures, however, the sludge may have to be dewatered to a certain extent to improve its handling characteristics. By reducing the sludge to 75 percent moisture, sludge can be moved by a shovel or garden fork and transported in non-watertight containers. This, for instance, would facilitate transit to a landfill site, incinerator, or to a removed site in the ocean. Methods of dewatering include: vacuum filters, drying beds, centrifuges, heat dryers, and presses (1-441). This investigation was concerned with the vacuum filtration method of sludge dewatering.

Nature of the Project

One of the primary concerns a community must consider upon adoption of a sludge disposal program is that of operating costs. The operating costs of a vacuum filtration process are relatively high due to the large amounts of chemical coagulants which are generally required to condition the sludge so that it will exhibit its best dewatering characteristics.
This project was undertaken to assess the value of lime-softening sludge as a conditioning agent for digested sewage sludge preceding vacuum filtration.

The sludges studied were obtained from the Sioux Falls Water Treatment Plant and the Sioux Falls Wastewater Treatment Plant. Sioux Falls is presently lagooning both these sludges, but is considering the adoption of a vacuum filtration process for wastewater sludge dewatering.

Very little work appears to have been done regarding the vacuum filtration of combined lime sludge and sewage sludge. Sisk (4) after interviewing a representative of the Komline-Sanderson Company, related that several municipalities throughout the United States have attempted to dewater combined sludges, but obtained unfavorable results. He also reported, as a counterpoint, that Nebraska City, Nebraska and Superior, Nebraska have obtained successful results by adding the lime softening sludge from their water treatment plants directly into the sanitary sewers. The raw combined sludge, accumulated in the primary settling tanks at the sewage treatment plant, was then vacuum filtered. Each of the two cities reported that the cost of conditioning chemicals was greatly reduced and the biochemical oxygen demand reduction of the wastewater was greatly increased in the plant.

Because each sludge exhibits characteristics dependent upon the process from which it was derived, it is necessary that the sludges
used in a study be defined as to their origin. Also important to this study were the amounts of sludge produced at both the water and wastewater treatment plants.

The wastewater treatment plant produces a digested-primary-activated sludge which is presently being lagooned immediately adjacent to the plant. The sludge, which accumulates in the primary settling basins, flows to a sludge thickener and is thereafter pumped to one of four anaerobic digesters. After digestion for a 26 day period, it flows to the lagoons. An average of 200,000 gallons per day (gpd) of sludge is produced with the digested sludge having a solids content of approximately two percent. Figure 1 is an aerial photograph which shows the Sioux Falls Wastewater Treatment Plant and the relatively large area required for sewage sludge lagooning.

The water treatment plant partially softens Sioux Falls' water supply of 10 million gallons per day (mgd). Slaked pebble lime is added to the water in the form of a slurry, with a minimum amount of mixing. Lime sludge production amounts to approximately 144,000 gallons per day, exhibiting an average solids content of about 10 percent. The lime sludge is presently being lagooned in an area in close proximity to the wastewater treatment plant.

**Scope of Data**

This research was undertaken as a follow-up of studies conducted by Sisk (4) at this University. He reported, that the Sioux Falls
Figure 1. Aerial photograph of Sioux Falls Wastewater Treatment Plant
wastewater required elutriation and concentration before it could be effectively vacuum filtered. He also indicated that the addition of lime-softening sludge to the sewage sludge was beneficial for dewatering purposes.

The purpose of this research was to investigate the combination of lime sludge and elutriated sewage sludge which would exhibit the best dewatering characteristics and to further determine the feasibility of the practical use of lime sludge as a conditioning agent. Data were therefore accumulated using the same source of sludges and the advanced knowledge that concentration and elutriation appeared mandatory to obtain desirable results.

A settling column was used to determine relative settling velocities with the various combinations of sludge. Buechner funnel and filter test leaf procedures were used to evaluate filterability of the sludges. Laboratory analyses consisted of pH, alkalinity, and total solids.

The primary concern of this project was the disposal of sewage sludge solids while the disposal of lime sludge solids was considered incidental. Consequently, it appeared that it would not be economically feasible to vacuum filter a sludge containing less than 50 percent sewage sludge solids. Therefore the ratio of lime sludge solids to sewage sludge solids was limited to 1.0 in this study. At Sioux Falls the ratio of lime sludge solids to sewage sludge solids produced per day is about 3.2; therefore, the supply of lime sludge would be sufficient.
REVIEW OF LITERATURE

Introduction

Sludge disposal is one of the most controversial phases of sewage treatment today. The treatment and ultimate disposal of sludge, as an end-product of modern sewage treatment processes, presents a costly as well as a troublesome situation. In essence, the enigma of sewage treatment is the disposal of ever-accumulating sludge (5). Bloodgood (6) summarizes the situation quite well in saying that sludge disposal presents as paramount a problem as the purification of the sewage.

Frequently, the sludge disposal program is considered secondary to other operations in the sewage treatment plant. As a result, trouble is often encountered in a well designed and otherwise properly operated plant. When the solids disposal system is poor, the tendency is to allow the solids to build up in the flow-through treatment units; therefore, the resulting overall efficiency of the treatment plant is decreased.

As previously mentioned, many methods of sludge disposal are available. Cost considerations are of extreme importance in the selection of an appropriate disposal system. Labor costs are presently favoring mechanical methods of sludge handling, and the speediest method of mechanical sludge dewatering is to remove the bulk of the water by some type of filtration (7). In the United States, the most successful mechanical approach has been the vacuum filtration process (5).
There are many inherent advantages which have made vacuum filtration an attractive process for sewage and industrial waste treatment. Among the principle advantages are (8):

1. Plant area requirements are greatly reduced when a small sludge dewatering building is substituted for drying beds or lagoons.
2. Mechanical dewatering can be placed on a routine schedule coordinated with the rest of the plant, and unaffected by weather conditions.
3. Improved plant operation is permitted, and a greater degree of flexibility in plant operation is afforded.
4. Digester requirements may be reduced, since capacity need not be designed into them for winter storage, or it is possible that digesters may be eliminated entirely with the dewatering of fresh sludge.

Description of a Vacuum Filter

A vacuum filter, as illustrated in Figure 2, consists of a hollow cylinder covered with a filtering cloth supported on a wire netting or, as in the Coilfilter, of two layers of steel coil springs placed in corduroy fashion around the filter drum (9-616). Internally, the drum is divided into shallow drainage compartments connected by pipes to automatic valves so that pressure or vacuum can be applied to each individual compartment. Ancillary equipment necessary for vacuum filtration systems include vacuum receivers, filtrate pumps, moisture traps, and vacuum pumps. Figure 3 shows the typical equipment necessary for the filtration process (10-161).

The filter is suspended in a trough containing the sludge to be dewatered at a depth such that 15 to 40 percent of the filter surface is submerged. A vacuum of 12 to 26 inches of mercury is applied to the submerged cells to attach a mat of sludge to the
Figure 2. Rotary drum vacuum filter.

Figure 3. Ancillary equipment typical of a vacuum filtration system.
filter media. The emerging mat is subjected to a drying vacuum of 20 to 26 inches of mercury, and the sludge liquor is drawn into the vacuum cells and returned to the influent of the treatment plant. The dried cake is removed from the filter by a scraper and is carried away for ultimate disposal. If necessary, a slight pressure is applied to the cell of the drum which is about to engage the scraper. This lifts the cake from the media and facilitates its removal (2-786).

Operation of a Vacuum Filter

Filter Cycle. The filter cycle, which is one full revolution of the drum, consists of three parts; the form time, the drying time, and the discharge time (11).

The first part of the cycle, when the drum is submerged, is the cake formation or form time. It is during this part of the cycle that sludge solids are being drawn to the media by the effect of the vacuum and are receiving the initial compression necessary to form a cohesive cake. Initially, the water and fine particles are drawn through the media, leaving only the coarser particles on the face. However, as the drum continues to rotate, and the thickness of the sludge cake is increased, the finer particles are trapped as well as the coarse solids. There is an indication that the rate of cake formation is proportional to the square root of the time elapsed since the start of cake formation, but this is modified by an upper limit of cake thickness beyond which the cake formation
falls rapidly. This upper limit occurs as the flow resistance of the cake approaches the available pressure differential supplied by the vacuum. This consequently places an upper limit, which is the minimum time necessary to form a cake of sufficient thickness to be successfully discharged. Within these limits, the form time can be varied by changing the total cycle time, or by changing the submergence (11).

The second portion of the cycle is the drying time. During this part of the cycle, moisture is removed from the cake and a certain amount of compression takes place. The amount of moisture removed is dependent upon two controlling factors. First, the cake may be compressed to a level beyond which resistance to air flow prevents additional dewatering at the pressure differential available. Secondly, drying may be carried to a point where the cake begins to crack and the pressure differential across the cake drops due to leakage of air through the cracks. The moisture content of the cake may be altered by making adjustments in the total cycle time, or by changing the submergence (11).

The third and final portion of the total cycle time is the discharge time. In the case of a belt type filter, the media with the cake is separated from the drum, the cake is discharged, and the media is washed and returned to the drum. In a scraper discharge filter, however, the media is not separated from the drum, but the cake is discharged by a scraper after being loosened by a compressed air blowback (11).
**Operational Procedures.** It is evident that there is a considerable latitude for adjustment in the control of submergence and cycle time. Other procedural variations also have a considerable effect on filter performance. The following relationships exist (11):

Yield is directly proportional to solids content of feed sludge, cake formation time, and vacuum level. Yield is inversely proportional to total cycle time, cake solids content, and media and cake resistance.

One can readily control a number of the variables listed. For instance, the solids content of the feed sludge can be controlled by varied amounts of concentrational effort. The total cycle time can be changed by varying the speed of rotation of the drum. The ratio of the time used for cake formation to the time used for drying can be changed by varying the drum submergence. In some cases, the vacuum level applied to the drum can be adjusted for either the cake formation part or the cake drying part of the cycle. Finally, with vacuum filters employing cloth media, the filter characteristics can be altered by changing the media. Each of these variables has a definite effect on the filter performance and affords an opportunity for considerable variation of results (11).

**Operational Objectives.** The desired objectives of vacuum filtration vary widely from plant to plant, depending on the different conditions encountered in each case. To substantiate this, three illustrative examples relate the desired objectives with the corresponding operational procedure necessary to attain these objectives (11).
First, consider a sewage treatment plant in which the sludge disposal facilities are overloaded in comparison with the sewage treatment units. Here, the vacuum filters may be the plant "bottleneck", and the entire success of the plant may depend on the ability of the filter to dewater sludge at a rate equivalent to which it is produced. Since the main objective is high filter yield, the filter would possibly operate continuously, and at higher unit costs due to the necessary additional chemical conditioning.

In contrast there are some plants in which vacuum filters are not overloaded and the primary objective is to dewater the sludge as economically as possible. A lower filter yield may be satisfactory in this operation with less chemical coagulants required; thus, unit costs may be reduced to a minimum.

A third objective may be illustrated by a plant in which the sludge cake is ultimately disposed of by incineration. In this instance, the objective of the vacuum filtration process is to produce a cake of the lowest possible moisture content so as to reduce the costs of auxiliary fuel required for incineration (11). For instance, if the moisture in the sludge cake increases from 75 to 80 percent, the resultant increase of pounds of water per pound of dry solids is from 3 to 4, or an increase of 33 percent (12).

Selection of Filter Media

The selection of an appropriate filter media is extremely important in the performance and life of the filter. As far as filter
performance, the media affects the quality of the filtrate, the filtration rate, and the degree of blinding. The life of the filter coordinately affects the economics of the situation.

Among the media selections available are stainless steel fabrics, coil springs, and a variety of cloth media, including many man-made synthetics as well as natural fibers. Concerning the cloth media, materials that have been used and studied include: cotton, untreated wool, treated wool, vinyon, nylon, saran, dynel, orlon, dacron, and various combinations of the preceding (9-616).

Cloths with close weave, such as flannel or napped wool, make a fairly impervious strainer and are capable of giving filtrates of very low solids content, on the order of 100 to 200 mg/l of suspended solids. Such close weaves require more frequent washing, give lower yields because of higher resistance to air flow, and tend to be short-lived (11). Also, with close weaved media there are more operational difficulties, such as filter blinding. This phenomenon occurs when fine particles become imbedded in the interstices of the cloth. As a result, the porosity of the cloth is reduced and excessive resistance to the passage of air and filtrate is encountered, which is directly reflected in lower filter rates (13).

Cloths made of synthetic fibers are generally more abrasion-resistant, have a much longer life, and often are used in somewhat coarser weaves. Synthetic materials tend to stay cleaner than cotton or wool and are easier to clean when they do become dirty. Although
the initial cost of the synthetic fiber is greater, the higher cost is usually compensated for by the correspondingly lower maintenance cost (11).

Woven, stainless steel fabric or coil springs comprise the most recent advances in the field of vacuum filtration. This type of media possesses several inherent advantages over cloth media, despite its higher initial cost. The use of metallic media permits more rapid rotation of the drums, a thinner cake can be handled, and the life of the media is longer (9-618). Because the media can be flexed and spray washed during operation, filter blinding is rarely experienced (13).

**Sludge Characteristics Affecting Filterability**

Most of the sludge characteristics that effect filterability vary with the sludge source. Fresh sludges generally are more filterable after chemical conditioning than digested sludges, and primary sludges are generally more filterable than secondary sludges (7).

**Solids Particles.** The size, shape, and density of the solid particles of a sludge affect filterability due to the role they play in compaction and in the requirements of coagulating chemicals. Irregularly shaped and sized particles, or small particles have a tendency to form a compact mat under vacuum, therefore leaving a small ratio of voids for migration of liquid. It has been found that the smallest particles of sludge exercise the greatest coagulating chemical demand per unit of solids (7)(8). For example, during the digestion
process, the particle size is reduced, and fibrous material is broken down into a homogeneous mixture having a smaller particle size. As a result, digested sludge is more difficult to filter than raw sludge (14).

Particles of compressible sludges tend to deform with increasing pressure, and the result is a tighter filter cake that resists liquid separation. Genter indicates that the compressibility of sludge solids is a direct function of organic matter (7).

**Chemical Composition.** The chemical composition of a sludge is the primary factor which controls the amounts of chemicals required for conditioning. The coagulant or conditioner requirements of sludge may be comprised of two parts: the liquid demand and the solids demand. The chemical demand of the liquid fraction of the sludge which is exerted by the alkalinity or bicarbonates utilizes the conditioner before it can achieve its primary objective, that of coagulation (2-782). The solids fraction, in turn, exerts its demand which is dependent upon the volatile-to-ash ratio of the sludge. Thus, the coagulant demand of the sludge is directly proportional to the alkalinity and volatile or organic matter in the sludge (15).

Digested sludges generally require more conditioning chemicals than do fresh sludges. This is attributed to the gain in bicarbonate alkalinity during the process of anaerobic digestion. During digestion, the anaerobic bacteria convert the putrescible compounds to methane, carbon dioxide, and ammonia. The carbon dioxide then combines with ammonia in water to form ammonium bicarbonate, resulting
in an increase in the alkalinity. Therefore, although the solids demand of the sludge is reduced due to the reduction in volatile matter, the liquid demand is substantially increased by the presence of the newly formed bicarbonates of ammonia (16).

In summary, where the alkalinity is relatively low as in primary sludge and elutriated sludge, most of the chemical coagulant is used for the solids demand. The opposite is true in the case of un-elutriated digested sludges in which, despite lower volatile-to-ash ratios, the high alkalinity makes the liquid demand predominant in coagulant requirements (15).

Concentration. It is a well established fact that an increase in concentration of the solids of a sludge produces a corresponding increase in filtration rate (7)(8)(17). Shepman and Cornell (17) have shown a linear relationship between feed concentration and filter rate over a wide range of solids concentrations. This is understandable, for as the feed solids concentration is increased, less filtrate results for each unit of cake solids deposited and the filter loading increases (18-280). Although most sewage sludges exhibit a linear relationship, their slopes vary markedly as do the absolute values of the filtration rates.

Several methods are available to accomplish sludge concentration prior to filtration. Trubnick and Mueller (8) cite three methods generally used: (a) secondary digesters promote sludge thickening
by providing a means of quiescent settling and also by allowing the thorough release of gases adhering to the sludge particles; (b) elutriation, in addition to reducing the alkalinity, frequently promotes a concentration of digested sludge solids; (c) mechanical thickening, either by slow agitation with revolving rakes equipped with picket arms, or by aeration, is an effective means of concentrating either fresh or digested sludge.

**Conditioning of Sewage Sludge Prior to Vacuum Filtration**

The nature of a sludge is dependent upon the characteristics of the sewage flow and the type of treatment it has received. To alter the sludge characteristics such that the sludge will be amenable to vacuum filtration requires some method of conditioning. The conditioning process strives for the following characteristics (9-619):

(a) The suspended solids must be readily separated from the liquid.

(b) The solids must form a cake which is sufficiently thick to be easily removed from the filter media.

(c) The liquid must drain well from the solids through the filter media.

(d) The sludge cake formed must be porous to permit drying.

Methods of treatment used to condition sludge include digestion, concentration, elutriation, mixing, and chemical addition. Substances
which have been added to condition sludge include sulfuric acid, sulfur dioxide, ferric sulfate, alum, bone ash, peat, ground garbage, paper pulp, ashes, and clay (19). The chemicals most commonly used, however, are ferric chloride, either with or without lime (19), and the relatively new polyelectrolytes.

**Chemical Conditioning.** Little information could be found in the literature relating to the mechanism of the influence of coagulants for conditioning sludge. The mechanisms of coagulation for chemical conditioning of sludge may, however, parallel coagulation mechanisms in water.

Coagulation results from two mechanisms: electrokinetic coagulation, in which the zeta potential of the negatively charged solids particles is reduced by ions of opposite charge to a level below the van der Waals attractive forces; and orthokinetic coagulation, in which a precipitate or floc is formed thereby providing a nucleus for the agglomeration and enmeshment of colloidal particles (20-90).

Since the vast majority of colloids in water, and probably in a waste sludge, possesses a negative charge, the zeta potential of the solids particles is lowered and coagulation is induced by the addition of high-valence cations (20-90). The Shulze-Hardy Rule states that the coagulating power of ions of opposite charge rises rapidly with an increase in valence; i.e., the flocculating power of bivalent ions is approximately 20-80 times that of univalent ions, and the flocculating power of trivalent ions is 10-100 times that of bivalent ions (21).
The most commonly used high-valence cation for sludge conditioning is the Fe+++ ion in the form of ferric chloride. This chemical is generally added with lime (CaO) in the conditioning process.

The probable role that ferric chloride plays in the conditioning process is not only electrokinetic in nature, but also orthokinetic. The ferric chloride reacts with the bicarbonate alkalinity forming the precipitate ferric hydroxide as shown by the following equation (11):

$$2 \text{FeCl}_3 + 3 \text{Ca(HCO}_3\text{)}_2 \rightarrow 2 \text{Fe(OH)}_3 + 3 \text{CaCl}_2 + 6 \text{CO}_2$$

Similarly, the addition of hydrated lime results in a series of reactions which forms the precipitate of CaCO$_3$. This is illustrated by the reaction of lime with ammonium bicarbonates as follows (11):

$$\text{NH}_4\text{HCO}_3 + \text{Ca(OH)}_2 \rightarrow \text{CaCO}_3 + 2 \text{H}_2\text{O} + \text{NH}_3$$

The role of these two chemicals, involving precipitation of chemical salts, is orthokinetic in nature. That is, the precipitate forms a nucleus for the agglomeration and entrapment of fine sludge particles which may then be removed by the filter media (11).

Genter (15) has formulated a method of determining the ferric chloride and lime requirements for sludge conditioning that considers solids concentration, alkalinity, and percent volatile solids of the sludge, and the relative cost and conditioning effectiveness of the lime and ferric chloride.

Trubnick and Mueller (8) reported that the type of lime used has a bearing on the efficiency of filtration. The conditioning value is
dependent upon the calcium oxide content of the lime and not upon its calcium or magnesium content. Tests have shown that magnesium hydroxide is ineffective as an aid to filtration.

The sequence in which the lime and ferric chloride are added also can have a profound effect upon the filter rate. In a particular digested sludge tested by Trubnick and Mueller (8), a lower sludge resistance was evidenced when the ferric chloride was added first up to 5.5 percent dosage. At greater ferric chloride dosages the sequence of addition did not appear to be a factor.

There is varied opinion as to the effects of overdosing of ferric chloride in the filter operation. Although it is generally agreed that overdosing is an uneconomical practice, there is some dispute on whether a decreased yield results. Trubnick and Mueller (8) and Simpson (11) indicated reduced yields by overdosing with ferric chloride, whereas Brown (14) contended that overdosing neither increased nor decreased filter yields. Overdosing with ferric chloride does lower the pH, however, which in turn results in a decreased colicidal effect (8).

Use of Lime Sludge as a Conditioner. The use of lime sludge from a water softening process could prove beneficial for conditioning sewage sludge for vacuum filtration for the following reasons:

(a) Lime softening sludge frequently contains significant amounts of unspent lime which would combine with the bicarbonate alkalinity and induce orthokinetic coagulation.
(b) Lime sludge, which is primarily calcium carbonate, may aid in the formation of a more porous cake in the vacuum filtration process, thereby increasing the filter rate.

Sisk (4), in studying the effects of a lime softening sludge on a digested-primary-activated sludge, concluded that the addition of lime sludge proved beneficial for sludge dewatering on the basis of specific resistance and combined filter yield determinations.

Two cities in Nebraska, Nebraska City and Superior, have indicated that successful results were obtained in the vacuum filtration process when the water softening sludge was discharged directly into the sanitary sewer. Vacuum filtration was then performed on the raw combined sludge from the primary settling tanks at the sewage treatment plant. Chemical costs were greatly reduced and the biochemical oxygen demand reduction was increased in the plant (4).

Use of Elutriation for Sludge Conditioning. Sludge elutriation is essentially a process of adding water or plant effluent to the sludge, mixing thoroughly, and allowing the sludge to settle. Two basic results are obtained: (a) there is a marked decrease in the alkalinity of the settled sludge and (b) improved settling conditions are evidenced (22).

Sludge elutriation is generally practiced with digested sludge to reduce the high alkalinity produced in the digestion process. The alkalinity of digested sludge generally ranges between 3,000-4,000 mg/l
and therefore exhibits an extremely high liquid demand for coagulants. The simplest method of removing this liquid demand is by some dilution technique, mainly elutriation. The elutriation process may be carried out in single stage, multiple stage (series), or two stage countercurrent operation; the last method accomplishing the greatest amount of sludge washing with the least amount of water (7). Genter (15) has formulated a method of computing elutriation ratios which is based on the alkalinitities of the wash water and the sludge water, and the alkalinity desired in the elutriated sludge.

Elutriation, in addition to removing alkalinity and reducing coagulant demand, frequently promotes improved settling conditions of the sludge. Torpey and Lang (23) showed that satisfactory increases in sludge concentration were obtained by elutriation of digested sludge. They showed that elutriation more than doubled the solids concentration and that a single stage elutriation tank is as effective in concentrating digested sludge solids as a secondary digester with 12 times the volume.

In the elutriation of digested sludge, the floc concentrates and the mass settles as a blanket forming a distinct interface between the floc and supernatant. The settling process, called zone settling, may be distinguished by three zones, the hindered settling zone, the transition zone, and the compression zone (18-167).

During the initial settling period, the sludge floc settles at a uniform velocity under conditions of hindered settling. The
magnitude of this velocity is a function of the solids concentration and the flocculation characteristics of the suspension. The concentration of solids will remain constant during hindered settling until the settling interface approaches an interface of critical concentration. As the depth of the settled sludge solids decreases, the floc begins to press on layers below and a transition zone occurs. In the transition zone, the settling velocity will decrease due to the increasing density and viscosity of the suspension surrounding the particles. The compression zone occurs when the floc concentration becomes so great as to be mechanically supported by the layers of floc below. The concentration of solids in the compression zone is related to the depth of sludge and the detention of the solids in this zone (18-167). The original components of a digested sludge, the time of digestion, the degree of digestion, and numerous other factors all influence the velocity-concentration curve displayed by a particular sludge (24).

Procedures for Evaluating Sludge Filterability

**Buechner Funnel.** The Buechner funnel test, up until about 1955, was used widely as a measure of sludge filterability. The test usually involved filtration of a given volume of sludge under a vacuum until a cake was formed which eventually cracked and resulted in a drop in pressure. The time to reach this point was frequently taken as a measure of the filterability of a sludge. Obviously, the
time before the cracking point was reached depended on a number of variables. These were as follows (25):

1. The initial solids content of the sludge.
2. The volume of sludge filtered.
3. The area of the filtering surface.
4. The pressure at which the filtration is carried out.

In much of the published work on filtration, these variables were not recorded, and even when they were it was impossible to make any direct comparison of the results obtained (25). For this reason, this test is seldom used at present.

**Specific Resistance.** In view of the disadvantages of the Buechner funnel test, an investigation into the application of the various theories of filtration of sewage sludge was carried out. Preliminary work by Carman in 1933 using Poiseuilles and D'Arcy's laws, laid the foundation for the concept of specific resistance as formulated by Coackley (25). The specific resistance is numerically equal to the pressure differential required to produce a unit rate of filtrate flow of unit viscosity through a unit weight of cake (20-237).

The rate of sludge filtration as developed by Carman and extended by Coackley is as follows (20-236).

\[
\frac{dV}{dt} = \frac{PA^2}{\mu(rcV + R_mA)} \tag{Equation 1}
\]

- \(V\) = volume of filtrate
- \(t\) = cycle time (approximates form time in continuous drum filters)
- \(P\) = vacuum
- \(A\) = filtration area
- \(\mu\) = filtrate viscosity
Integration of Equation 1 yields:

\[
\frac{t}{V} = \frac{\mu c}{2 \rho A^2} V + \frac{\mu R_m}{\rho A}
\]  

(Equation 2)

From Equation 2 a linear relationship results from a plot of \(\frac{t}{V}\) versus \(V\). The specific resistance can be computed from this plot:

\[
r = \frac{2b \rho A^2}{\mu c}
\]  

(Equation 3)

where \(b\) is the slope of the plot of \(\frac{t}{V}\) versus \(V\). The weight of solids per unit of volume of filtrate \(c\) is computed from the following relationship:

\[
c = \frac{1}{c_i/(100 - c_i) - c_f/(100 - c_f)}
\]  

(Equation 4)

where \(c_i\) = initial moisture content of the sludge
\(c_f\) = final moisture content of the sludge

The laboratory method of determining specific resistance utilizes essentially the same apparatus as employed for the Buechner funnel test; however, additional data are recorded.

Table 1 shows specific resistance data obtained by Coackley and Jones (25) using digested sludge and data obtained by Sisk (4) using digested-primary-activated sludge. From the data obtained by Coackley and Jones, it is apparent that elutriation greatly
reduces the specific resistance, as does ferric chloride dosages.

The data obtained by Sisk (4) indicate reduced specific resistance by conditioning with lime sludge.

Table 1.
Comparison of Specific Resistance of Conditioned Sludges.

<table>
<thead>
<tr>
<th>Sludge</th>
<th>FeCl₃ Dosage¹</th>
<th>Specific Resistance sec²/gram</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Digested (25)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Not elutriated</td>
<td>0</td>
<td>160 x 10⁸</td>
</tr>
<tr>
<td>b) Not elutriated</td>
<td>13.3</td>
<td>0.92 x 10⁸</td>
</tr>
<tr>
<td>c) Elutriated</td>
<td>0</td>
<td>11 x 10⁸</td>
</tr>
<tr>
<td>d) Elutriated</td>
<td>13.5</td>
<td>0.35 x 10⁸</td>
</tr>
<tr>
<td>B. Digested-Primary-Activated (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Not elutriated</td>
<td>15</td>
<td>11 x 10⁸</td>
</tr>
<tr>
<td>b) Not elutriated (50% lime sludge)</td>
<td>15</td>
<td>2.0 x 10⁸</td>
</tr>
<tr>
<td>c) Elutriated</td>
<td>10</td>
<td>2.4 x 10⁸</td>
</tr>
<tr>
<td>d) Elutriated (50% lime sludge)</td>
<td>10</td>
<td>1.1 x 10⁸</td>
</tr>
</tbody>
</table>

¹ As percentage of total sludge solids.

Filter Yield. The most commonly used method of predicting and measuring filter performance is by determining filter yield. Filter yield is a measure of the total cake output of a filter expressed as pounds of dry weight of total solids discharged per square foot of effective area per hour of operation (11).

Laboratory determination of filter yield is accomplished by a filter test leaf procedure. This test involves the use of a small
test leaf which is essentially a model of the filter to be used. By simulating the vacuum, media, and cycle time of the actual vacuum filter to be used, a prediction can be made concerning its performance. Jones (26) reported that reasonable agreement was obtained between predicted and measured yields for vacuum filters.

The filter yield, expressed in units of lb/ft$^2$/hr, is computed as follows (18):

$$\text{Filter Yield} = \frac{\text{dry weight sludge (grams) x cycles/hr}}{453.6 \text{ grams/lb} \times \text{test leaf area (ft}^2\text{)}}$$

Shepman and Cornell (17) in a survey of filter yields from actual plant operations showed that a properly conditioned digested-primary-activated sludge produced a yield of about 3.0 lb/ft$^2$/hr. Filtration of the type sludge when elutriated produced yields ranging from 3.4 to 6.3 lb/ft$^2$/hr.

Sisk (4), utilizing the filter test leaf procedure with a digested-primary-activated sludge, obtained the following results as shown in Table 2:

<table>
<thead>
<tr>
<th>Conditioning</th>
<th>Filter Yield (lb/ft$^2$/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Not elutriated</td>
<td></td>
</tr>
<tr>
<td>a) 10% FeCl$_3$</td>
<td>0.05</td>
</tr>
<tr>
<td>b) 10% FeCl$_3$, 50% lime sludge</td>
<td>0.13</td>
</tr>
<tr>
<td>B. Elutriated</td>
<td></td>
</tr>
<tr>
<td>a) 10% FeCl$_3$</td>
<td>0.45</td>
</tr>
<tr>
<td>b) 10% FeCl$_3$, 50% lime sludge</td>
<td>0.25</td>
</tr>
</tbody>
</table>
From these data, it may be seen that although extremely low yields were obtained, elutriation did result in an improved filter rate.
Throughout this study, it was very important to follow exacting testing procedures so that the results obtained could be justly and accurately compared. That is, when a series of sewage sludge samples was conditioned with varied proportions of ferric chloride or lime sludge, they could be compared, relative to one another, with a high degree of confidence. In order to obtain reproducible and comparable data, a definite methodology was developed for the sampling and laboratory procedures.

**Sampling Procedures**

When the two waste sludges, lime sludge and sewage sludge, were collected from their respective treatment plants, large volumes were obtained at one time; i.e., 25 gallons of sewage sludge and 5 gallons of lime sludge. This procedure was followed so that a series of tests could be run on a particular sludge sample and results compared without the interference involved with using different sludges. The sludges collected were refrigerated, so as to restrict further biological degradation of the sludge which could alter its physical and/or chemical characteristics.

From this gross amount of sludge, it was necessary to obtain a representative sample to work with for ensuing tests. In order to obtain a representative sample, a stirring mechanism was used.
to assure complete mixing and uniform solids content throughout
the large sludge volume whenever a sludge sample was being drawn.
This apparatus is shown in Figure 4.

Methods of Sludge Elutriation

Two methods were utilized to accomplish elutriation of the
sludge, each being used depending upon the objectives desired.
First, a settling column was used to study the effects of lime
sludge on the settling characteristics of the combined sludge
while simultaneously elutriating. Secondly, a 50 gallon barrel
was used to obtain a large volume of elutriated, concentrated
sludge.

Utilizing a graduated settling column, as shown in Figure 5,
it was possible to elutriate and accrue settling data simultaneously.
Various proportions of lime sludge and sewage sludge were added
during the elutriation process, and the resulting concentrated
sludge was evaluated as to its dewatering characteristics. Also,
the sludge and the supernatant were analyzed for alkalinity and
total solids concentrations. The following elutriation procedure
was used with the settling column:

1. The total solids content was determined for each sludge,
lime sludge and sewage sludge, in accordance with Standard
Methods for the Examination of Water and Wastewater (27-534).
2. Eleven liters of unconcentrated sewage sludge were placed
into the settling column.
Figure 4. Stirring apparatus used to maintain uniformity of sludge samples.

Figure 5. Settling column used for elutriation and concentration of sludge.
3. A calculated amount of lime sludge was added, depending upon the proportion desired. See Appendix I for sample calculation.

4. The settling column was filled to the 44 liter level with tap water, thereby making an elutriation ratio of one volume of sludge to three volumes of water.

5. Air was blown into the bottom of the test cylinder for two minutes to assure complete mixing.

6. The combined sludge was allowed to settle to one-half the original sludge volume during which time the height of the solid-liquid interface was recorded at regular time intervals.

7. A sample of supernatant from the tap at the two foot depth was drawn off.

8. The remaining supernatant was siphoned from the cylinder and the sludge drawn off.

9. Alkalinity and total solids determinations were run on the supernatant and a total solids determination of the sludge was made.

10. Specific resistance and filter leaf tests were performed on the elutriated sludge.

Using a similar methodology, but with a 50 gallon barrel instead of a settling column, larger volumes of sewage sludge were elutriated without lime sludge additions. That is, 12 gallons of sewage sludge
were elutriated with 36 gallons of tap water, and concentrated by settling to yield 6 gallons of elutriated sludge.

**Methods of Sludge Conditioning**

The sewage sludge was chemically conditioned by adding ferric chloride, lime sludge, and lime (CaO) in various combinations and sequences. These included: (a) elutriation with lime sludge followed by ferric chloride dosages, (b) elutriation, followed by lime sludge and ferric chloride additions, and (c) elutriation, followed by ferric chloride and lime (CaO) dosages. As reported in the literature (2-782), the chemical dosages were expressed as a percentage of the pure chemical to the weight of the solids fraction on a dry basis.

The ferric chloride in each phase of the experiment was added in dosages of 5, 10, and 15 percent of the total solids. In the case of elutriation with lime sludge, these were percentages of the total lime sludge plus sewage sludge solids; whereas, in the case of elutriation with tap water only, dosages were made on the basis of the percent of sewage sludge solids. Lime sludge was added at various percentages of total sludge solids ranging from 0 to 50 percent. Lime (CaO) was similarly added at dosages ranging from 0 to 16.7%.

The following procedure was used in conditioning the sewage sludge:
1. A predetermined amount of lime sludge was added to 700 ml of elutriated sewage sludge in a one liter beaker. Lime sludge quantities were computed similar to the sample calculation in Appendix I.

2. The sludge was mixed for 30 seconds at 140 revolutions per minute (rpm) using a gang stirring apparatus.

3. A predetermined amount of ferric chloride was added to the mixture and mixed for three minutes at 140 rpm. See Appendix II for sample calculation.

4. The specific resistance and filter yield determinations were performed on the conditioned sludge.

Step one was eliminated when elutriation was performed with lime sludge, since the lime sludge would have previously been added. Also, steps one and three were interchanged in cases where the sewage sludge was conditioned by adding the ferric chloride before the lime sludge.

**Specific Resistance Test Procedure**

The Buechner funnel test apparatus, used in determining the specific resistance, is shown in Figure 6, and includes a vacuum source, vacuum gage, Buechner funnel, 500 ml graduated cylinder, stopwatch, and appropriate valving to regulate the pressure.

The procedure used for this test was taken from procedures outlined by Sisk (4) and Eckenfelder and O'Connor (18-284) and was as follows:
1. The solids content and temperature of the feed sludge were determined.

2. A vacuum was applied to a moistened filter paper (No. 2, Whatman) to obtain a seal.

3. The vacuum was turned off and a 100 ml sludge sample was poured into the funnel.

4. After a suitable time was allowed for a cake to form (5-15 seconds), the desired vacuum of 18 inches of mercury was applied.

5. The filtrate volume was recorded at frequent time intervals until the cake cracked and a vacuum break occurred.

6. The solids content of the final cake was determined.

The filtrate volume was recorded at 10 second intervals for the first two minutes, at 30 second intervals from two to five minutes, and at two minute intervals thereafter.

The solids content of both the initial sludge feed and the final filter cake was determined by methods prescribed in Standard Methods (27-534).

The results of this test are utilized in the calculation of the specific resistance of the sludge. See Appendix III for the sample calculation.

**Filter Test Leaf Procedures**

The apparatus used to perform the filter leaf test, as shown in Figure 7, included a vacuum source, vacuum gage, filtrate flask,
Figure 6. Buechner funnel test apparatus.

Figure 7. Filter test leaf apparatus.
stopwatch, filter test leaf, and appropriate valving. The filter media used on the filter test leaf was a synthetic cloth (Eimco-Corporation's POPR - 859, 2/2 Twill, Monofilament yarn, with a 68 x 30 thread count).

The filter test leaf was circular in shape, and had an area of 0.1 square foot. The filter media was clamped onto the test leaf by means of a stainless steel band and filter leaf supports were inserted between the band and the test leaf to prevent the leaf from touching the bottom of the pan. The test leaf, which was fitted with a 1/2 inch pipe nipple and shutoff valve, was connected to a filtrate receiver which was attached to a vacuum source.

The procedure was that used by Sisk (4) who adapted it from methods outlined in the Nalco Chemical Company Bulletin Number TF 52 (28) and another published procedure (18-284). The procedure is as follows:

1. Conditioned sewage sludge, about 600 ml, was poured into a container of suitable size to hold the sludge and accommodate the filter leaf.

2. The filter leaf was immersed in the sludge sample for 1 1/2 minutes during which time a vacuum of 18 inches of mercury was applied. This represented the form time of the filter cycle.

3. Maintaining this vacuum, the leaf was then withdrawn and held in a vertical position for three minutes. This represented the drying time of the filter cycle.
4. The vacuum was turned off, and a 1 1/2 minute discharge time was simulated.

5. The filter cake was removed with a spatula and dried in a 103°C oven for at least 24 hours. It was then weighed to determine the amount of dry sludge.

It can be seen from the three portions of the simulated filter cycle, the 1 1/2 minute form time, the 3 minute drying time, and the 1 1/2 minute discharge time, that a total cycle time of six minutes was accrued. This correspondingly, represented 10 cycles per hour.

As previously described in the literature review, the filter test leaf procedure is necessary to determine the filter yield obtained with a specific sludge. See Appendix IV for the sample calculation.
PRESENTATION OF RESULTS

Introduction

The characteristics evaluated in this study were selected on the basis of the conclusions made by Sisk (4). He concluded from the results of his experimentation, that the sludge studied had to be elutriated and concentrated before it could be vacuum filtered effectively. He also indicated that the addition of lime sludge was beneficial for conditioning sewage sludge, based on the filterability of the combined sludges. Thus, the foundation for this investigation was constructed on the basis of the previous information.

The elutriation process was conducted by maintaining a constant elutriation ratio of 3 to 1, and varying the percent lime sludge solids addition from 0 to 50 percent on a dry weight basis. Comparison of these various proportions of lime sludge to sewage sludge solids was made on the basis of settling characteristics of the sludge and sludge filterability.

Effect of Elutriation with Lime Sludge on Settling Characteristics

The effect on the settling characteristics of the sewage sludges with varied additions of lime sludge are shown in Figure 8, a plot of time of settling versus height of solids-liquid interface. The settling velocities of the three combinations of lime sludge and sewage sludge were essentially the same as sewage sludge alone as indicated by their similar slopes in the hindered settling zone.
Figure 8. Settling characteristics of sewage sludge elutriated with varied percentages of lime sludge
The approximate settling velocity was found to be 13.3 ft/hr. The rate of compression of each of the sludge combinations was also quite similar as represented by the comparatively equal slopes in, the compression zone. It was determined that it took about 6 hours for the sludge to settle to its original volume and substantially greater lengths of time were required to further concentrate the sludge.

**Filterability of Sewage Sludges Elutriated with Lime Sludge**

Elutriation of sewage sludge with varied additions of lime sludge was also evaluated on the basis of the filterability of the elutriated sludge. The sewage sludge, elutriated with varied portions of lime sludge, was conditioned with ferric chloride additions of 5, 10, and 15 percent. The specific resistance and filter yield were determined for each dosage of ferric chloride and for each respective lime sludge addition.

Increased ferric chloride dosages and/or lime sludge additions resulted in a definite decrease in specific resistance and a corresponding increase in filter yield. The decreased specific resistance is shown by a plot of percent lime sludge versus specific resistance for varied ferric chloride additions in Figure 9. The resulting increase in filter yield is shown by a plot of percent ferric chloride dosage versus filter yield at varied lime sludge additions in Figure 10.
Figure 9. Specific resistance of sewage sludges elutriated with various proportions of lime sludge and conditioned with varied dosages of ferric chloride.
Figure 10. Filter yield of sewage sludges elutriated with various proportions of lime sludge and conditioned with varied dosages of ferric chloride.
Effect of Sequence of Chemical Additions on the Filterability of Elutriated Sludge

After determining the filterability of sewage sludge elutriated with lime sludge, it was deemed necessary to evaluate the filterability of sewage sludge elutriated with tap water only, and to compare the two elutriation procedures on the basis of sludge filterability. Preceding this comparison, it was required that the sequence be determined for adding the conditioners, lime sludge and ferric chloride, which would yield the better dewatering characteristics for the elutriated sludge. The two sequences of chemical addition were:

1. Ferric chloride dosages followed by lime sludge additions.
2. Lime sludge additions followed by ferric chloride dosages.

The specific resistance results, as shown graphically in Figure 11, indicate that at the lower lime sludge addition (25 percent) there was little difference whether the lime sludge or ferric chloride was added first. However, at a high percentage of lime sludge addition (50 percent) it appeared that adding ferric chloride first was the better method.

Comparison of Elutriation Procedures

After determining the better sequence of chemical addition using sludge elutriated with tap water, it was possible to compare
Figure 11. Specific resistance as influenced by the sequence of adding ferric chloride with 25 percent and 50 percent lime sludge solids.
these results with the results obtained by elutriating with lime sludge. The comparison was made on the basis of the specific resistance and filter yield of the sludges.

The comparison, from the standpoint of specific resistance, is shown in Figure 12(A) which is a plot of specific resistance versus percent lime sludge solids for a 15 percent ferric chloride addition. Lower resistances were evidenced when using sewage sludge elutriated with lime sludge compared with sewage sludge elutriated with tap water. Correspondingly, Figure 12(B) which is a plot of filter yield versus percent ferric chloride for a 50 percent lime sludge addition, shows higher filter yields for the sludge elutriated with lime sludge.

Before making any definite conclusions to the effect that elutriation with lime sludge was the better method, it was considered that the ferric chloride was not added on the same basis in the two methods. That is, in elutriating with lime sludge the ferric chloride was added as a percent of the combined sludge solids; whereas, in elutriating with tap water only, the ferric chloride was added as a percent of the sewage sludge solids.
Figure 12. Comparative relationship of elutriation with lime sludge and elutriation with tap water on the basis of filter yield and specific resistance.
DISCUSSION OF RESULTS

Elutriation with Lime Sludge

The two basic parameters used for the evaluation of a sludge's settling characteristics, those of settling velocity and rate of compression, were generally not improved by the addition of lime sludge in the elutriation process. Regardless of the percentage of lime sludge added, it was found that it took about 6 hours for the sludge to settle to its original volume and substantially longer periods of time to further concentrate the sludge. Consequently, in viewing the effect of increasing lime sludge additions in the elutriation process, it may be stated that the settling characteristics of the sludge were not significantly altered. Also, concerning the quality of the supernatant in the elutriation process, it was found that there was no appreciable difference in the total solids content or the alkalinity with increased additions of lime sludge. This can be seen from the following table:

Table 3.
Solids Content and Alkalinity of the Supernatant Resulting from Elutriation with Increasing Lime Sludge Additions

<table>
<thead>
<tr>
<th>Percent Lime Sludge Solids</th>
<th>Total Solids in Supernatant (mg/l)</th>
<th>Alkalinity in Supernatant (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.6</td>
<td>1530</td>
<td>1047</td>
</tr>
<tr>
<td>37.5</td>
<td>1520</td>
<td>980</td>
</tr>
<tr>
<td>50.0</td>
<td>1460</td>
<td>998</td>
</tr>
</tbody>
</table>
Increased additions of lime sludge in the elutriation process did, however, have a beneficial effect on the filterability of the combined sludges. The increased filter rate could be attributed to the higher solids concentration resulting from increased percentages of lime sludge additions. For instance, the settled sludge from the 16.7 percent lime sludge addition had a total solids content of 3.55 percent; whereas, the settled sludge from the 50 percent lime sludge addition had a total solids content of 5.94 percent. Both samples of combined sludges were settled for approximately the same length of time to essentially the same volume. The increase in filter rate with corresponding increases in solids concentrations was in agreement with the literature. Shepman and Cornell (17) have shown that as the feed concentration increased, the filter rate proportionately increased.

Consequently, it has been shown that increased lime sludge addition, incorporated in the elutriation process, enhanced the filterability of the sludge, but was of little or no advantage in improving the settling characteristics and in concentrating the sewage sludge.

**Sequence of Chemical Addition**

Using sewage sludge elutriated with tap water, and the conditioning agents ferric chloride and lime sludge, the sequence of chemical additions which would yield the better dewatering
characteristics was determined. It was found that the elutriated sludge conditioned first with ferric chloride and then with lime sludge exhibited the better dewatering characteristics on the basis of specific resistance and filter yield determinations. This was found to be true only at high lime sludge additions, with little, if any, difference exhibited at low lime sludge additions.

Trubnick and Mueller (8) have shown similar results using ferric chloride and lime (CaO) as conditioning agents. Lime sludge, consisting primarily of calcium carbonate (CaCO₃), does contain relatively small amounts of unspent lime (CaO); therefore, there is a justifiable comparison between the results obtained in this study with those of Trubnick and Mueller. In correlation with the literature, it was found that the better sequence of chemical additions after elutriation was ferric chloride dosages first, followed by lime sludge additions.

**Comparison of Elutriation Procedures**

In comparing the results from the two basic elutriation procedures, elutriation with lime sludge and elutriation with tap water, it appeared that better filter rates were obtained by elutriating with lime sludge. However, when using sludge elutriated with lime sludge, the ferric chloride dosages were calculated and added as a percentage of the combined lime sludge plus sewage sludge solids; whereas, in elutriating with tap water, the ferric chloride dosages were calculated and added only as a percentage.
of the sewage sludge solids present. Thus, the increased filter-
ability when elutriating with lime sludge may have resulted from 
the greater amount of ferric chloride added to represent a given 
percentage. Because comparative ferric chloride dosages did not 
exist, no definite conclusion was drawn concerning the addition of 
lime sludge during the elutriation process.

Feasibility of Practical Use of Lime Sludge as a Conditioning Agent

The results have shown that increasing additions of lime sludge 
have produced improved dewatering characteristics on the basis of 
specific resistance and filter yields of the combined sludges. 
However, because the primary concern of this project was the dis-
posal of sewage sludge solids, the results should be interpreted 
on that basis as opposed to a combined sludge solids basis. That 
is, the filter yields should be compared on the basis of sewage 
sludge yields instead of combined sludge yields.

To adjust the combined sludge yields to sewage sludge yields, 
the filter cake was considered to be of the same proportion of 
lime sludge solids as the mixture from which the cake was derived. 
For example, if the combined sludge yield from a sludge consisting 
of 50 percent lime sludge solids was 2.4 lb/ft²/hr, the sewage 
sludge yield would be 50 percent of the combined sludge yield or 
1.2 lb/ft²/hr. By adjusting all of the filter yields in this 
manner, a more realistic evaluation could be made of the effective-
ness of lime sludge as a conditioning agent.
The relative effectiveness of various lime sludge additions on the computed yield of sewage sludge solids is shown in Figures 13 and 14. Both figures are plots of "computed" sewage sludge yields versus percent ferric chloride dosages for varied lime sludge additions. Figure 13 is a graphical presentation of the results obtained by elutriating with tap water; whereas, Figure 14 is a similar presentation of the results obtained by elutriating with lime sludge. Both elutriation procedures exhibited quite similar results as follows:

1. There was a slightly higher sewage sludge yield with large lime sludge additions (50 percent) and low ferric chloride dosages (less than 10 percent) compared to yields without lime sludge additions.

2. At ferric chloride dosages of greater than 10 percent, a lower sewage sludge yield was produced with additions of lime sludge compared to yields without lime sludge additions.

3. Computed sewage sludge yields ranged up to 1.5 lb/ft$^2$/hr compared to a range of 3.4 to 6.3 lb/ft$^2$/hr which were reported as satisfactory values in the literature.

Evidence of the incapability of lime sludge to beneficially condition sewage sludge was further demonstrated by comparing results using lime sludge with results using lime (CaO) to condition
Figure 13. Influence of increased dosages of FeCl₃ and lime sludge on the computed sewage sludge yield using sludge elutriated with tap water.
Figure 14. Influence of increased dosages of FeCl₃ and lime sludge on the computed sewage sludge yield using sludge elutriated with lime sludge.
elutriated sludge. The comparative effects of lime and lime sludge on the specific resistance and computed sewage sludge yields are shown in Figure 15. In both cases, the sludge was also chemically conditioned with a 10 percent ferric chloride dosage. A rapid decrease in specific resistance, using lime (CaO) as a conditioner, compared to a relatively gradual decrease in resistance using lime sludge is shown in Figure 15(A). A rapid increase in the sewage sludge yield using lime (CaO) as a conditioner compared to a decrease in the computed sewage sludge yield using increasing dosages of lime sludge is shown in Figure 15(B).

Although evidence points to the conclusion that lime sludge has little or no benefit as a conditioning agent, this may not be true. Although the lime sludge did not improve the sewage sludge yields, it did condition the sludge to the extent of reducing the specific resistance. It may, therefore, have a beneficial effect as to the improvement of filter operation in that it may reduce blinding of the filter media and facilitate cake discharge. Lime sludge may be especially useful in the conditioning of digested sludge where the presence of high percentages of fines induces filter blinding.

It must also be realized that this research has centered around the conditioning effects of lime sludge on only one type of sludge, that of digested-primary-activated sludge. It may be that the same lime sludge could have an entirely different effect on another sewage
Figure 15. Influence of dosages of lime (CaO) compared to dosages of lime sludge on specific resistance and computed sewage sludge yield at a FeCl₃ dosage of 10 percent.
sludge, such as raw-primary or digested-primary sludge. Specifically, attention is directed to the reported results from the vacuum filtration of combined lime sludge and raw-primary sludge in Nebraska City, Nebraska. Greatly improved yields were reported, as well as improved biochemical oxygen demand reduction within the treatment plant. In this case, the lime sludge was added directly to the sanitary sewer system.

Consequently, without further research in this area, an all-inclusive statement cannot be made as to the benefit of lime sludge as a conditioning agent. It can only be stated that for the particular sewage sludge studied, there was no apparent improvement in sewage sludge yield with increased lime sludge additions.
CONCLUSIONS

The following conclusions were drawn from experimental data obtained using lime softening sludge to condition digested-primary-activated sewage sludge for vacuum filtration:

1. In the elutriation process, the settling characteristics were not improved with increased additions of lime sludge.
2. The filterability of the combined lime sludge and sewage sludge was improved with increasing additions of lime sludge.
3. The better sequence of chemical addition after elutriation with tap water was: ferric chloride dosages first, followed by lime sludge additions.
4. There was a slightly higher sewage sludge yield with large lime sludge additions (50 percent) and low ferric chloride dosages (less than 10 percent) compared to yields without lime sludge additions.
5. At ferric chloride dosages of greater than 10 percent, a lower sewage sludge yield was produced with additions of lime sludge compared to yields without lime sludge additions.
6. Computed sewage sludge yields ranged up to 1.5 lb/ft²/hr compared to a range of 3.4 to 6.3 lb/ft²/hr which were reported as satisfactory values in the literature.
7. On the basis of sewage sludge yield, it does not appear beneficial to use lime sludge to condition digested sewage sludge for vacuum filtration; however, use of lime sludge may aid in the filtration of sewage sludge from an operational standpoint.
During this investigation to evaluate the suitability of lime sludge to condition sewage sludge for vacuum filtration, several possibilities were noted which may warrant future investigation.

1. Because this study was concerned only with the conditioning effect of lime sludge on digested-primary-activated sludge, further investigation might be performed on a sewage sludge which had been otherwise treated; such as, raw-primary-activated, raw-primary or digested-primary sludge.

2. A pilot plant could be set up to evaluate the conditioning effectiveness of lime sludge in the improvement of filter operation. That is, lime sludge additions may reduce filter blinding and facilitate cake removal.

3. The conditioning effectiveness of lime (CaO) added to the combined lime sludge and sewage sludge could be studied.

4. A study could be made of the effects of adding ferric chloride and/or lime (CaO) during the elutriation process, basing the evaluation on settling characteristics and sludge filterability.

5. An evaluation could be made of the soil conditioning characteristics of the combined lime and sewage sludges. A combination of the two sludges could be found which exhibits the optimum soil conditioning value, therefore improving its commercial value on the market.


Appendix I
Sample Calculation for the Determination of the Volume of Lime Sludge to Add in the Elutriation Procedure

1. Lime sludge solids to sewage sludge solids ratio desired = 1.0 (or 50% Lime Sludge)

2. Total solids content in sewage sludge sample = 0.0175 gm dry solids/gm of sludge

3. Specific gravity of sewage sludge sample = 1.007 gm/ml

4. Total solids content in lime sludge sample = 0.1719 gm dry solids/gm of sludge

5. Specific gravity of lime sludge sample = 1.118 gm/ml

6. Volume of sewage sludge used for this test = 11.0 liters

7. Computation of the volume of lime sludge necessary \( V_1 \) to satisfy a lime sludge solids to sewage sludge solids ratio of 1.0:

\[
\frac{(0.1719 \text{ gm/gm}) (V_1) (1.118 \text{ gm/ml})}{(0.0175 \text{ gm/gm}) (11,000 \text{ ml}) (1.007 \text{ gm/ml})} = 1.0
\]

\[ V_1 = 1008 \text{ ml} \]
1. Ferric chloride dosage = 5%

2. Total solids content in the elutriated sludge sample = 0.0316 gm dry solids/gm of sludge

3. Specific gravity of the elutriated sludge = 1.008 gm/ml

4. Size of sludge sample to be dosed = 700 ml

5. Total solids content of the ferric chloride solution = 188 mg dry solids/gm of solution

6. Compute weight of dry solids per ml of elutriated sludge:
   \[ 0.0316 \text{ gm/gm} \times 1 \text{ ml} \times 1.008 \text{ gm/ml} = 0.0319 \text{ gm/ml} \]

7. Compute weight of ferric chloride necessary per ml of elutriated sludge to satisfy the 5% dosage requirement:
   \[ \frac{0.05 \text{ mg FeCl}_3}{\text{mg sludge solids}} \times \frac{31.9 \text{ mg sludge solids}}{\text{ml sludge}} = 1.595 \text{ mg FeCl}_3/\text{ml sludge} \]

8. Compute ferric chloride requirement for 700 ml of sludge:
   \[ 1.595 \text{ mg FeCl}_3/\text{ml sludge} \times 700 \text{ ml} = 1117 \text{ mg FeCl}_3 \]

9. Find the amount of FeCl$_3$ solution, at a concentration of 188 mg/ml, which will contain 1117 mg of chemical:
   \[ \frac{1117 \text{ mg}}{188 \text{ mg/ml}} = 5.94 \text{ ml} \]
Appendix III
Sample Calculation for the Determination of Specific Resistance

Elutriated sludge, conditioned as follows:
Ferric Chloride ------------------------ 5%
Lime Sludge --------------------------- 50%

Results of Buechner Funnel Test

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<th>ml</th>
<th>t/v</th>
<th>Determination of Slope (b)</th>
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<tr>
<td>10</td>
<td>24</td>
<td>.42</td>
<td>( b = \frac{.88 - .42}{68 - 24} = 0.01045 )</td>
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<tr>
<td>20</td>
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<td>.54</td>
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<td>1.77</td>
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</table>

Determination of Specific Resistance

\[ P = 633 \text{ gm/cm}^2 \]
\[ A = 95 \text{ cm}^2 \]
\[ \mu = 0.00875 \text{ poise} \]
\[ b = 0.01045 \]
\[ c_i = 94.50\% \]
\[ c_f = 65.24\% \]

\[ c = \frac{94.50}{100.0 - 94.50} - \frac{65.24}{100.0 - 65.24} = 0.0654 \]

\[ \text{Specific Resistance} = r = \frac{2bPA^2}{\mu c} = \frac{2(0.01045)(633)(95)^2}{(0.00875)(0.0654)} \]

\[ r = 2.09 \times 10^8 \text{ sec}^2/\text{gm} \]
Appendix IV
Sample Calculation for the Determination of Filter Yield

Elutriated sludge, conditioned as follows:
Ferric Chloride ------------------------ 5%
Lime Sludge Solids --------------------- 50%

1. Area of filter surface on test leaf = 0.1 ft$^2$

2. Cycle time = 6 min. or 10 cycles per hour

3. Dry weight of the filter cake = 6.8371 gm

4. Computation of the filter yield (L):

\[
L = \frac{\text{dry weight sludge, gm} \times \text{cycles/hour}}{453.6 \text{ gm/lb} \times \text{test leaf area}}
\]

\[
L = \frac{6.8371 \text{ gm} \times 10 \text{ cycles/hour}}{453.6 \text{ gm/lb} \times 0.1 \text{ ft}^2}
\]

\[
L = 1.506 \text{ lb/ft}^2/\text{hr}
\]