EPA-670/2-75-012
April 1975

Environmental Protection Technology Series

LIME STABILIZED SLUDGE: ITS STABILITY AND EFFECT ON AGRICULTURAL LAND

National Environmental Research Center
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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LIME STABILIZED SLUDGE: ITS STABILITY AND EFFECT ON AGRICULTURAL LAND

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OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in:

- studies on the effects of environmental contaminants on man and the biosphere, and

- a search for ways to prevent contamination and to recycle valuable resources.

The research reported here was performed for the Ultimate Disposal Section of the Advanced Waste Treatment Research Laboratory to optimize and demonstrate an alternative method of sludge (concentrated pollutant stream) stabilization. Since sludge handling and disposal represents a significant part of the total wastewater treatment cost, a new stabilization technique which promises elimination of obnoxious odors and essentially all pathogenic bacteria at a high treatment rate and reduced cost is very welcome.

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ABSTRACT

An optimum system for the lime stabilization of municipal sewage sludge was first developed and then evaluated. The primary objectives of this work were: 1) to determine the degree of stability induced in a sludge by lime addition and 2) to determine the effects of spreading lime-stabilized sludge on agricultural land. Lime doses and contact times required to eliminate the pathogenic bacteria and odors from a raw sludge were determined by laboratory studies, and the information obtained was translated into design and operational parameters for a pilot scale, continuous flow process. Physical, chemical, and biological characteristics of both the raw and stabilized sludges were measured. Soil and crop studies, both in a greenhouse and on controlled outdoor plots, were performed to determine the effects of spreading lime-stabilized sludge.

Effective lime stabilization of sludge was accomplished by elevating the pH to 12.0 with lime addition and maintaining this pH level for at least 30 minutes. Air sparging of the lime sludge system provided better mixing than mechanical methods and resulted in approximately a 50 percent reduction in sludge NH_3-N concentration. From 102 to 208 g of $Ca(OH)_2$ was needed to stabilize 1.0 kg of sludge solids. The average amount required was 150 g. Total O&M costs for lime stabilization were estimated to be $10 per metric ton. Improved sludge thickening capability was an additional benefit of lime stabilization.

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FIGURES

FIGURES (continued)

TABLES

TABLES (continued)

TABLES (continued)

ACKNOWLEDGMENTS

Dr. A. J. Shuckrow served as program manager for this study with C. A. Counts acting as deputy program manager. Professional assistance was provided by J. F. Cline, M. P. Fujihara, B. W. Mercer, and R. C. Routson. The excellent technical assistance provided by J. A. Coates, C. C. Hill, M. J. Mason, R. G. Parkhurst, G. S. Schneiderman, R. G. Swank, and R. G. Upchurch is especially appreciated. The secretarial and technical typing efforts of Pattie Freed, Jan Greenwell, Nancy Painter, Dee Parks, Shirley Rose, Nancy Straalsund, and Sheree Whitten are gratefully acknowledged.

Special thanks go to various members of the staff of the EPA National Environmental Research Center/Cincinnati, Ohio. Dr. James E. Smith, Jr., Dr. R. B. Dean, and B. A. Kenner provided helpful guidance throughout the program.

SUMMARY AND CONCLUSIONS

A procedure for the lime stabilization of sludge was developed and operated successfully at pilot scale. Significant reductions in pathogenic bacteria and obnoxious odors resulted from lime treatment. Growth studies, both in a greenhouse and on outdoor plots, indicated that disposal of lime-stabilized sludge on cropland had no detrimental effects. On the basis of laboratory, pilot plant, and crop growth studies, the following major conclusions were drawn.

LABORATORY STUDIES

- Lime dose required to raise the pH of a given sludge to a specified level was significantly influenced by the chemical characteristics of the sludge and by the technique used to mix the lime and sludge. The required amount of lime to elevate the pH of mixed primary and trickling filter sludge to 12.4 was found to vary from 4 to 10 gm/l as the sludge's total solids varied from 1.0 to 4.4 percent.

- The chemical demand for lime exerted by the chemical components of the sludge caused a pH decay over time, although an oversupply of OH^- ions by addition of excess $Ca(OH)_2$ can retard this decay.

- Significant reductions in indicator and pathogenic bacteria were achieved by lime treatment of sludge to pH $\geq$ 12.0.

- Lime treatment had a deodorizing effect on sludge. The threshold odor number (TON) in a sludge with a 2.0 percent TS concentration was reduced by 88 percent at pH $\geq$ 11.2. Eighty-three percent TON reduction was obtained in a sludge with a 4.4 percent TS concentration at pH $\geq$ 11.6. This effect is not permanent, however, and as the pH of the sludge drops due to absorption of CO_2 from the air, an optimum growth environment will again be present for microorganisms which create obnoxious odors. The addition of surplus amounts of lime to the sludge can retard pH decay.

- For sludge, air mixing was found to be superior to mechanical mixing.

- Process control should be based on direct measurement of system pH. This approach achieves positive control through optimization of lime dose at the level required to maintain pH at a point where consistently high pathogen kills will be effected.

PILOT PLANT STUDIES

- The lime dose required to maintain the pH at or above the desired level was affected by the natural variability of a sludge's chemical composition and by any type of sludge treatment which altered the sludge's chemical makeup. The lime dose was found to vary with the sludge solids concentration, and this variation can be approximately represented as: Dose (gm/l) = 4.2 gm/l + 1.6 (TS), where TS = fraction of total solids in the sludge.

- Continuous processing of sludge to pH $\geq$ 12.0 reduced the pathogenic bacteria indicator organism populations by $\geq$ 99.0 percent.

- Lime treatment significantly increased the total alkalinity of the sludge.

- The ammonia nitrogen concentration in sludge was reduced by approximately 50 percent with lime treatment to high pH levels and air sparging.

- The filterable phosphorus concentration decreased as a result of lime treatment.

- The biochemical oxygen demand and total organic carbon concentration in the sludge liquid phase increased as a result of lime treatment.

- Threshold odor numbers in the supernatants from settled lime treated sludges were from 83-97 percent lower than those from settled raw sludges.

- Total solids in the supernatants from settled lime treated sludges were consistently higher than those from settled raw sludges.

- Lime treatment significantly improved the sludge's settling characteristics.

- In sand drying bed studies, lime-treated sludge dewatered at a more rapid rate and yielded a higher utlimate total solids concentration than raw sludge.

GROWTH STUDIES

- In a silt loam type soil, application of sludge appeared to increase permeability with water; whereas, sludge application to a sandy soil appeared to decrease permeability.

- Application of lime-treated sludge did not significantly increase soil pH. The pH level in the soil-sludge mixtures was lower after plant growth than before.

- Application of lime-treated sludge to cropland did increase the concentration of nutrients available to plants.

- Application of the proper amount of lime-treated sludge appeared to improve soil productivity as indicated by mass of plant material produced.

- Excessive concentration of nutrients by plants did not appear to be a problem. The concentration of iron was consistently higher in the soils which received sludge applications.

INTRODUCTION

Sludge treatment and ultimate disposal represent a major portion of municipal wastewater treatment costs. Most efforts have been directed toward reducing the quantity of sludge requiring disposal and the sludge's potential for producing nuisance conditions and public health hazards during and after disposal. Processes such as aerobic digestion, anaerobic digestion, and incineration have been used extensively for sludge treatment. However, each of these processes adds significantly to the cost of wastewater treatment, and none totally eliminates residues which require disposal.

The practice of returning organic waste material to cropland to restore nutrients and improve soil tillability has been practiced for centuries in many parts of the world. A revival of interest in developing this concept of waste disposal for widespread use in the United States is presently underway. The idea of returning nutrients and organic material to the soil for reuse is especially appealing at this time of increased public awareness of resource limitations.

Although spreading of sewage sludge on land may at first appear to be a simple and uncomplicated method of disposal, many factors must be considered in order to make the practice operationally feasible. The amount of sludge and the frequency of application are two important factors. If the only objective of sludge spreading operations were disposal and soil protection was considered unimportant, high application rates would be acceptable within the limitations of preventing water and air pollution, and nuisance conditions. However, if the sludge is spread on cropland to add nutrients, water, and organic matter, the operating options are more limited since the productivity of the soil and the integrity of the crops must be protected.

The use of sewage sludge on cropland is limited by several factors which are of particular concern to environmentalists and public health officials: the nitrogen content of the sludge, the concentration of metals and other trace elements, and the survival of pathogens. Treatment of sludge to reduce its pathogen content and, therefore, its potential for introducing pathogens into cropland was a major concern of this program.

Historically, lime has been used to treat nuisance conditions resulting from open pit privies and the graves of deceased domestic animals. The scope of this program followed from the work of Farrell, et al.,[1] at the Lebanon, Ohio, wastewater treatment plant. In that work, Farrell and his co-workers were concerned with developing a treatment technique for processing that portion of the plant's sludge production which exceeded its digester design capacity. In the Lebanon study, lime addition to the sludge was found to be effective in both deodorization and disinfection. The current program was designed as an investigation of the pertinent operating parameters for lime stabilization of sludges and the subsequent effects of application of the lime-treated sludges directly to cropped lands.

The two major objectives of this program were: 1) to determine the degree of stability caused in sludges by the addition of large amounts of lime and resulting pH elevation, and 2) to determine the effects of spreading lime stabilized sludges on land used for crop production. Initial work to achieve the first objective was accomplished through bench scale laboratory studies designed to aid in selection of pilot plant equipment and operational parameters. The majority of the work in this part of the study, however, was conducted on the larger pilot scale. Work on the second objective was accomplished in small scale greenhouse studies and on larger outdoor plots which received varying amounts of sludge. After sludge application, the outdoor plots were cultivated and cropped using standard agricultural techniques.

RECOMMENDATIONS FOR FUTURE RESEARCH

GENERAL

Results from laboratory and pilot scale testing show that addition of large amounts of lime to achieve high pH in sludge results in excellent pathogen reductions. Greenhouse and outdoor growth studies indicate that large applications of lime-stabilized sludge to cropland have no detrimental effects on soil productivity. Areas where additional research would be beneficial are discussed below.

EFFECT OF LIME STABILIZATION ON HIGHER ORGANISMS

Work should be initiated to determine the effect of lime treatment on higher organisms such as Ascaris, nematodes, and amoebic cysts. This type work might best be accomplished by acclimating cultured organisms to a raw sludge environment and then observing their response to lime treatment to pH ≥12.0. This approach would provide direct measurement of the effects of lime treatment on these organisms.

LONG TERM EFFECTS OF SPREADING LIME-TREATED SLUDGE ON CROPLAND

The crop growth studies conducted in this program indicated that the spreading of lime-treated sludges had no detrimental effect on soil productivity. The sludge spreading and crop growth studies were conducted over a period of only one growing season so prediction of long term effects from these results should not be attempted. Therefore, research into the long term effects of spreading lime-stabilized sludges on soil should be undertaken.

PRIOR STUDIES ON LIME STABILIZATION

The chemical reactions between lime and sewage sludge have not been extensively studied and, consequently, are not well understood. It can be said, however, that mild reactions such as the splitting of complex molecules by hydrolysis, saponification, and acid neutralization should occur.

More information is available on the effectiveness of lime in reducing the microbiological hazards in water and wastewater. Riehl, et al.,[2] reviewed the work done in treating water with excess lime to destroy bacteria and concluded that lime clearly has bactericidal properties. They reported that *Escherichia coli* and *Salmonella typhosa* were destroyed in the pH range of 11.0 to 11.5 when held at 15°C for 4 hours. Grabow, et al.,[3] added lime and maintained the pH level of humus tank effluent at 11.5 for 1 hour. This treatment destroyed all gram-negative bacteria and reduced the plate count by more than 99 percent. Surviving microorganisms were spore formers. In a study of the removal of algal nutrients from wastewater with lime, Buzzell and Sawyer[4] observed that pH levels of 10.9 or greater maintained for 1 hour produced fecal coliform reductions in excess of 99 percent. Black and Lewandowski[5] added 175 mg/l of lime to raw sewage and noted that the chemical solids resulting were stable, readily thickened, and contained no coliform bacteria after 4 weeks storage.

Morrison and Martin[6] studied lime disinfection of raw settled domestic sewage and secondary sewage effluent at low temperature. These studies showed that rapid destruction of coliform indicator bacteria occurred at pH 11.5 and 12.0, even at temperatures as low as at 1°C. Lime treatment to pH 11.5 reduced the fecal coliform concentration in raw sewage from about 1.25×10^6 to 7.00×10^4 counts/100 ml within a 90-minute contact time. At pH 12.0, the reduction in fecal coliform content was even more dramatic, and the concentration of viable organisms dropped from about 1.30×10^6 counts/100 ml before lime addition to less than 50 after treatment. Contact time was again 90 minutes. Total bacterial counts were reduced at the elevated pH levels but in a less consistent manner than the coliforms. This reflects the varying resistances of diverse organism types. Treatment at pH values of $\geq$11.0 failed to adequately disinfect effluents within a reasonable time period at any of the treatment temperatures studied. Indications are that some critical factor exists which influences the rate of disinfection at a pH value above 11.0. Whether this factor is pH alone or a combination of pH, osmotic pressure, and some threshold phenomenon, however, was not determined.

Information is also available on bactericidal effects of adding lime to sludge. Experience at the Allentown, Pennsylvania, wastewater treatment plant showed that all pathogenic enteric bacteria and odors were eliminated in anaerobically digested sludge which had been lime treated to pH 10.2-11.0, vacuum filtered, and then stored.[7] Evans[8] noted that lime addition to sludge caused the release of ammonia and destroyed Bacillus coli.

Trubnick and Mueller[9] presented data which showed the relationship between pH and viable coliforms for dewatered raw sludge. They concluded that coliform counts are low in most sludges that are lime treated prior to dewatering, since these sludges are usually dewatered in the pH range of 11.5 to 12.5.

Doyle[10] observed variations in the intensity of obnoxious odors produced during vacuum filter operations. He correlated reductions in odor intensity with increases in the amount of lime used to condition the sludge prior to dewatering and concluded that the elevated pH in lime conditioned sludges produced an environment hostile to survival of microbial populations which could cause nuisance conditions. Further investigations showed that pH values greater than 12.0 held for contact times of approximately 2 hours yielded complete destruction of Salmonella typhosa. Doyle also noted that after lime addition, the pH decays significantly from its initial value unless excess lime is added to raise the initial pH above 12.0. Sontheimer[11] also observed the phenomenon of pH decay with time after elevation to an initial level.

Farrell, et al.,[1] conducted studies to determine the effects of lime treatment on a sludge's filterability, odor reduction, chemical characteristics, and pathogen reductions. The results of these studies showed that the addition of lime to alum and iron chemical-primary sludges increased vacuum filter yields to reasonable rates. These workers also restated the fact that lime addition does not significantly reduce the amount of organic matter present in the sludge. The system pH may decrease and regrowth of surviving bacteria as well as that of bacteria inoculated into the sludge from the soil may occur if conditions become favorable. The microbiological portions of these investigations indicated that lime treatment of sludge to a pH of 11.5 reduced bacterial (and probably viral) hazards to a negligible value. Higher organisms such as Ascaris (round worms) survived short term exposure at pH 11.5. These investigators stated that the hazards from higher organisms in the lime-treated sludge are probably no greater than from a well-digested sludge, and hazards from bacteria and virus are probably far less.

Work by Paulsrud and Eikum[12] in Norway was designed to obtain information which could be used in the operation of lime stabilization processes. They found that the minimum amount of lime required to raise the pH of a particular type sludge to a specified level could not be used in plant operations, since lime doses in excess of this amount were required to prevent pH decay to levels where growth of microbial populations could occur. The lime additions required to keep pH >11.0 for at least 14 days in various type sludges are summarized in Table 1.

TABLE 1. Lime Dose Required to Keep Sludge pH >11.0 for at Least 14 Days[12]

Type of Sludge	$Ca(OH)_2$ Dose g/kg ss	lbs/ton ss
Primary sludge	100-150	200- 300
Septic tank sludge	100-300	200- 600
Biological sludge	300-500	600-1000
Al-sludge (secondary precipitation)	400-600	800-1200
Al-sludge (secondary precipitation + Primary sludge ($SS_{Al}:SS_{Prim}=1:1$)	250-400	500- 800
Fe-sludge (secondary precipitation)	350-600	700-1200

SS = suspended solids in the raw sludge

Temperature during the storage tests was maintained at 20°C.

Paulsrud and Eikum[12] used adenosine triphosphate (ATP) levels as a measure of microbial activity during storage of lime-stabilized sludges. These workers determined the ATP content of sludges prior to lime addition and at different time intervals after lime additions were made. The results from this study are summarized in Table 2. Microbial activity was observed in the biological sludge even 4 days after lime addition. However, this was not the case for primary sludge where, at the highest dose used, no ATP was detected 30 minutes after lime addition and no increase was observed during the 4-day storage period.

TABLE 2. Variation of ATP During Storage of Lime-Stabilized Sludge

Type of Sludge	Lime Added $\frac{g\ Ca(OH)_2}{kg\ SS}$	ATP Before Lime Addition (µg/l)	ATP After Lime Addition (µg/l)			
			1/2 hr	6 hrs	24 hrs	96 hrs
Primary Sludge	28	1430	125	66	92	37
	56	1430	96	25	26	<1
	140	1430	52	<1	<1	<1
	280	1430	<1	<1	<1	<1
Biological Sludge	44	2500	718	177	251	476
	88	2500	850	259	96	45
	220	2500	648	130	49	112
	440	2500	533	81	42	32

Other areas studied in the Norwegian work included the effect of storage temperature on pH decay, causes of pH decay, and the effect of sludge solids concentration on the amount of lime required to achieve a desired pH level.

Work in the area of lime stabilization of sewage sludge appears to be following a typical evolutionary path toward development of the type of information required to objectively assess the worth of the process.

LABORATORY STUDIES

GENERAL

Bench scale laboratory studies were conducted to develop basic information on the lime stabilization process itself and to develop data for use in design and operation of a pilot plant. These bench scale studies were concerned with:

1. lime requirements to achieve specified pH levels within a range of pH 11.0 to 12.4,

2. pathogenic bacteria and obnoxious odor reduction as a function of pH and contact time between the lime and the raw sludge,

3. time dependency of the lime/sludge reaction, and

4. comparison of paddle mixing with air diffusion agitation.

Studies 1 and 2 provided information about the lime dose required to attain a pH level which achieved consistently high reductions in pathogen counts and obnoxious odor levels. This information was useful in design and operation of the pilot plant lime feed system. Studies 2 and 3 were designed to determine the lime/sludge contact time required for good pathogen/odor reductions and the resulting information was used to design the pilot plant lime/sludge contact tank. Study 4 was undertaken to determine the most effective mixing technique for use in the pilot plant.

Other laboratory work conducted during this initial phase included a feasibility study to assess the desirability and accuracy of monitoring lime dose with conductivity rather than pH.

Unless otherwise noted, all sludge used in the laboratory studies was a mixture of primary sludge and trickling filter humus and was taken from the digester feed line at the Richland, Washington municipal sewage treatment plant.

LIME DOSE REQUIREMENTS

Laboratory studies were conducted at the beginning of the program to determine the lime dose required to raise the pH to a specified level. The results of these studies were used in design and operation of the pilot plant facility, which was employed to produce lime-stabilized sludges for use on the plots used in outdoor growth studies.

The pH levels chosen for investigation were 11.0, 11.2, 11.4, 11.6, 11.8, 12.0, and 12.4. One liter raw domestic sewage sludge samples with known total solids concentrations were dosed with a 100 mg $Ca(OH)_2$/ml lime slurry and mixed with a paddle stirrer until the change in pH reached equilibrium. Lime dose and the resulting pH were then recorded. This procedure was repeated until the specified pH level was reached. Sludges with different total solids concentrations were treated to raise the pH to specified levels in sludges with different solids contents.

The results from these studies are shown in Figure 1 and Table 3. These results indicate that total solids concentration affects the lime dose required to raise the pH to a specified level. As can be seen from Figure 1, the lime requirements increased as total solids concentration increased. This variation in lime requirements is probably caused by

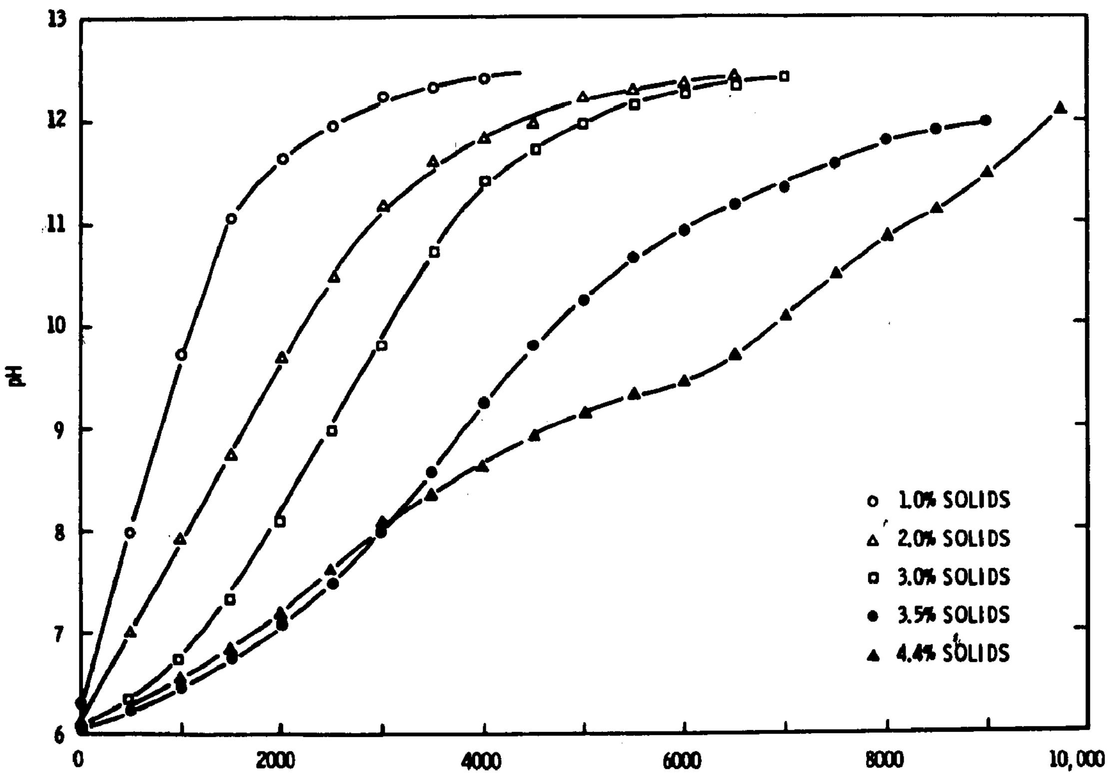


FIGURE 1. Lime Doses Required to Raise pH in Sludges With Different Solids Concentrations

TABLE 3. pH Response to Varying Lime Dose in Sludges With Different Solids Concentrations

$Ca(OH)_2$ Dose, mg/l	Total Solids Concentration (percent by weight): 1%		2%		3%		3.5%		4.4%	
	pH	g/kg*	pH	g/kg*	pH	g/kg*	pH	g/kg*	pH	g/kg*
0	6.3	0.0	6.0	0.0	6.1	0.0	6.1	0.0	6.1	0.0
500	8.0	50.0	7.0	25.0	6.35	16.7	6.25	14.3	6.25	11.4
1000	9.75	100.0	7.9	50.0	6.75	33.3	6.45	28.6	6.6	22.7
1500	11.1	150.0	8.75	75.0	7.35	50.0	6.75	42.9	6.8	34.1
2000	11.7	200.0	9.7	100.0	8.1	66.7	7.1	57.1	7.2	45.5
2500	12.0	250.0	10.5	125.0	9.0	83.3	7.5	71.4	7.65	56.8
3000	12.25	300.0	11.2	150.0	9.8	100.0	8.0	85.7	8.10	68.2
3500	12.35	350.0	11.6	175.0	10.75	116.7	8.6	100.0	8.35	79.5
4000	12.4	400.0	11.8	200.0	11.4	133.3	9.25	114.3	8.65	90.9
4500			12.0	225.0	11.75	150.0	9.8	128.6	8.9	102.3
5000			12.25	250.0	12.0	166.7	10.25	142.8	9.15	113.6
5500			12.3	275.0	12.2	183.3	10.7	157.1	9.3	125.0
6000			12.35	300.0	12.3	200.0	10.9	171.4	9.4	136.4
6500			12.4	325.0	12.35	216.7	11.2	185.7	9.7	147.7
7000					12.4	233.3	11.35	200.0	10.1	159.1
7500							11.6	214.3	10.5	170.5
8000							11.8	228.6	10.85	181.8
8500							11.9	242.9	11.15	193.2
9000							12.0	257.1	11.5	204.5
9500									12.15	215.9
10,000									12.4	227.3

*Lime dose expressed as grams $Ca(OH)_2$ per kilogram of raw sludge total solids.

a combination of factors including: 1) difficulty in establishing good mixing patterns in the thicker sludges and 2) chemical demand caused by reaction of the hydroxyl ions with dissolved CO_2, bicarbonate alkalinity, and organic materials (neutralizing organic acids, hydrolysis, saponification). A low shear, paddle mixing technique was used to prevent homogenization of the sludge. Difficulty in establishing good mixing patterns in the sample container was encountered with the sludges which had higher solids concentrations. This difficulty could possibly have prevented intimate contact between the lime slurry and the liquid phase component of the sludge. Thus, dissolution of $Ca(OH)_2$ introduced into the sludge would be hindered and more lime would be required to elevate the pH of the system. The lime demand would also increase as solids content increased, since more organic matter would be introduced, with a concomitant increase in the hydroxyl ion requirement for neutralizing organic acids and reactions involving hydrolysis and saponification.

From this discussion, it appears that the lime dose required to raise the pH of a given sludge to a specified level would be significantly influenced by the chemical characteristics and the solids concentration of the sludge and by the technique used to mix the lime and sludge.

LIME-SLUDGE pH REACTION TIME DEPENDENCY

Previous work on lime-sludge systems has shown that a pH decay is experienced as the treated sludge ages.[1,10,12] Decay from high pH levels to lower levels can change the system environment from one hostile to microbial survival to one suitable for organism existence and growth. Therefore, laboratory studies were undertaken to define the extent of pH decay experienced in sludges with different total solids concentrations. Sludge samples with total solids concentrations of 2.0 and 4.4 percent were collected and divided into one liter batches which were then lime treated to pH levels of 11.0, 11.2, 11.4, 11.6, 11.8, 12.0, and 12.4. pH decay in each of these samples was monitored over a 24 hour time period. Results from this study are shown in Table 4 and Figure 2.

As can be seen from the results, pH decay was observed in all samples as the lime-treated sludges aged. However, the degree of decay significantly decreased when the initial value of a sample was 12.0 or greater. This decay is believed to be caused by the sludge chemical demand exerted on the hydroxyl ions supplied in the lime slurry.

TABLE 4. Lime-Sludge pH Reaction Time Dependency Data

	Mixed Primary and Secondary Sludge													
	Total Solids = 2%							Total Solids = 4.4%						
Elapsed Time (Hrs)	pH Value							pH Value						
0.0	11.0	11.2	11.4	11.6	11.8	12.0	12.4	11.0	11.2	11.4	11.6	11.8	12.0	12.4
0.5	10.4	10.6	11.1	11.4	11.8	11.9	12.2	10.7	11.3	10.7	11.5	11.8	11.8	11.9
1.0	10.1	10.5	10.8	11.3	11.7	11.9	12.0	11.0	10.7	10.4	10.8	11.2	11.7	11.9
1.5	10.1	10.4	10.6	11.1	11.7	11.8	12.0	10.2	10.5	10.3	10.7	10.9	11.7	11.8
2.0	10.0	10.2	10.5	10.9	11.5	11.9	12.2	10.1	10.5	10.2	10.7	10.9	11.6	11.8
2.5	9.8	10.0	10.5	10.9	11.5	11.9	12.2	10.1	10.5	10.1	10.6	10.7	11.5	11.7
3.0	9.8	10.0	10.4	10.9	11.6	11.9	12.3	10.2	10.4	10.0	10.4	10.6	11.4	11.6
3.5	9.8	10.0	10.3	10.8	11.6	11.9	12.3	10.0	10.2	9.9	10.4	10.5	11.4	11.6
4.0	9.8	10.0	10.3	10.8	11.5	12.0	12.3	9.9	10.1	9.7	10.2	10.3	11.3	11.4
5.0	9.8	9.9	10.2	10.8	11.5	11.9	12.3							
24.0	9.2	9.2	9.6	9.8	11.5	11.8	12.3	9.8	10.0	9.9	10.1	10.2	11.2	11.4
% Change Between Initial & Final pH	16.0	22.0	16.0	16.0	3.0	2.0	1.0	11.0	11.0	13.0	13.0	15.0	7.0	8.0

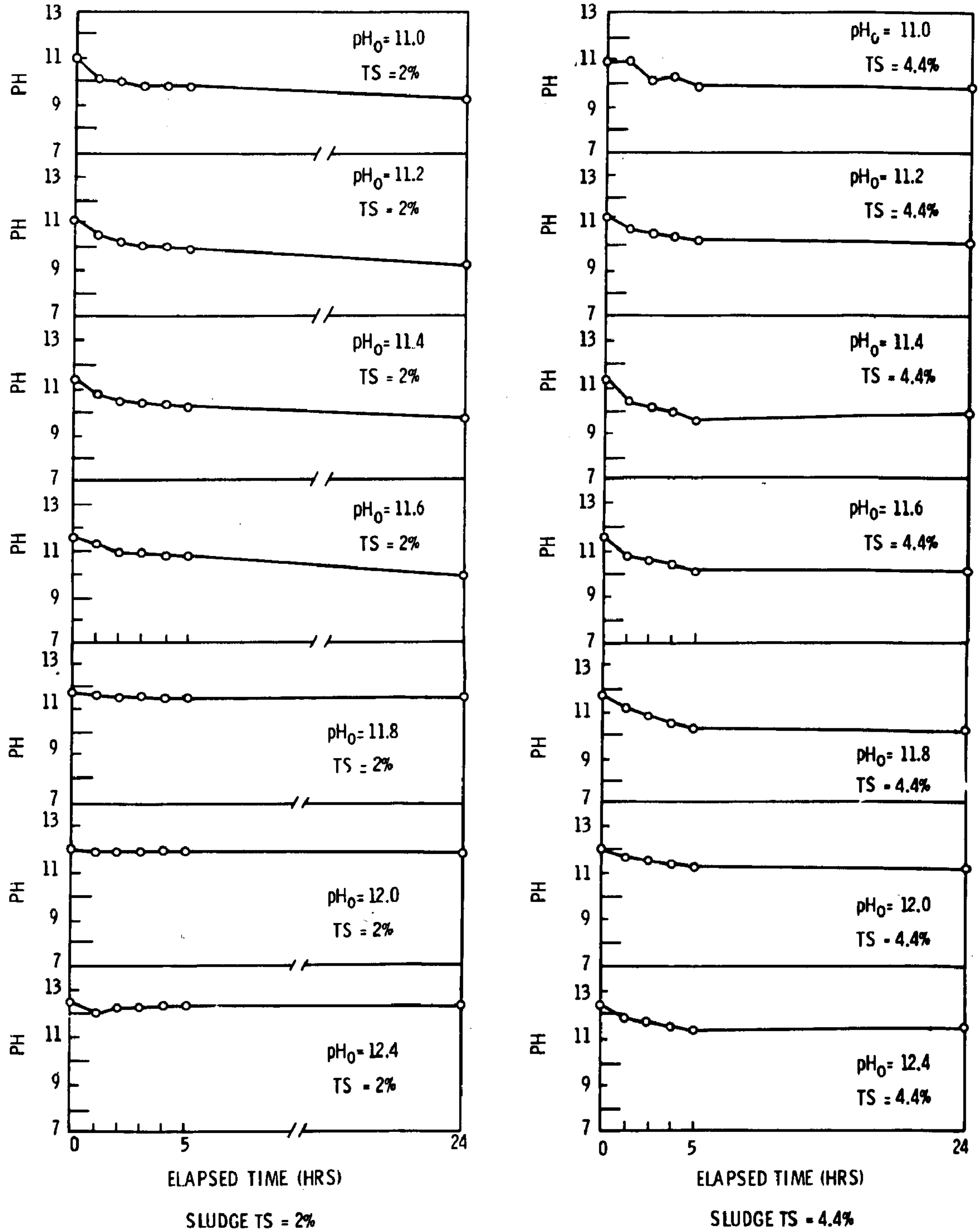


FIGURE 2. Lime-Sludge pH Reaction Time Dependency for Sludges With Different Solids Concentrations

Many of the reactions which exert this demand probably proceed slowly in this type of system (nonoptimal chemical reactor) and thus pH decays slowly as hydroxyl ions enter into chemical reactions. The degree of decay probably decreases as initial pH increases because of the extremely large quantities of lime required to elevate pH to 12.0 or greater. Large concentrations of both hydroxyl ions and undissociated $Ca(OH)_2$ are supplied in the slurry. Therefore, at high pH, sufficient OH^- species are present in the system to allow chemical reactions to proceed without an attendant decrease in pH. In summary pH decay depends upon both the quantity of lime added and the total solids concentration of the sludge.

EFFECT OF LIME TREATMENT ON PATHOGENS

Public health protection must be carefully considered in any attempt at sewage sludge disposal on agricultural land. Protection of public health can best be achieved by elimination of the pathogens present in sludge. A major portion of this program was concerned with definition of the effects of high lime dose on the pathogen populations in sewage sludges. Therefore, a laboratory study was conducted in which mixed primary and secondary sludges with total solids concentrations of 2.0 and 4.4 percent were lime treated to various pH levels within the 11.0 to 12.4 range. Laboratory beakers containing the lime-treated sludge were allowed to stand open to the atmosphere at room temperature and samples for bacteriological analysis were collected after lime-sludge contact times of 1 and 24 hours. The microorganisms chosen as indicators of pathogen response to lime treatment were fecal coliform, fecal streptococci, *Salmonella* species, and *Pseudomonas aeruginosa*. Bacteriological methods used for determination of *Salmonella* species and *Pseudomonas aeruginosa* were developed by Kenner, et al.[13] The membrane filter technique and plate count technique, both described in *Standard Methods*,[14] were used to count fecal coliforms and fecal streptococci, respectively.

Results of these studies are shown in Tables 5 through 8. After 1 hour of contact time, pathogen reductions were observed in the lime-treated sludges at all pH values within the range under study. In general, the degree of reduction increased as pH increased with consistently high pathogen reductions occurring only after the pH reached 12.0. Fecal streptococci appeared to resist inactivation by lime treatment particularly well at the lower pH values in the study range. However, at pH $\geq$12.0 these organisms were also inactivated after 1 hour of contact time.

TABLE 5. Effect of Lime on Fecal Coliform and Fecal Streptococci at 2 Percent Sludge Solids Concentration

Initial pH Value	Lime Contact Time (hrs)	pH When Sample Taken	Fecal Coliform per 100 ml	Fraction of Original Remaining	Fecal Streptococci per 100 ml	Fraction of Original Remaining
6.0 (Raw Sludge)			$1.63x10^7$		$6.3x10^6$	
6.0 (Raw Sludge)			$1.90x10^7$		$6.7x10^6$	
11.0	1	10.9	$1.00x10^4$	$5.6x10^{-4}$	$3.30x10^5$	0.05
11.0	1	10.9	0.00	0.00	$3.75x10^5$	0.06
11.0	24	9.3	$2.00x10^4$	$1.13x10^{-3}$	$3.77x10^6$	0.58
11.0	24	9.3	$2.25x10^4$	$1.27x10^{-3}$	$1.25x10^7$	1.92
11.2	1	11.1	0.00	0.00	$5.85x10^6$	0.90
11.2	1	11.1	$5.00x10^3$	$2.83x10^{-4}$	$1.60x10^6$	0.25
11.2	24	9.5	0.00	0.00	$1.77x10^7$	2.72
11.2	24	9.5	0.00	0.00	$3.75x10^6$	0.58
11.4	1	11.2	0.00	0.00	$3.15x10^5$	0.05
11.4	1	11.2	$5.00x10^3$	$2.83x10^{-4}$	$1.20x10^5$	0.02
11.4	24	9.8	$1.00x10^4$	$5.67x10^{-4}$	$9.20x10^5$	0.14
11.4	24	9.8	$5.25x10^4$	$2.97x10^{-3}$	$9.20x10^5$	0.14
11.6	1	11.5	$2.00x10^4$	$1.13x10^{-3}$	$1.40x10^5$	0.02
11.6	1	11.5	$1.00x10^4$	$5.67x10^{-4}$	$3.00x10^4$	$4.16x10^{-3}$
11.6	24	10.2	$2.50x10^4$	$1.41x10^{-3}$	$3.60x10^7$	5.54
11.6	24	10.2	$5.00x10^4$	$2.83x10^{-3}$	$4.00x10^6$	0.61
11.8	1	11.6	0.00	0.00	$2.00x10^5$	0.03
11.8	1	11.6	0.00	0.00	$1.70x10^5$	0.03
11.8	24	10.7	0.00	0.00	$4.00x10^6$	0.61
11.8	24	10.7	$1.00x10^4$	$5.67x10^{-4}$	$4.00x10^6$	0.61
12.0	1	11.7	$2.00x10^4$	$1.13x10^{-3}$	2500	$3.84x10^{-5}$
12.0	1	11.7	$2.50x10^4$	$1.41x10^{-3}$	2600	$4.00x10^{-5}$
12.0	24	10.4	$9.60x10^5$	0.05	$3.30x10^6$	0.51
12.0	24	10.4	$4.50x10^4$	$2.55x10^{-3}$	$3.00x10^6$	0.46
12.4	1	11.9	0.00	0.00	2000	$3.07x10^{-5}$
12.4	1	11.9	0.00	0.00	2700	$4.15x10^{-5}$
12.4	24	11.5	0.00	0.00	$3.35x10^6$	0.52
12.4	24	11.5	0.00	0.00	$1.90x10^6$	0.29

TABLE 6. Effect of Lime on *Salmonella* Species and *Pseudomonas Aeruginosa* at 2 Percent Sludge Solids Concentration

Initial pH Value	Lime Contact Time (hrs)	pH When Sample Taken	*Samonella* Species per 100 ml	Fraction of Original Remaining	*Pseudomonas Aeruginosa* per 100 ml	Fraction of Original Remaining
6.0 (Raw Sludge)			270		520	
6.0 (Raw Sludge)			460		310	
11.0	1	10.9	130	0.36	74	0.18
11.0	1	10.9	76	0.21	36	0.09
11.0	24	9.3	110	0.30	0	0.00
11.0	24	9.3	45	0.12	0	0.00
11.2	1	11.1	45	0.12	18	0.04
11.2	1	11.1	40	0.11	18	0.04
11.2	24	9.5	110	0.30	0	0.00
11.2	24	9.5	68	0.19	0	0.00
11.4	1	11.2	0	0.00	0	0.00
11.4	1	11.2	20	0.05	0	0.00
11.4	24	9.8	45	0.12	0	0.00
11.4	24	9.8	20	0.05	0	0.00
11.6	1	11.5	0	0.00	18	0.04
11.6	1	11.5	0	0.00	20	0.05
11.6	24	10.2	45	0.12	0	0.00
11.6	24	10.2	110	0.30	0	0.00
11.8	1	11.6	45	0.12	20	0.05
11.8	1	11.6	45	0.12	20	0.05
11.8	24	10.7	20	0.05	20	0.05
11.8	24	10.7	20	0.05	0	0.0
12.0	1	11.7	45	0.12	0	0.00
12.0	1	11.7	45	0.12	0	0.00
12.0	24	10.4	340	0.93	0	0.00
12.0	24	10.4	130	0.36	0	0.00
12.4	1	11.9	45	0.12	0	0.00
12.4	1	11.9	20	0.05	0	0.00
12.4	24	11.5	45	0.12	20	0.05
12.4	24	11.5	0	0.00	0	0.00

TABLE 7. Effect of Lime on Fecal Coliform and Fecal Streptococci at 4.4 Percent Sludge Solids Concentration

Initial pH Value	Lime Contact Time (hrs)	pH When Sample Taken	Fecal Coliform per 100 ml	Fraction of Original Remaining	Fecal Streptococci per 100 ml	Fraction of Original Remaining
6.8 (Raw Sludge)			$1.60x10^{7}$		$4.13x10^{7}$	
6.8 (Raw Sludge)			$2.03x10^{7}$		$4.67x10^{7}$	
11.0	1	10.3	$3.65x10^{4}$	$2.01x10^{-3}$	$5.37x10^{7}$	1.22
11.0	1	10.3	$4.35x10^{4}$	$2.40x10^{-3}$	$6.50x10^{7}$	1.47
11.0	24	8.6	$2.87x10^{4}$	$1.58x10^{-3}$	$7.33x10^{7}$	1.66
11.0	24	8.6	$3.25x10^{4}$	$1.79x10^{-3}$	$7.50x10^{7}$	1.70
11.2	1	10.6	$3.72x10^{4}$	$2.05x10^{-3}$	$8.50x10^{7}$	1.93
11.2	1	10.6	$2.70x10^{4}$	$1.49x10^{-3}$	$8.50x10^{7}$	1.93
11.2	24	8.7	$1.70x10^{4}$	$9.37x10^{-4}$	$7.70x10^{7}$	1.75
11.2	24	8.7	$1.37x10^{4}$	$7.55x10^{-4}$	$7.50x10^{7}$	1.70
11.4	1	10.7	$1.63x10^{4}$	$8.90x10^{-4}$	$6.43x10^{7}$	1.46
11.4	1	10.7	$2.10x10^{4}$	$1.16x10^{-3}$	$6.57x10^{7}$	1.49
11.4	24	9.2	$3.20x10^{4}$	$1.76x10^{-3}$	$8.47x10^{7}$	1.93
11.4	24	9.2	$4.95x10^{4}$	$2.09x10^{-3}$	$8.57x10^{7}$	1.95
11.6	1	11.1	$5.15x10^{4}$	$2.84x10^{-3}$	$4.47x10^{6}$	0.10
11.6	1	11.1	$5.03x10^{4}$	$2.77x10^{-3}$	$4.53x10^{6}$	0.10
11.6	24	9.5	$2.55x10^{4}$	$1.40x10^{-3}$	$8.30x10^{7}$	1.89
11.6	24	9.5	$3.80x10^{4}$	$2.09x10^{-3}$	$8.33x10^{7}$	1.89
11.8	1	11.5	$6.65x10^{4}$	$3.66x10^{-3}$	$8.33x10^{6}$	0.19
11.8	1	11.5	$3.48x10^{4}$	$1.92x10^{-3}$	$8.50x10^{6}$	0.19
11.8	24	9.9	$5.34x10^{4}$	$2.94x10^{-3}$	$8.27x10^{6}$	0.19
11.8	24	9.9	$5.77x10^{4}$	$3.18x10^{-3}$	$8.70x10^{6}$	0.20
12.0	1	11.8	$3.70x10^{4}$	$2.04x10^{-3}$	$3.27x10^{5}$	$7.43x10^{-3}$
12.0	1	11.8	$2.25x10^{4}$	$1.24x10^{-3}$	$3.37x10^{5}$	$7.66x10^{-3}$
12.0	24	10.6	$1.15x10^{4}$	$6.34x10^{-3}$	$3.09x10^{6}$	0.07
12.0	24	10.6	$2.20x10^{4}$	$1.21x10^{-3}$	$2.50x10^{6}$	0.06
12.4	1	12.1	$2.70x10^{4}$	$1.49x10^{-3}$	$7.20x10^{5}$	0.02
12.4	1	12.1	$5.35x10^{4}$	$2.95x10^{-3}$	$7.87x10^{5}$	0.02
12.4	24	11.4	$7.13x10^{4}$	$3.93x10^{-3}$	$2.61x10^{6}$	0.06
12.4	24	11.4	$7.78x10^{4}$	$4.28x10^{-3}$	2.55x106	0.06

TABLE 8. Effect of Lime on *Salmonella* Species and *Pseudomonas Aeruginosa* at 4.4 Percent Sludge Solids Concentration

Initial pH Value	Lime Contact Time (hrs)	pH When Sample Taken	Samonella Species per 100 ml	Fraction of Original Remaining	Pseudomonas Aeruginosa per 100 ml	Fraction of Original Remaining
6.8 (Raw Sludge)			10,800		2800	
6.8 (Raw Sludge)			5600		8600	
11.0	1	10.3	1080	0.13	144	0.03
11.0	1	10.3	220	0.03	128	0.02
11.0	24	8.6	340	0.04	7000	1.23
11.0	24	8.6	340	0.04	1400	0.25
11.2	1	10.6	340	0.04	28	4.91×10^{-3}
11.2	1	10.6	340	0.04	28	4.91×10^{-3}
11.2	24	8.7	440	0.05	9	1.58×10^{-3}
11.2	24	8.7	260	0.03	9	1.58×10^{-3}
11.4	1	10.7	22	2.68×10^{-3}	100	0.02
11.4	1	10.7	320	0.04	94	0.02
11.4	24	9.2	560	0.07	1840	0.32
11.4	24	9.2	260	0.03	62	0.01
11.6	1	11.1	44	5.37×10^{-3}	14	2.39×10^{-3}
11.6	1	11.1	98	0.01	16	2.74×10^{-3}
11.6	24	9.5	220	0.03	8	1.40×10^{-3}
11.6	24	9.5	52	6.34×10^{-3}	4	7.02×10^{-4}
11.8	1	11.5	260	0.03	4	7.02×10^{-4}
11.8	1	11.5	98	0.01	4	7.02×10^{-4}
11.8	24	9.9	220	0.03	9	1.58×10^{-3}
11.8	24	9.9	34	4.14×10^{-3}	9	1.58×10^{-3}
12.0	1	11.8	4	4.88×10^{-4}	0	0.00
12.0	1	11.8	9	1.10×10^{-3}	0	0.00
12.0	24	10.6	28	3.41×10^{-3}	0	0.00
12.0	24	10.6	28	3.41×10^{-3}	8	1.40×10^{-3}
12.4	1	12.1	16	1.90×10^{-3}	0	0.00
12.4	1	12.1	14	1.66×10^{-3}	0	0.00
12.4	24	11.4	40	4.88×10^{-3}	26	4.56×10^{-3}
12.4	24	11.4	66	8.05×10^{-3}	26	3.86×10^{-3}

An increase in pathogen counts was usually observed in the samples taken after 24 hours of contact time. It should also be noted that the pH of the lime-sludge system usually decreased during this time period. Work done by Paulsrud and Eikum[12] on lime stabilization of sewage sludges in Norway showed that pH could be maintained at high levels by over-dosing the system with $Ca(OH)_2$. This procedure provides surplus lime to the system so that the chemical demand for hydroxyl ions does not cause a significant decrease in pH. For sludge which is to be spread on agricultural land, the addition of excess quantities of lime in some cases might harm crop production.

EFFECT OF LIME TREATMENT ON SLUDGE ODOR

An important factor in any stabilization process is its ability to significantly reduce the obnoxious odor-producing potential of the sludge. Odors usually result from anaerobic decomposition of the sludge's organic content. Conventional methods of reducing the odor-producing potential in sludge are based on controlled biochemical degradation of the sludge organic matter (aerobic and anaerobic digestion) or total destruction of the organic matter (incineration). The lime stabilization process achieves reductions in odor-producing potential by creating a high pH, hostile environment in the sludge, thus eliminating or suppressing the growth of micro-organisms that produce nuisance conditions.

Tests to quantitatively measure odor are subject to inaccuracies, since test panels of supposedly unbiased, randomly selected people are usually required. However, since no standard tests were available, the threshold odor number test described in Standard Methods[14] was used in this study to measure odor in raw and lime-treated sludges. Threshold odor number is defined as the greatest dilution of the sample with odor-free water which yields the least perceptible odor. The tests were conducted on mixtures of primary and secondary sludge which had been lime-treated to pH levels of 11.0, 11.2, 11.4, 11.6, 11.8, 12.0, and 12.4. The threshold odor numbers of the treated samples were compared to those of sludge samples which had received no treatment. Sludge samples with total solids concentrations of 2.0 and 4.4 percent were used. Samples were tested after 1 and 24 hour contact times.

The results from this study are shown in Table 9. In both cases, the threshold odor number of the raw sludges was found to be 8000 while that of the treated samples usually ranged

TABLE 9. Threshold Odor Numbers for Treated and Untreated Sludges With Different Solids Concentrations

Sludge Type and pH Level	Threshold Odor Numbers			
	1 Hr Contact	% Reduction	24 Hr Contact	% Reduction
Total Solids=2.0%				
6.8 (Untreated)	8000		8000	
11.0	1000	88	8000	0
11.2	1000	88	1000	88
11.4	1000	88	1000	88
11.6	1000	88	1000	88
11.8	1000	88	1000	88
12.0	1000	88	1000	88
12.4	1000	88	1000	88
Total Solids=4.4%				
6.8 (Untreated)	8000		8000	
11.0	1330	83	4000	50
11.2	1330	83	1330	83
11.4	1330	83	4000	50
11.6	1330	83	1330	83
11.8	800	90	800	90
12.0	800	90	1330	83
12.4	1330	83	1330	83

from 800 to 1330. This data indicates that lime treatment does have a deodorizing effect. Qualitative observations in the laboratory substantiate this finding. The intense putrid odors liberated from the raw sludge samples at the commencement of each test changed to relatively innocuous humus-like odors after lime treatment. This deodorizing effect is not permanent, however. Surplus amounts of lime added to the sludge can retard pH decay and reoccurrence of nuisance conditions. Further, once the lime stabilized sludge is incorporated into the soil, odors are no longer a problem.

EFFECT OF MIXING TECHNIQUE

A study to determine the best method of mixing the lime-sludge systems was initiated early in the program. Mechanical mixing by paddles and air sparge mixing were chosen as the two mixing techniques for testing. The mechanical mixing device was simply a flat-bladed paddle driven by a laboratory gang stirrer. The air mixing device was a length of plastic tubing formed to fit around the bottom of a mixing vessel. The wall of the tubing was punctured at intervals to provide air release ports. Mixing effectiveness was determined by observing pH change with elapsed mixing time after 1 liter sludge batches had been subjected to step additions of 5 g and 10 g of $Ca(OH)_2$. The equilibrium pH value and the time required to reach that value were observed and recorded.

Results from the comparison study of mechanical and air mixing are shown in Table 10 and Figure 3. In both tests

TABLE 10. Results of Test Comparing Mechanical Mixing and Air Mixing at 4 Percent Sludge Solids Concentration

$Ca(OH)_2$ Concentration (g/l)	Mixing Time	pH Mechanically Mixed	pH Air Mixed
5	0	5.8	5.8
	10 sec	7.6	7.0
	20 sec	9.0	7.3
	30 sec	9.2	8.2
	1 min	9.4	9.7
	2 min	9.6	10.8
	3 min	9.7	10.6
	5 min		10.6
	6 min		10.5
	11 min	9.5	
10	0	5.8	5.8
	10 sec	9.1	9.7
	20 sec	9.5	11.4
	30 sec		12.0
	40 sec	10.0	12.1
	1 min	10.2	
	1.5 min	11.2	12.3
	2 min	12.3	12.4
	3 min	12.3	12.4

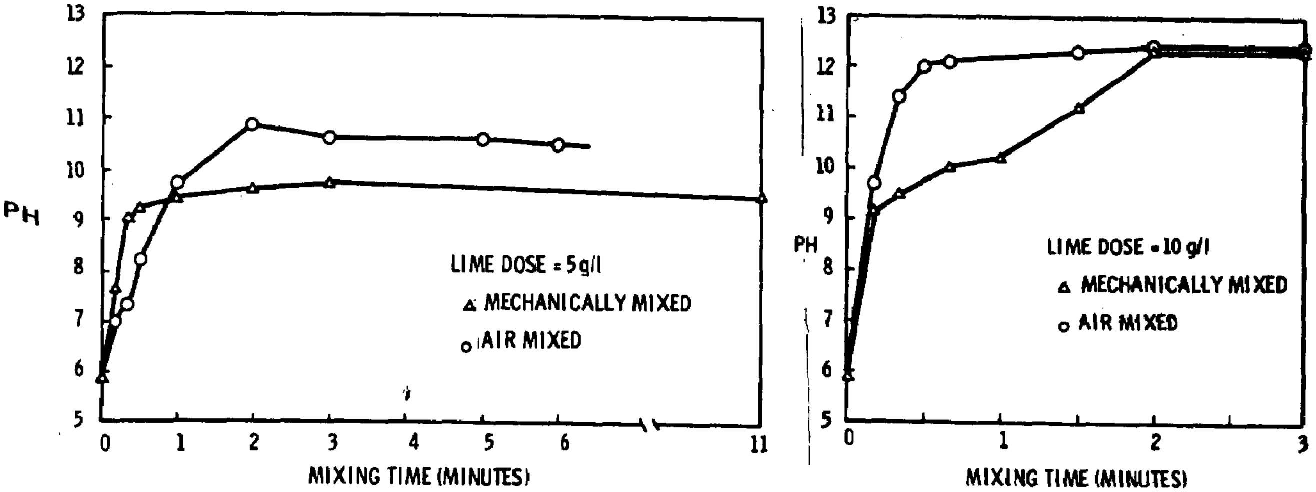


FIGURE 3. Comparison of Mechanical and Air Sparge Mixing

equilibrium levels were reached within two minutes after $Ca(OH)_2$ addition. Also, in both cases the equilibrium pH values were higher in the air sparged system. This phenomenon may be the result of CO_2 liberation from the sludge during aeration. CO_2 liberation would reduce the hydroxyl ion sink in the system, thus allowing the existence of more free OH^- ions and consequently, a higher ultimate pH. Qualitative observations made during the test indicated that mixing action in the air sparged system was much better than in the mechanically mixed system. Observations during other tests where the mechanical paddle stirrers were used revealed the paddles to be subject to blade fouling by fibrous material in the sludge. This blade fouling greatly reduced mixing action. No similar fouling problem was encountered in the air sparged mixing system.

Based on the results of this study, the decision was made to use air sparge mixing in the pilot plant.

USE OF CONDUCTIVITY MEASUREMENTS FOR PROCESS CONTROL

A short study was conducted to determine the feasibility of using conductivity as an alternative to direct pH measurement for process control purposes. In this study primary-secondary sludge mixtures with varying total solids concentrations were dosed with lime slurry and mixed until system pH reached equilibrium. Lime dose and corresponding pH and conductivity of the system were continuously monitored. Measurement was made with a specific conductance cell and conductivity calculated as described in Standard Methods.[14]

The relationships between sludge conductivity and pH for sludges with different solids concentrations are shown in Figure 4 and Table 11. At pH levels below 11.5, conductivity is not highly sensitive to changes in pH. However, at values greater than pH 12.0, it appears that conductivity could be used as an approximate indicator of pH in a lime-sludge system. In the process under study, the most dramatic reductions in pathogens occurred at pH values of 12.0 and greater. If a certain value of conductivity were chosen as the set point in a control system, the corresponding pH in the system could be any value within a range influenced by sludge solids concentration, ionic species present in the sludge at any point in time, and chemical demand. Sludge solids concentration could be maintained at a relatively constant value by use of properly operated sludge thickening processes; however, the ionic species present and the components which exert lime demand may be subject to temporal variations. Therefore, it is recommended that process control be based on direct measurement of pH. This approach allows optimization of lime dose at the level required to maintain pH at a point where consistently high pathogen kills are obtained.

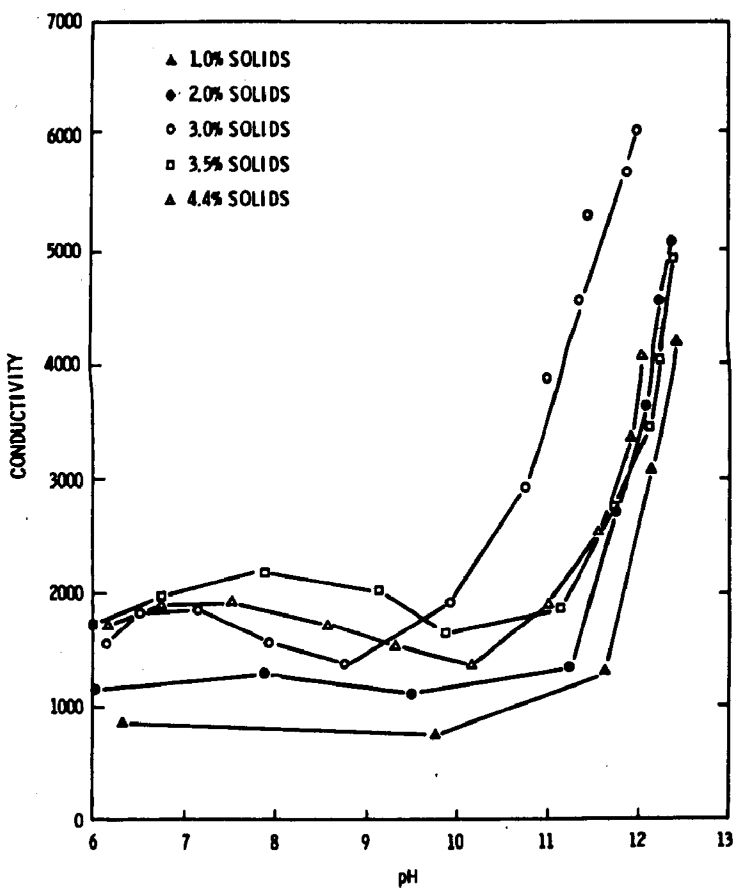


FIGURE 4. Relationship Between Conductivity and pH in Lime-Stabilized Sludge

TABLE 11. Lime Dose and Corresponding pH and Conductivity in Sludges With Different Solids Concentrations

$Ca(OH)_2$ Dose (mg/l)	Solids Concentration (% by Wt.) 1% pH	1% Conduct. (µM/cm)	2% pH	2% Conduct. (µM/cm)	3% pH	3% Conduct. (µM/cm)	3.5% pH	3.5% Conduct. (µM/cm)	4.4% pH	4.4% Conduct. (µM/cm)
0	6.3	870	6.0	1150	6.1	1570	6.1	1700	6.1	1700
500	8.0	800	7.0	1210	6.35	1700	6.25	1800	6.25	1710
1000	9.75	750	7.9	1250	6.75	1810	6.45	1900	6.6	1810
1500	11.1	1110	8.75	1190	7.35	1780	6.75	1970	6.8	1870
2000	11.7	1610	9.7	1110	8.1	1500	7.1	2020	7.2	1900
2500	12.0	2600	10.5	1210	9.0	1450	7.5	2100	7.65	1900
3000	12.25	3500	11.2	1320	9.8	1820	8.0	2180	8.10	1800
3500	12.35	3700	11.6	2200	10.75	1950	8.6	2100	8.35	1760
4000	12.4	4300	11.8	2780	11.4	4750	9.25	1960	8.65	1700
4500			12.0	3400	11.75	5400	9.8	1650	8.9	1600
5000			12.25	4400	12.0	6010	10.25	1700	9.15	1580
5500			12.3	4600	12.2	6700	10.7	1750	9.3	1530
6000			12.35	4750	12.3		10.9	1800	9.4	1480
6500			12.4	5300	12.35		11.2	2000	9.7	1420
7000					12.4		11.35	2110	10.1	1390
7500							11.6	2500	10.5	1580
8000							11.8	2900	10.85	1790
8500							11.9	3170	11.15	2050
9000							12.0	3200	11.5	2450
9500									12.15	4000
10,000									12.4	5800

*µM/cm = micromhos/centimeter

PILOT PLANT STUDIES

GENERAL

After development of pilot plant design and operational parameters, construction of the pilot facility commenced. A schematic diagram of the process is shown in Figure 5. The process flowsheet is quite simple, since it basically consists of a sludge-lime mixing vessel and contact tank to provide the desired contact time. Process control was maintained by periodically monitoring pH of the discharge from the sludge-lime contactor. Since initial laboratory studies showed that air diffusion mixing was more effective than paddle mixing, an air diffuser was employed in the sludge-lime mixing vessel.

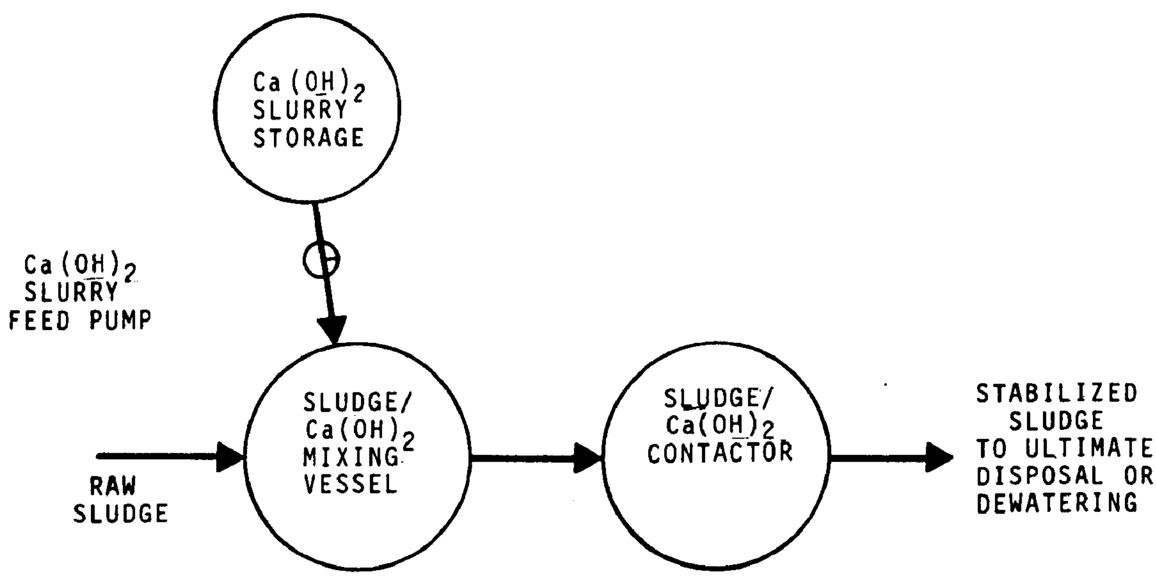


FIGURE 5. Lime Stabilization Process Flowsheet

Sludge flows ranging from 3 to 5 gpm were treated during pilot plant operations. Lime dose required to achieve the desired sludge pH was monitored routinely and recorded. This allowed optimization of lime feed to minimize process operating costs. For the most part, influent to the reactor consisted of a mixture of primary and secondary sludge from the Richland, Washington municipal trickling filter plant. This mixture of sludges was pumped directly from the line which feeds the Richland plant's anaerobic digesters. Additional work was carried out with raw primary sludge and trickling filter secondary sludge, separately, and on mixed sludge prethickened with gravity settling.

The pilot operation was monitored routinely with a comprehensive analytical program. Measurements made and information recorded included type and flow rate of sludge, total solids concentration, nitrogen forms (NH_3, NO_3^-, organic), pH and alkalinity, phosphorus forms (total and filterable), and bacterial content including fecal coliforms, fecal streptococci, Salmonella species and Pseudomonas aeruginosa. Occasional filterability and settling tests were also performed on both the limed and unlimed sludges. TOC, BOD, odor, and total solids content of the supernatants from these tests also were determined.

The bacterial content of the lime-treated sludges was determined from samples taken 60 minutes and 24 hours after treatment. Fecal coliform, fecal streptococci, Salmonella species, and Pseudomonas aeruginosa were determined as previously described. Sludge physical and chemical characterizations were also conducted using sludge samples composited daily during pilot plant runs. Analytical techniques prescribed in Standard Methods[14] were used.

Most of the sludge produced during pilot plant operations was applied to the outdoor growth study plots; however, several batches were used in sand-drying beds which were constructed adjacent to the pilot plant. The sludge blankets on the bed surfaces were periodically monitored for solids content as a function of drying time.

LIME DOSE REQUIRED TO MAINTAIN pH ≥12.0

In order to optimize chemical feed during pilot plant operations, the lime dose applied to the raw sludge was varied and system pH response was observed. The system was allowed to come to equilibrium after each dose change and pH was recorded. The results from this study are shown in Table 12.

TABLE 12. Summary of Pilot Plant Operating Data

No. of Process Control Checks Made	July 24 Ca(OH)$_2$** Dose			July 25 Ca(OH)$_2$ Dose			July 26 Ca(OH)$_2$ Dose			July 31 Ca(OH)$_2$ Dose			August 1 Ca(OH)$_2$ Dose		
	g/ℓ	g/kg*	pH	g/ℓ	g/kg*	pH	g/ℓ	g/kg*	pH	g/ℓ	g/kg*	pH	g/ℓ	g/kg*	pH
1	2.4	61.5	12.0	4.9	144.1	12.4	4.2	120.0	12.0	4.8	123.1	12.2	4.6	135.3	12.3
2	3.8	97.4	12.1	4.9	144.1	12.3	4.3	122.9	12.1	5.1	130.8	12.3	4.8	141.2	12.3
3	4.2	107.7	12.2	4.9	144.1	12.3	4.4	125.7	12.2	5.4	138.5	12.3	4.7	138.2	12.3
4	4.8	123.1	12.3	4.9	144.1	12.3	4.8	137.1	12.2	5.8	148.7	12.3	4.7	138.2	12.3
5	4.6	117.9	12.3	4.8	141.2	12.3	5.2	148.6	12.3	5.6	143.6	12.4	4.7	138.2	12.3
6	4.9	125.6	12.3	4.8	141.2	12.4	5.2	148.6	12.3	5.4	138.5	12.4			
7				4.5	132.4	12.4	5.4	154.3	12.3	5.4	138.5	12.4			
8				4.6	135.3	12.3	5.7	162.9	12.2	5.3	135.9	12.4			
9				4.4	129.4	12.1	6.4	182.9	12.2						
10															
Averages	4.2	105.5	12.2	4.7	139.5	12.3	5.1	144.8	12.2	5.4	137.2	12.3	4.7	138.2	12.3

No. of Process Control Checks Made	August 6 Ca(OH)$_2$ Dose			August 7 Ca(OH)$_2$ Dose			August 8 Ca(OH)$_2$ Dose			August 13 Ca(OH)$_2$ Dose			August 14 Ca(OH)$_2$ Dose		
	g/ℓ	g/kg*	pH	g/ℓ	g/kg*	pH	g/ℓ	g/kg*	pH	g/ℓ	g/kg*	pH	g/ℓ	g/kg*	pH
1	4.9	140.0	12.3	4.4	200.0	12.2	4.4	125.7	12.3	6.3	218.8	12.4	4.7	95.9	12.1
2	4.9	140.0	12.4	4.4	200.0	12.2	4.4	125.7	12.3	6.1	174.3	12.4	4.8	97.9	12.3
3	4.9	140.0	12.3	4.6	209.1	12.3	4.7	134.3	12.3	5.8	165.7	12.4	4.5	91.8	12.3
4	4.9	140.0	12.2	4.6	209.1	12.4	4.8	137.1	12.3	5.7	162.9	12.4	5.0	102.0	12.3
5	5.0	142.9	12.4	4.8	218.2	12.4	5.0	142.9	12.3	5.5	157.1	12.3	5.0	102.0	12.3
6	5.0	142.9	12.4	4.8	218.2	12.4	5.0	142.9	12.3	5.5	157.1	12.3	5.4	110.2	12.4
7	4.9	140.0	12.3	4.4	200.0	12.4	5.0	142.9	12.3	5.3	151.4	12.3	5.3	108.2	12.4
8	5.0	142.9	12.3							5.2	148.6	12.3	5.2	106.1	12.4
9	4.9	140.0	12.2							5.6	160.0	12.3	5.2	106.1	12.4
10	5.3	151.4	12.3							5.8	165.7	12.4			
Averages	5.0	142.0	12.3	4.6	207.8	12.3	4.8	135.9	12.3	5.7	166.2	12.4	5.0	102.2	12.3

*Grams Ca(OH)$_2$ per kilogram total solids in the raw sludge.
**To obtain Ca(OH)$_2$ dose in lbs/ton dry sludge solids multiply dosage in gm/kg by 2.

Average system pH for the series of daily runs ranged from 12.2 through 12.4, and at no time during the runs did pH fall below the desired 12.0 level. The average lime dose ranged from 4.2 to 5.7 g $Ca(OH)_2$ per liter of sludge, and the average overall pilot plant studies was 4.9 g/l. The daily average lime dose expressed as grams $Ca(OH)_2$ per kilogram of raw sludge total solids ranged from 102.2 through 207.8, and the for the average was 141.9. These lime doses are considered the minimum required to maintain pH at or above the desired level (pH $\geq$12.0) during sludge processing. However, since excess lime was not added to the system, slight pH decay with time would be expected to occur. Paulsrud and Eikum[12] determined that the lime dose required to maintain sludge pH greater than 11.0 for 14 days varied considerably with the type sludge being treated and prior chemical treatment.

Regression analysis of pilot plant operating data resulted in the following equation which related the required lime dose and the sludge total solids concentration:

$$\text{lime dose} = 4.2 + 1.6\ (TS)$$

where: lime dose is expressed as grams $Ca(OH)_2$ per liter of sludge
TS = total solids fraction in the sludge

This equation suggests that the greatest portion of the lime requirement is associated with the liquid phase and only a small fraction of the lime demand is dependent upon the solids concentration. It should be recognized, however, that the above equation describes only the initial lime demand and does not take pH decay with time into account.

Data used to derive the relationship were obtained during pilot plant operation when lime dose was adjusted to maintain a pH range between 12.2 and 12.4 and lime-sludge contact time was 30 minutes. Lime dose is defined as the amount of lime required to satisfy the chemical demand present in the sludge and to provide the hydroxyl ion concentration necessary to raise the pH to the desired level. The total sludge chemical demand is a combination of the demand present in the liquid phase and that present in the solid phase. The demand present in the sludge liquid phase is largely governed by the reaction of the lime with dissolved CO_2 and biocarbonate ion. This demand is probably satisfied with relatively short lime-sludge contact time. The solids demand is characterized by much slower reactions of hydroxyl ions with organic materials in the sludge (neutralizing organic acids, hydrolysis, and saponification) so that this demand may be exerted over long periods of time (hours or days). This long term demand exerted by the sludge solids causes the pH decay discussed earlier and may account in part for the greater lime doses required to reach pH 12.4 in the laboratory jar tests than in the pilot plant study. In the jar tests, system pH was allowed to equilibrate after each incremental lime dose, so that several hours were usually required to reach pH 12.4. During this time period, hydroxyl ions were satisfying liquid and solids demand as well as elevating pH. In the pilot plant study, the sludge received slug doses of lime to elevate and maintain pH ≥12.0 after a 30-minute sludge-lime contact time. Therefore, in the laboratory tests, more time was available for reaction with organic material in the sludge solids and thus more lime was required than in the pilot plant study. In conclusion, the lime dose required to achieve pH ≥12.0 is significantly affected by the chemical demand exerted by the chemical components in the sludge liquid and solid phases, and the long term chemical demand is a function of the sludge total solid concentration.

The results derived in this study also indicate that the lime dose required to maintain the pH at or above the desired level will be affected by the natural variability of sludge chemical composition and by any type of sludge treatment which alters the sludge chemical makeup. Therefore, in practice, lime dose requirements would have to be determined for each specific sludge to be treated.

BACTERIOLOGICAL RESULTS

As part of the comprehensive testing work conducted during the pilot plant phase of the program, studies were made of the reductions in pathogenic organisms achieved by lime treatment in the pilot process. Once again the organisms measured were fecal coliforms, fecal streptococci, *Salmonella* species, and *Pseudomonas aeruginosa*. The results from these studies are shown in Tables 13 and 14.

These results show that significant pathogen reductions can be achieved in sludges which have been continuously lime treated to pH ≥12.0. Reductions of fecal coliforms and fecal streptococci were consistently greater than 99 percent. *Salmonella* species and *Pseudomonas aeruginosa* appear to be almost totally inactivated by lime stabilization.

TABLE 13. Fecal Coliform and Fecal Streptococci in Untreated and Treated Sludge Samples (pilot runs were made on mixed primary sludge and humus unless otherwise noted)

Initial pH Value	Lime Contact Time (hrs)	pH When Sample Taken	Fecal Coliform per 100 ml	Fraction of Original Remaining	Fecal Streptococci per 100 ml	Fraction of Original Remaining
June 25, 1973						
Untreated sludge						
6.0	0.0	6.0	2.00×10^7		7.23×10^6	
6.0	0.0	6.0	2.37×10^7		7.53×10^6	
Treated sludge						
12.3	0.5	12.3	<1000	$<4.56 \times 10^{-5}$	100	1.35×10^{-5}
12.3	0.5	12.3	<1000	$<4.56 \times 10^{-5}$	300	4.06×10^{-5}
July 9, 1973						
Untreated sludge						
6.1	0.0	6.1	5.10×10^7		5.83×10^7	
6.1	0.0	6.1	4.50×10^7		7.40×10^7	
Treated sludge						
12.2	0.5	12.2	<1000	$<2.09 \times 10^{-5}$	100	1.51×10^{-6}
12.2	0.5	12.2	<1000	$<2.09 \times 10^{-5}$	100	1.51×10^{-6}
July 16, 1973						
Untreated sludge						
6.1	0.0	6.1	1.56×10^7		1.72×10^7	
6.1	0.0	6.1	2.28×10^7		1.65×10^7	
Treated sludge						
12.3	0.5	12.3	<1000	$<5.22 \times 10^{-5}$	200	1.18×10^{-5}
12.3	0.5	12.3	<1000	$<5.22 \times 10^{-5}$	170	1.01×10^{-5}
July 23, 1973						
Untreated sludge						
6.0	0.0	6.0	4.8×10^7		9.23×10^6	
6.0	0.0	6.0	5.2×10^7		8.76×10^6	
Treated sludge						
12.0	0.5	11.8	<1000	$<2.00 \times 10^{-5}$	1330	1.47×10^{-4}
12.0	0.5	11.8	<1000	$<2.00 \times 10^{-5}$	1160	1.29×10^{-4}
July 25, 1973						
Untreated sludge						
6.2	0.0	6.2	4.95×10^7		5.00×10^6	
6.2	0.0	6.2	3.70×10^7		5.50×10^6	
Treated sludge						
12.2	0.5	12.2	500	1.16×10^{-5}	100	1.90×10^{-5}
12.2	0.5	12.2	<1000	9.25×10^{-5}	0	0.0
July 26, 1973						
Untreated sludge						
6.1	0.0	6.1	1.08×10^7		7.96×10^6	
6.1	0.0	6.1	1.12×10^7		8.53×10^6	
Treated sludge						
12.1	0.5	12.1	2.50×10^4	1.87×10^{-4}	0	0.0
12.1	0.5	12.1	1.00×10^4	4.69×10^{-4}	0	0.0
July 31, 1973 (1)						
Untreated sludge						
5.9	0.0	5.9	5.20×10^7		1.89×10^7	
5.9	0.0	5.9	5.45×10^7		1.88×10^7	
Treated sludge						
12.0	0.5	11.7	1.00×10^4	1.87×10^{-4}	200	1.06×10^{-5}
12.0	0.5	11.7	2.50×10^4	4.69×10^{-4}	0	0.0

(1) Primary sludge

TABLE 13 (continued)

Initial pH Value	Lime Contact Time (hrs)	pH When Sample Taken	Fecal Coliform per 100 ml	Fraction of Original Remaining	Fecal Streptococci per 100 ml	Fraction of Original Remaining
August 1, 1973 (2)						
Untreated sludge						
6.4	0.0	6.4	6.5×10^7		4.6×10^6	
6.4	0.0	6.4	5.60×10^7		5.9×10^6	
Treated sludge						
12.3	0.5	12.3	1.85×10^4	3.05×10^{-4}	<1000	1.90×10^{-4}
12.3	0.5	12.3	1.80×10^4	2.97×10^{-4}	<1000	1.90×10^{-4}
August 6, 1973 (1)						
Untreated sludge						
6.2	0.0	6.2	5.80×10^6		7.80×10^6	
6.2	0.0	6.2	2.95×10^6		8.88×10^6	
Treated sludge						
12.4	0.5	12.4	<1000	2.29×10^{-4}	1.05×10^3	1.26×10^{-4}
12.4	0.5	12.4	<1000	2.29×10^{-4}	5.67×10^2	6.80×10^{-5}
August 7, 1973 (2)						
Untreated sludge						
6.2	0.0	6.2	4.25×10^6		6.30×10^6	
6.2	0.0	6.2	2.30×10^6		4.06×10^6	
Treated sludge						
12.3	0.5	12.3	<1000	$<3.05 \times 10^{-4}$	0	0.0
12.3	0.5	12.3	2.10×10^5	0.06	0	0.0
August 8, 1973 (2)						
Untreated sludge						
6.1	0.0	6.1	4.5×10^7		9.23×10^6	
6.1	0.0	6.1	3.6×10^7		8.46×10^6	
Treated sludge						
12.3	0.5	12.3	<1000	$<2.47 \times 10^{-5}$	560	6.33×10^{-5}
12.3	0.5	12.3	<1000	$<2.47 \times 10^{-5}$	33	3.73×10^{-6}
August 13, 1973 (1)						
Untreated sludge						
5.9	0.0	5.9	6.15×10^7		1.50×10^7	
5.9	0.0	5.9	7.00×10^7		1.55×10^7	
Treated sludge						
12.2	0.5	12.2	<1000	$<1.52 \times 10^{-5}$	100	6.56×10^{-6}
12.2	0.5	12.2	<1000	$<1.52 \times 10^{-5}$	70	4.59×10^{-6}
August 14, 1973						
Untreated sludge						
6.2	0.0	6.2	9.25×10^7		2.24×10^7	
6.2	0.0	6.2	6.35×10^7		1.60×10^7	
Treated sludge						
12.2	0.5	12.2	<1000	$<1.28 \times 10^{-5}$	100	5.21×10^{-6}
12.2	0.5	12.2	500	6.41×10^{-6}	170	8.85×10^{-6}

(1) Primary sludge
(2) Humus

TABLE 14. Salmonella Species and Pseudomonas Aeruginosa in Untreated and Treated Sludge Samples (pilot runs were made on mixed primary sludge and humus unless otherwise noted)

Initial pH Value	Lime Contact Time (hrs)	pH When Sample Taken	Salmonella Species MPN per 100 ml	Fraction of Original Remaining	Pseudomonas Aeruginosa MPN per 100 ml	Fraction of Original Remaining
June 25, 1973						
Untreated sludge						
6.0	0.0	6.0	4,400		28,000	
6.0	0.0	6.0	6,200		15,800	
Treated sludge						
12.3	0.5	12.3	0	0.0	0	0.0
12.3	0.5	12.3	0	0.0	0	0.0
July 9, 1973						
Untreated sludge						
6.1	0.0	6.1	28,000		320,000	
6.1	0.0	6.1	28,000		320,000	
Treated sludge						
12.2	0.5	12.2	9	3.20×10^{-4}	4	1.25×10^{-5}
12.2	0.5	12.2	8	2.85×10^{-4}	8	2.50×10^{-5}
July 16, 1973						
Untreated sludge						
6.1	0.0	6.1	9,200		9,800	
6.1	0.0	6.1	9,200		14,000	
Treated sludge						
12.3	0.5	12.3	0	0.0	0	0.0
12.3	0.5	12.3	0	0.0	0	0.0
July 23, 1973						
Untreated sludge						
6.0	0.0	6.0	2,200		22,000	
6.0	0.0	6.0	2,200		14,000	
Treated sludge						
12.0	0.5	11.8	0	0.0	0	0.0
12.0	0.5	11.8	0	0.0	0	0.0
July 25, 1973						
Untreated sludge						
6.2	0.0	6.2	5,200		34,000	
6.2	0.0	6.2	5,400		22,000	
Treated sludge						
12.2	0.5	12.2	0	0.0	0	0.0
12.2	0.5	12.2	0	0.0	0	0.0
July 26, 1973						
Untreated sludge						
6.1	0.0	6.1	4,200		70,000	
6.1	0.0	6.1	5,400		48,000	
Treated sludge						
12.1	0.5	12.1	0	0.0	0	0.0
12.1	0.5	12.1	0	0.0	0	0.0
July 31, 1973 (1)						
Untreated sludge						
5.9	0.0	5.9	6,800		<320,000	
5.9	0.0	5.9	7,800		<320,000	
Treated sludge						
12.0	0.5	11.7	0	0.0	0	0.0
12.0	0.5	11.7	0	0.0	0	0.0

(1) Primary sludge

TABLE 14 (continued)

Initial pH Value	Lime Contact Time (hrs)	pH When Sample Taken	*Salmonella* Species MPN per 100 ml	Fraction of Original Remaining	*Pseudomonas Aeruginosa* MPN per 100 ml	Fraction of Original Remaining
August 1, 1973 (2)						
Untreated sludge						
6.4	0.0	6.4	4,800		320,000	
6.4	0.0	6.4	5,400		320,000	
Treated sludge						
12.3	0.5	12.3	0	0.0	0	0.0
12.3	0.5	12.3	0	0.0	0	0.0
August 6, 1973 (1)						
Untreated sludge						
6.2	0.0	6.2	3,400		10,800	
6.2	0.0	6.2	4,400		7,000	
Treated sludge						
12.4	0.5	12.4	0	0.0	0	0.0
12.4	0.5	12.4	0	0.0	0	0.0
August 7, 1973 (2)						
Untreated sludge						
6.2	0.0	6.2	12,800		3,400	
6.2	0.0	6.2	8,600		14,000	
Treated sludge						
12.3	0.5	12.3	0	0.0	0	0.0
12.3	0.5	12.3	0	0.0	0	0.0
August 8, 1973 (2)						
Untreated sludge						
6.1	0.0	6.1	2,600		22,000	
6.1	0.0	6.1	7,000		15,800	
Treated sludge						
12.3	0.5		0	0.0	0	0.0
12.3	0.5		0	0.0	0	0.0
August 13, 1973 (1)						
Untreated sludge						
5.9	0.0	5.9	4,400		44,000	
5.9	0.0	5.9	4,800		108,000	
Treated sludge						
12.2	0.5	12.2	0	0.0	0	0.0
12.2	0.5	12.2	0	0.0	0	0.0
August 14, 1973						
Untreated sludge						
6.2	0.0	6.2	10,800		56,000	
6.2	0.0	6.2	7,000		56,000	
Treated sludge						
12.2	0.5	12.2	0	0.0	0	0.0
12.2	0.5	12.2	0	0.0	0	0.0

(1) Primary sludge
(2) Humus

Viable organisms of these types were observed only once after lime treatment in the pilot process (July 9 pilot plant run). The only unusual occurrence was found in the pilot plant runs made on July 26, July 31, and August 1. Lime treated sludges on these days were found to contain fecal coliform counts approximately ten times greater than had been encountered in other sludges which had received similar treatment. A review of pilot plant operating records for these days revealed nothing which would explain this decrease in killing efficiency. Sludge flow rates were constant at 5 gpm and pH levels were maintained above 12.0 during the entirety of the runs. Thus, pilot process conditions were identical to those which produced the lower residual pathogen counts. It should be noted that even though the treated sludge pathogen counts on those days were ten times higher than normal, reduction still exceeded 99 percent.

COMPREHENSIVE CHEMICAL ANALYSIS

Results from comprehensive physical and chemical characterization of raw and lime stabilized sludges from pilot process optimization operations are shown in Table 15. Analyses conducted on whole sludge samples included pH, total solids, total alkalinity, ammonia nitrogen, organic nitrogen, nitrate nitrogen, total phosphorus, total filterable phosphorus, filterability, and settling characteristics. Supernatants from settling tests were analyzed for TOC, BOD, odor, and total solids. Primary sludge, secondary sludge (trickling filter humus), a mixture of primary and secondary sludges (generally referred to as mixed sludge), and a gravity thickened mixed sludge were processed during this phase of the study. The total solids concentrations of the raw and unthickened sludges ranged from 2.2 to 3.9 percent by weight. The average solids concentration of these sludges was 3.4 percent. The total solids concentrations in the same sludges after lime treatment was always lower than before treatment, with the solids concentration range and average being 2.1-3.6 percent and 3.1 percent, respectively. Since about 50 ml of 100 g/l lime slurry was added to each liter of sludge, an average increase of 8 percent in total solids would occur if no volatile substances were formed. The loss of solids, therefore, indicates the formation of a significant amount of volatile substances which are evaporated during the drying step of the total solids determination. The formation of water by the reaction of lime with bicarbonate alkalinity would account for a small loss from the sum of solids initially present and the lime added. However, this represents only 1 percent of the total. The decomposition of pectin, a minor constituent of settleable organics in sewage, by reaction with lime forms methanol, which would also volatilize and cause a small loss in solids.

TABLE 15. Physical and Chemical Characterization of Sludges Processed During Pilot Plant Optimization Studies

Parameter and Sludge Treatment	7/24/73 Mixed Sludge[1]	7/25/73 Mixed Sludge	7/26/73 Mixed Sludge	7/31/73 Primary Sludge	8/1/73 Trick. Filt. Humus
Whole Sludge					
pH					
Raw Sludge	6.0	6.2	6.1	5.9	6.5
Treated Sludge	11.8	12.2	12.1	11.7	12.3
Total Solids (wt%)					
Raw Sludge	3.9	3.4	3.5	3.9	3.4
Treated Sludge	3.6	3.1	3.1	3.5	3.0
Total Alkalinity (mg/l as $CaCo_3$)					
Raw Sludge	1060	1260	1320	810	646
Treated Sludge	5080	5920	6280	6120	6260
Ammonia Nitrogen (mg N/l)					
Raw Sludge	206	148	222	238	148
Treated Sludge	90	90	82	90	131
Organic Nitrogen (mg N/l)					
Raw Sludge	1258	1135	1299	880	436
Treated Sludge	1274	1176	847	1085	806
Nitrate Nitrogen (mg N/l)					
Raw Sludge	23	19	5	2	11
Treated Sludge	29	31	32	23	27
Total Phosphate (mg P/l)					
Raw Sludge	441	369	595	323	157
Treated Sludge	339	340	333	215	118
Filterable Phosphate (mg P/l)					
Raw Sludge	92	72	75	118	49
Treated Sludge	33	22	27	42	16
Supernatant					
TOC (mg/l)					
Raw Sludge	1200	1125	1200	1075	600
Treated Sludge	2600	2150	2000	2250	1500
BOD (mg/l)					
Raw Sludge	1280	1020	1110	1120	536
Treated Sludge	2450	1980	1875	2357	1352
Threshold Odor Number					
Raw Sludge	400	400	2000	2666	4000
Treated Sludge	67	67	67	200	200
Total Solids (wt%)					
Raw Sludge	0.2	0.2	0.3	0.1	0.1
Treated Sludge	0.7	0.7	0.6	0.6	0.5

[1]Mixture of Primary Sludge and Trickling Filter Humus

TABLE 15 (continued)

Parameter and Sludge Treatment	8/6/73 Primary Sludge	8/7/73 Trick. Filt. Humus	8/8/73 Trick. Filt. Humus	8/13/73 Primary Sludge	8/14/73 Thick. Mixed Sludge
Whole Sludge					
pH					
Raw Sludge	6.2	6.2	6.1	5.9	6.2
Treated Sludge	12.4	12.3	12.3	12.2	12.2
Total Solids (wt%)					
Raw Sludge	3.5	2.2	3.5	3.5	4.9
Treated Sludge	3.2	2.1	3.1	3.0	4.5
Total Alkalinity (mg/l as $CaCo_3$)					
Raw Sludge	1220	1500	1308	1394	1632
Treated Sludge	6800	5640	6820	7840	7260
Ammonia Nitrogen (mg N/l)					
Raw Sludge	173	263	411	222	180
Treated Sludge	75	115	197	107	90
Organic Nitrogen (mg N/l)					
Raw Sludge	1225	1003	2097	1094	1464
Treated Sludge	1151	929	1250	1201	1250
Nitrate Nitrogen (mg N/l)					
Raw Sludge	2	5	5	5	7
Treated Sludge	20	20	18	32	32
Total Phosphate (mg P/l)					
Raw Sludge	369	291	467	333	392
Treated Sludge	372	242	346	320	310
Filterable Phosphate (mg P/l)					
Raw Sludge	69	104	134	88	85
Treated Sludge	26	16	20	29	26
Supernatant					
TOC (mg/l)					
Raw Sludge	775	850	1300	1150	1000
Treated Sludge	1800	1775	2375	2200	2000
BOD (mg/l)					
Raw Sludge		1455	900		
Treated Sludge		2130	2460		
Threshold Odor Number					
Raw Sludge	4000	8000	4000	8000	8000
Treated Sludge	400	400	400	800	800
Total Solids (wt%)					
Raw Sludge	0.1	0.1	0.1	0.1	0.2
Treated Sludge	0.5	0.5	0.5	0.6	0.6

The principal causes for the loss in total solids in the sludge following lime treatment are unknown but are believed to be largely related to reactions of nitrogenous organic matter with lime. Hydrolysis of proteins and destruction of amino acids are known to occur by reaction with strong bases. The formation of volatile substances such as ammonia, water, and low molecular weight amines or other volatile organics are strong possibilities.

Total alkalinity in the raw sludges varied from 646 to 1632 mg/l as $CaCO_3$. The initial pH of all these sludges was well below 8.3 (the phenolphthalein end point) so that all the alkalinity was present either in the bicarbonate form or as titratable organic matter (e.g., proteins). Total alkalinity in the lime treated sludges ranged from 5080-7840 mg/l as $CaCO_3$.

Ammonia nitrogen concentrations in the treated sludges were always lower than those in the raw sludges. This was caused by a shift in equilibrium conditions caused by the radical increase in system pH. In the raw sludges, which ranged from pH 5.9-6.5, ammonia was present as ammonium ion (NH_4^+), but after lime treatment, which elevated conditions to pH 11.7-12.3, ammonia existed as the dissolved gas NH_3. The air sparging technique used to mix sludge and lime slurry in the pilot process removed some of this gaseous NH_3 from the system, thus reducing the ammonia nitrogen concentration in the sludge. The nitrate nitrogen concentration increased during sludge processing. This increase is not understandable and there is no plausible explanation for it.

The organic nitrogen concentration in both the raw and lime treated sludges varied considerably, making it impossible to determine effects of lime treatment on this parameter. One would expect to observe a decrease in organic nitrogen after lime treatment, since high pH conditions should result in partial destruction of nitrogenous organic material in the sludge. This type of decrease was observed in five of the nine sludges analyzed, but significant organic nitrogen concentration increases were found in the remaining samples. Possible explanations for these results are sampling and analytical variations.

The results in Table 15 show that an average decrease of 4 percent in total phosphate resulted from lime treatment. Ideally, total phosphate concentration in the whole sludge would not be greatly affected by lime treatment, since the hydroxyapatite precipitate resulting from lime treatment should be redissolved during sample preparation prior to analysis. These decreases were probably caused by either unequal distribution of hydroxyapatite precipitate throughout the sludge when sample aliquots were drawn or the dilution effect of adding lime slurry. The dilution effect of adding lime slurry would account for about a 5 percent decrease in total phosphate.

As might be expected, filterable phosphorus concentration decreased as a result of lime treatment. The mechanism which causes this phosphate concentration decrease is the chemical reaction between $Ca(OH)_2$ and dissolved orthophosphate. This reaction results in a hydroxyapatite precipitate which removes phosphate from solution. Residual phosphorus in the supernatant liquid after lime treatment is believed to be largely organic in nature.

Biochemical oxygen demand (BOD) and total organic carbon (TOC) concentrations in supernatants from settling tests increased as a result of lime treatment. Reactions which would cause dissolution of organic material include, but are not limited to:

- saponification of fats and oils which releases soluble glycerine;
- hydrolysis of proteins which release soluble amino acids;
- dissolution of proteins; and/or
- destruction of pectins which form methanol.

Threshold odor numbers in the supernatants from lime treated sludges were significantly lower than those from raw sludges. This indicates that lime treatment does have a beneficial deodorizing effect.

Total solids in the supernatants from lime treated sludges were consistently higher than those from raw sludges as a result of the soluble lime and dissolved organics present.

EFFECT OF LIME TREATMENT ON SLUDGE FILTERABILITY AND SETTLING CHARACTERISTICS

Filterability Studies

Studies to determine the effect of lime treatment on sludge filterability were conducted on sludges processed in the pilot plant. Raw and lime treated sludge samples of a known volume and total solids concentration were dewatered in a Buchner funnel and the volume of accumulated filtrate recorded as a function of filter time. Total solids content of the filtrate was then determined and used in mass balance calculations to determine the total solids concentration of the sludge remaining in the Buchner funnel at various times. The results from these studies are shown in Table 16 and Figures 6-14.

TABLE 16. Results of Sludge Filterability Studies

Filter Time (Min.)	Total Solids Concentration (percent by wt.)																	
	July 24		July 25		July 26		July 31		August 1		August 6		August 7		August 13		August 14	
	Mixed Sludge		Mixed Sludge		Mixed Sludge		Primary Sludge		Humus		Primary Sludge		Humus		Primary Sludge		Thickened Sludge	
	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.
0	3.9	3.6	3.4	3.1	3.5	3.1	3.9	3.5	3.4	3.0	3.5	3.2	2.2	2.1	3.5	3.0	4.9	4.5
1	4.1	3.7	3.6	3.2	3.6	3.3	4.1	3.7	4.9	4.2	3.7	3.4	2.5	2.4	3.7	3.3	5.0	4.8
2	4.2	3.8	3.8	3.5	3.7	3.5	4.3	3.8	5.7	4.9	3.8	3.5	2.6	2.6	3.9	3.4	5.2	5.0
3	4.4	3.9	4.0	3.6	3.9	3.6	4.5	4.0	6.7	5.7	4.0	3.6	2.7	2.7	4.0	3.5	5.3	5.2
4	4.5	4.0	4.1	3.7	4.0	3.8	4.7	4.1	7.4	6.2	4.1	3.7	2.9	2.8	4.1	3.6	5.5	5.4
5	4.6	4.1	4.3	3.9	4.0	3.9	4.9	4.1	8.2	6.7	4.2	3.8	3.0	2.9	4.2	3.7	5.6	5.6
10	5.2	4.5	4.8	4.4	4.6	4.6	5.5	4.7	15.8	12.1	5.0	4.4	3.5	3.7	4.8	4.2	6.3	6.3
15	5.8	4.9	5.5	5.0	5.2	5.4	6.2	5.2	26.5	17.2	5.8	5.0	4.3	4.5	5.3	4.5	6.9	7.1
20	6.4	5.3	6.2	5.5	5.7	6.4	7.1	5.9	31.5	19.0	6.7	6.1	5.2	5.8	5.9	4.9	7.7	7.9
30	7.9	6.2	8.2	6.4	7.3	9.5	8.8	7.5	38.9	20.5	9.5	7.5	7.6		7.3	5.8	9.2	10.0
45	10.3	7.9	11.8	8.2	10.5	16.2	12.0	10.8	41.3	20.5	14.3	10.0	12.5	15.0	9.5	7.3	12.6	14.8
60	12.9	9.6	16.2	10.5	13.4	20.6	15.3	15.5	41.3	20.5	19.0	13.4	16.3	17.3	11.6	8.9	16.4	20.1
90	15.6	13.0	23.9	14.4	17.6	25.6	21.2	22.1	41.3	20.5	21.4	21.3	19.2	17.3	16.3	12.0	22.3	28.5
120	19.7	16.4	25.8	15.7	19.7	25.6	24.6	25.8	41.3	20.5	24.4	26.2	20.1	17.3	18.0	14.7	26.3	29.5

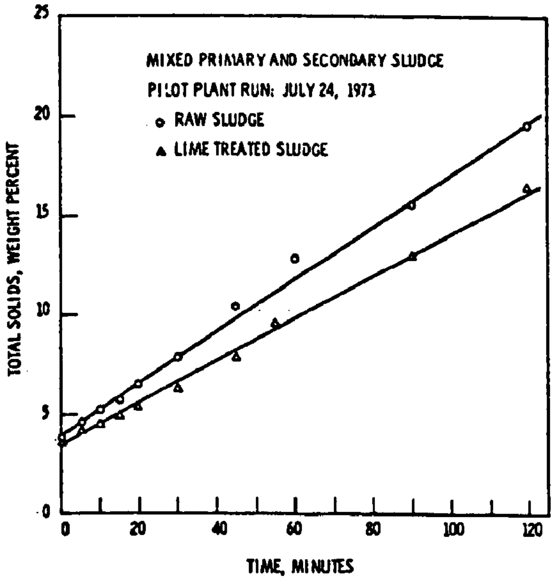


FIGURE 6
7/24/73

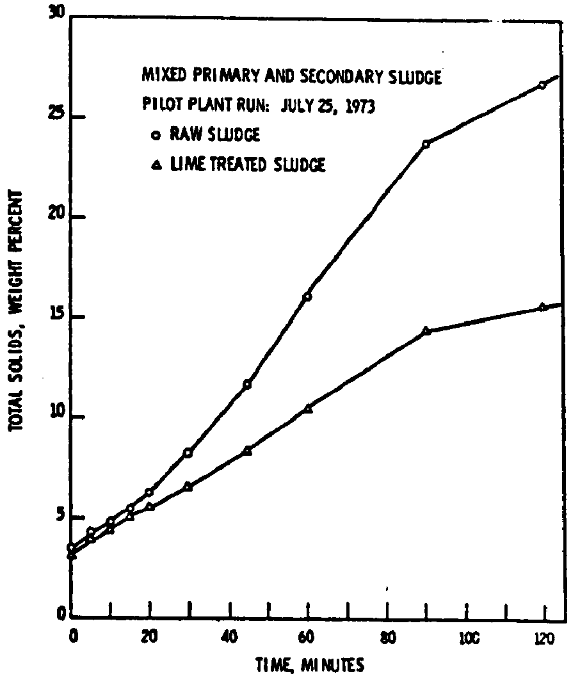


FIGURE 7
7/25/73

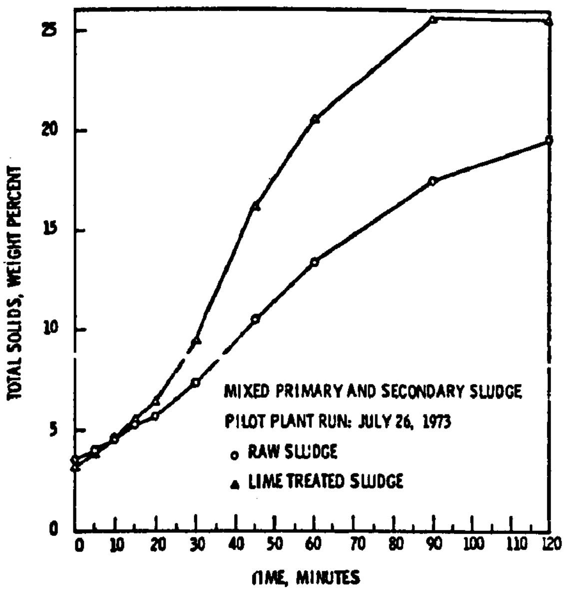


FIGURE 8
7/26/73

Effect of Lime Treatment on Sludge Filterability

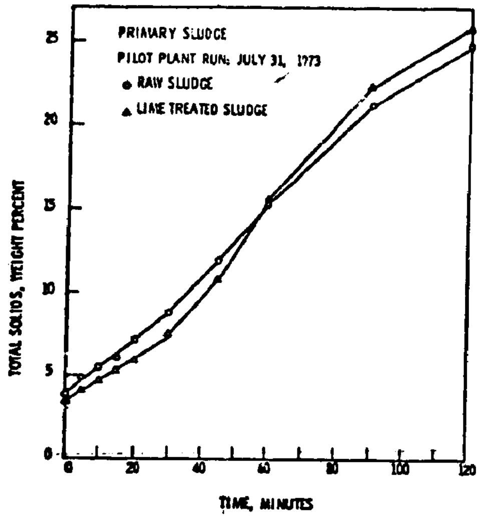


FIGURE 9
7/31/73

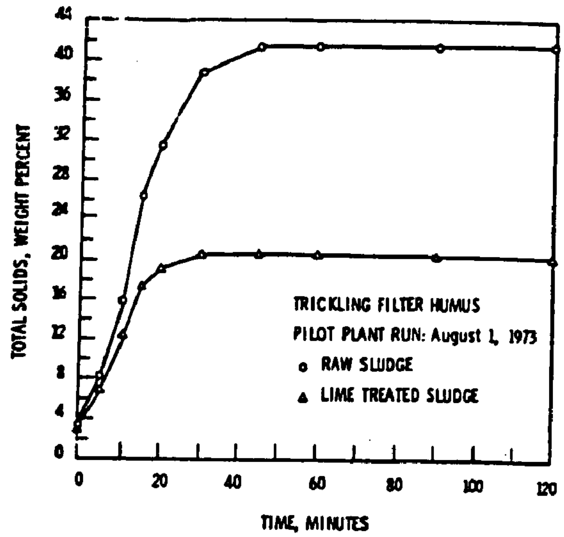


FIGURE 10
8/1/73

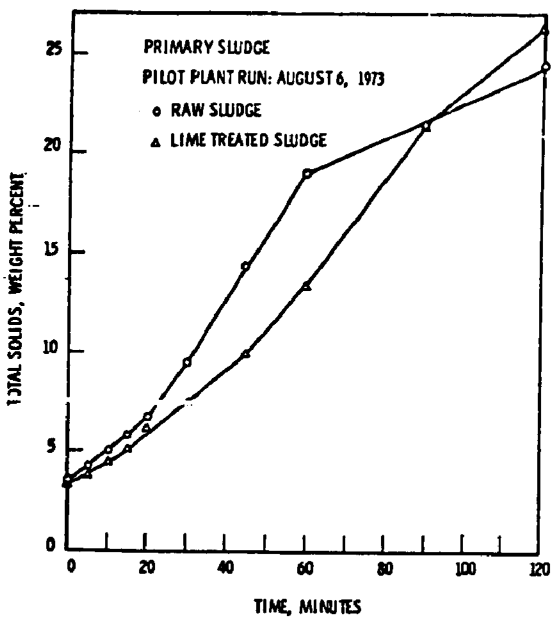


FIGURE 11
8/6/73

Effect of Lime Treatment on Sludge Filterability

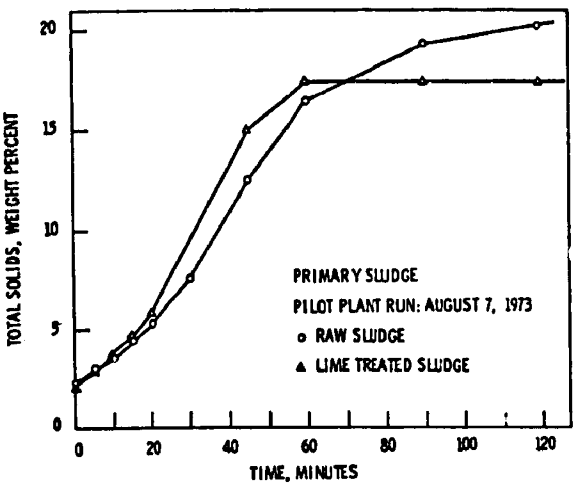
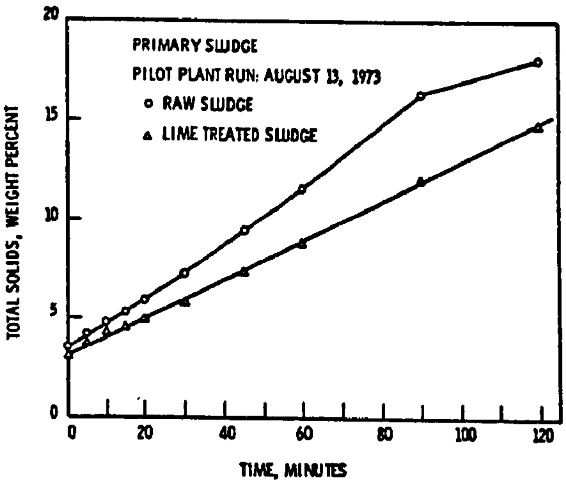


FIGURE 12
8/7/73

FIGURE 13
8/13/73



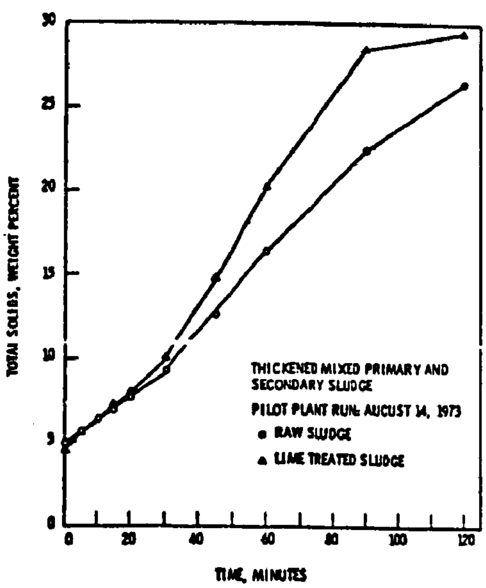


FIGURE 14
8/14/73

Effect of Lime Treatment on Sludge Filterability

Improved filterability should have been evident from an increased rate of total solids concentration buildup in the funnel and an increased ultimate total solids concentration at the end of the filtering time. The results do not indicate any trends which would lead to generalizations about the effect of lime treatment on sludge filterability. The rate of total solids buildup (or filtrate removal) appears to be about the same for both raw and treated sludges during the first 10 to 15 minutes of each test. After about 20 minutes of filtering time, the rates of solids buildup in the funnels usually changed. In some instances, the lime treated sludges exhibited enhanced filterability, and in others, the raw sludges dewatered more easily. The highest ultimate total solids concentration was usually achieved by the sludge which exhibited the highest rate of solids buildup during the latter stages of the filtration period.

SETTLING CHARACTERISTICS OF LIME-TREATED SLUDGE

Studies to determine the effect of lime treatment on sludge settling characteristics were conducted on sludge processed in the pilot process. One liter samples of raw and lime treated sludges were placed in 1 liter graduated cylinders and allowed to settle for a specified length of time. The sludge volume at the sludge-supernatant interface was read and recorded periodically. The sludge samples were also gently stirred periodically to eliminate the effect of bridging among sludge particles. The results of these tests are shown in Table 17 and Figures 15-23.

In all but one instance, sludge settling characteristics were enhanced by lime treatment. This phenomena is probably caused by the formation of floc which settles better than the dispersed particles in the raw sludge. The supernatants recovered from these tests were clear and had total solids concentrations ranging from 0.1 to 0.3 percent and 0.5 to 0.7 percent in the raw sludge and treated sludge supernatants, respectively. The higher total solids concentrations in the treated sludge supernatants are caused by the high concentrations of dissolved $Ca(OH)_2$ introduced in the lime slurry and by an increase in the concentration of dissolved organics as a result of lime treatment.

These results indicate that lime treatment of sludges prior to thickening operations would enhance the effectiveness of the thickener. Removal of a portion of the sludge liquid phase would reduce the overall volume of the sludge to be further treated or removed from the treatment plant. If the thickened, lime treated sludges were to be applied to agricultural land, removal of a portion of the liquid phase would reduce the volume of sludge to be transported to the disposal site. The high pH conditions created by lime treatment would also prevent

TABLE 17. Results of Studies of Sludge Settling Characteristics

Settling Time (min)	Volume at Sludge/Supernatant Interface (mls)									
	July 24		July 25		July 26		July 31		August 1	
	Mixed Sludge		Mixed Sludge		Mixed Sludge		Mixed Sludge		Mixed Sludge	
	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.
0	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
15	998	995	997	990	No settling occurred	985	1000	990	860	985
30	997	992	990	982		965	1000	985	700	965
60	996	988	988	974		940	995	967	555	925
90	996	981	982	960		910	995	945	480	880
120	996	975	975	945		880	993	930	440	835
180	995	965	963	920		845	990	895	390	750
240			950	900		815	990	860	380	680
300			940	870		760	990	835	380	610
360			930	842						

Settling Time (min)	Volume at Sludge/Supernatant Interface (mls)							
	August 6		August 7		August 13		August 14	
	Mixed Sludge		Mixed Sludge		Mixed Sludge		Mixed Sludge	
	Raw	Treat.	Raw	Treat.	Raw	Treat.	Raw	Treat.
0	1000	1000	1000	1000	1000	1000	1000	1000
15	1000	990	995	990	1000	990	995	988
30	995	985	990	970	997	985	995	985
60	990	975	980	945	995	985	990	975
90	985	965	970	915	995	975	985	965
120	980	953	965	885	993	970	980	955
180	978	940	945	830	990	955	970	920
240	970	910	925	770	990		960	890
300	970	890	900	715	990	905	955	865

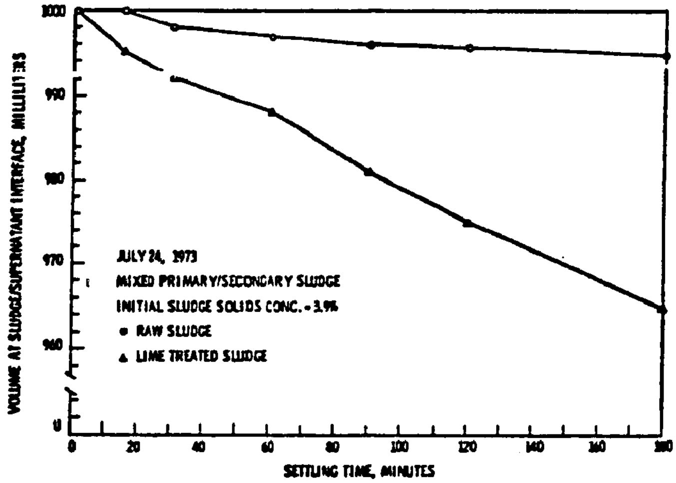


FIGURE 15
7/24/73

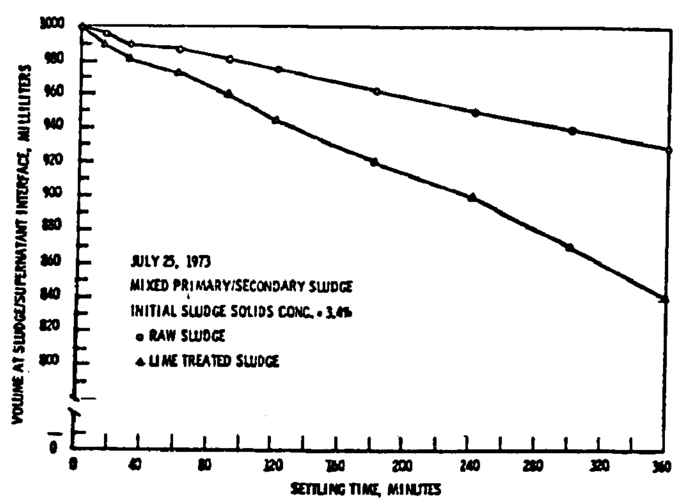


FIGURE 16
7/25/73

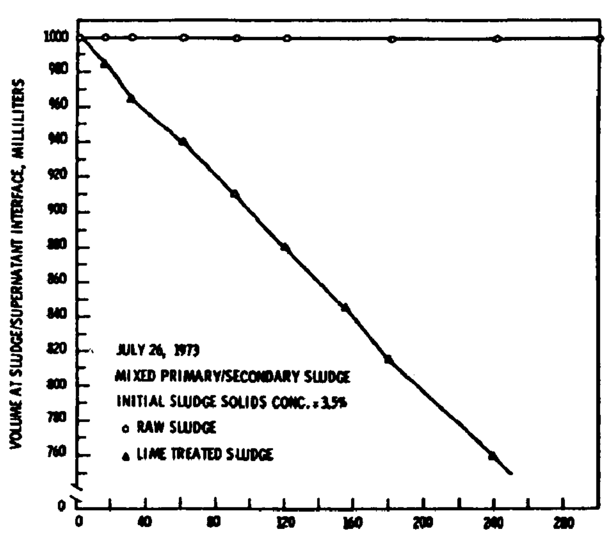


FIGURE 17
7/26/73

Effect of Lime Treatment on
Sludge Settling Characteristics

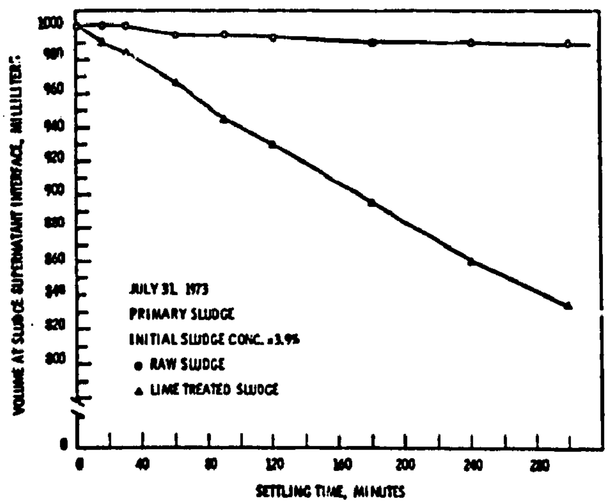


FIGURE 18
7/31/73

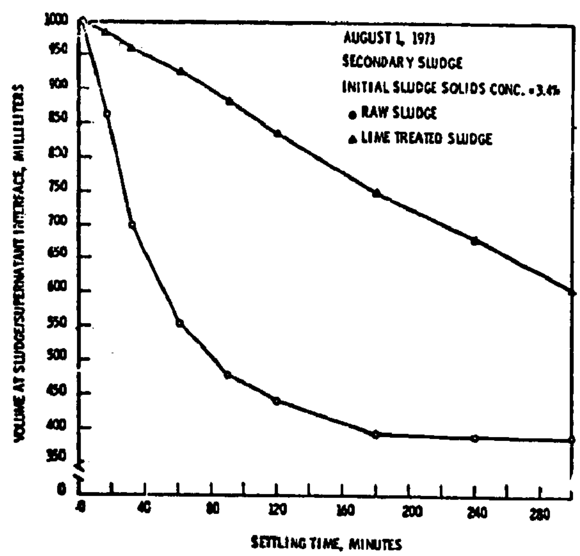


FIGURE 19
8/1/73

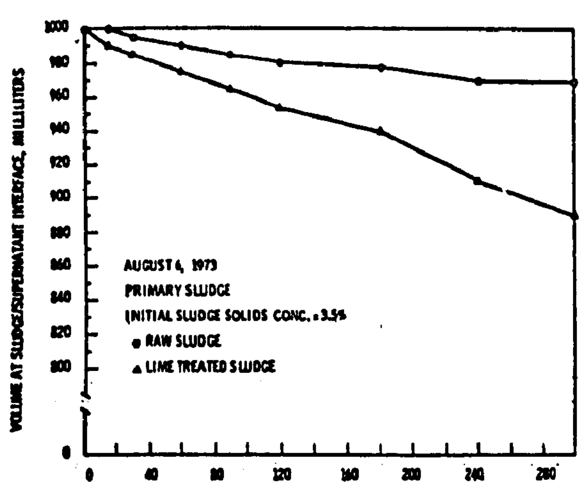


FIGURE 20
8/6/73

Effect of Lime Treatment on
Sludge Settling Characteristics

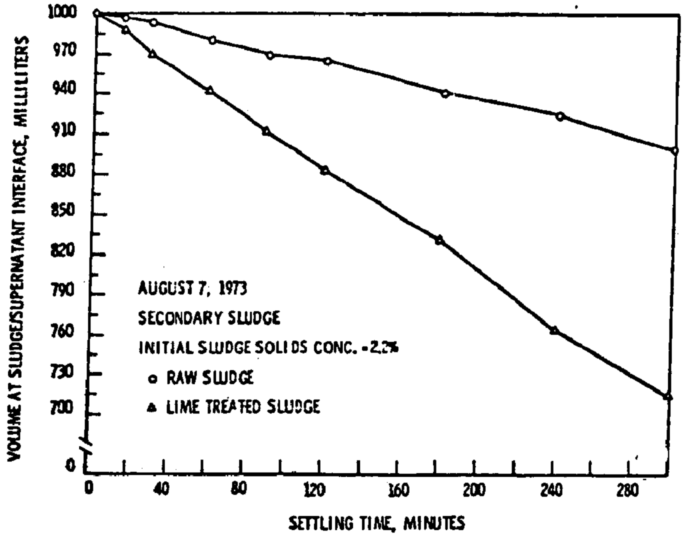


FIGURE 21
8/7/73

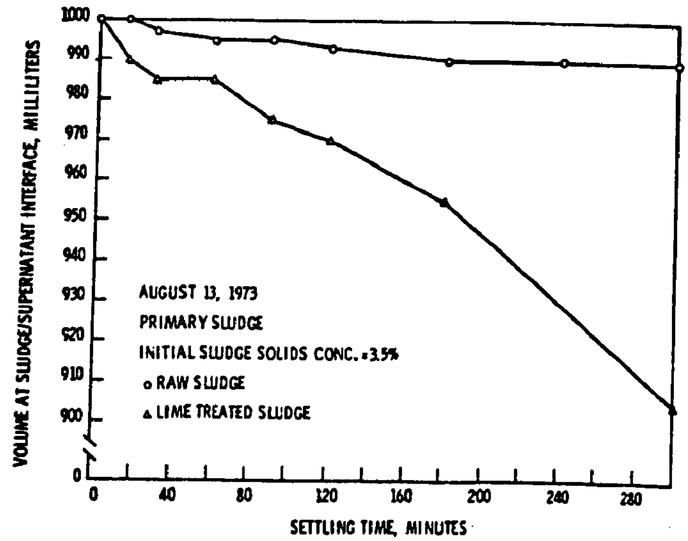


FIGURE 22
8/13/73

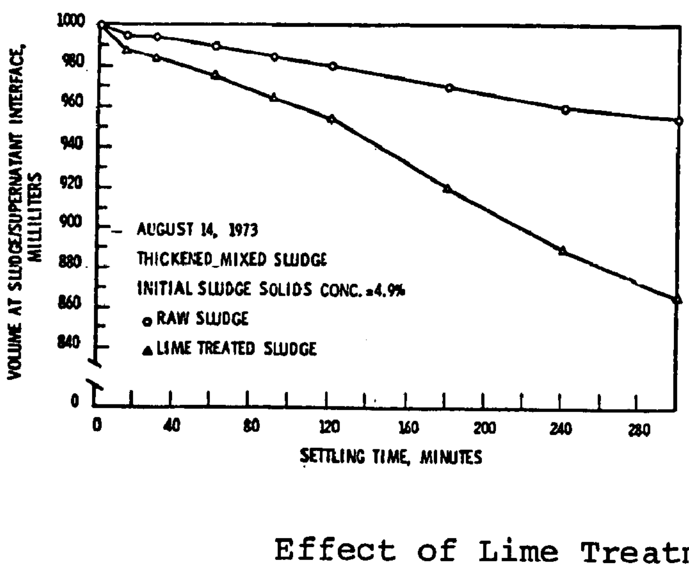


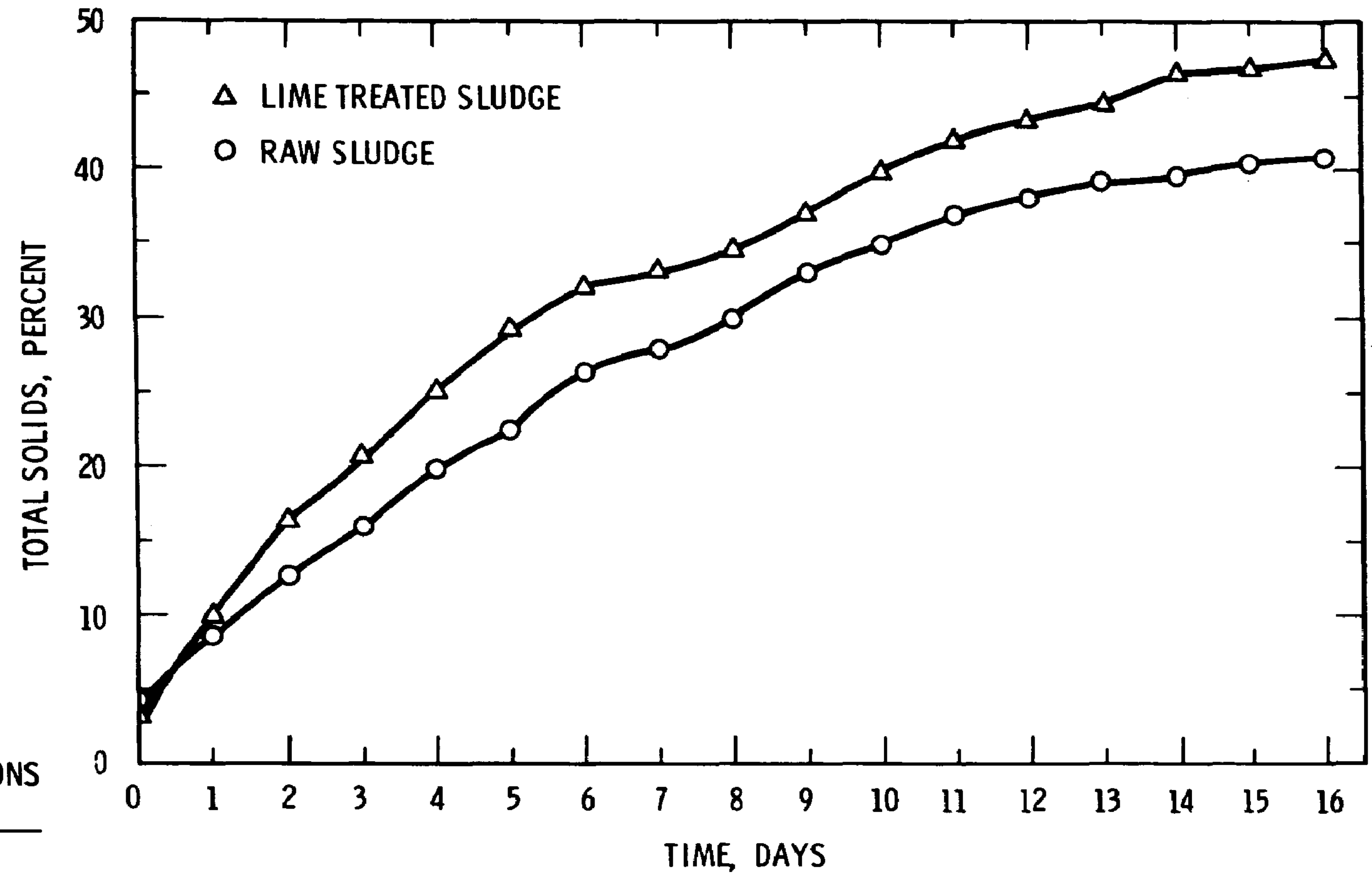
FIGURE 23
8/14/73

Effect of Lime Treatment on
Sludge Settling Characteristics

odor production in thickeners so longer residence times could be used. Longer residence times would also improve the effectiveness of the thickener.

SAND DRYING BED TESTS

Results from the comparative study of drying characteristics of raw and lime treated sludges are shown in Figure 24. Meteorological conditions existing during the test are also presented. The test was conducted in two adjacent sand drying beds, each having a surface area of approximately 1.5 m^2 (16 ft^2). The sludges were dried concurrently so both were exposed to the same climatic conditions. Ten centimeters (4 inches) of sludge were initially applied to each bed. The sludge blanket was sampled every working day and tested for total solids. The test was suspended when the drying rate decreased significantly. Two observations can be made from this test. First, the ultimate total solids concentration in the lime treated sludge was higher than in the raw sludge. Upon termination of the test, the lime treated sludge total solids concentration was 47 percent; whereas, the final total solids concentration in the raw sludge was 41 percent. This represents a 15 percent greater concentration of solids in the lime treated sludge than in the raw sludge. The second observation is that 16 days were required for the raw sludge to reach a total solids concentration of 41 percent, but only 10 days were necessary for the lime stabilized sludge to reach that same solids concentration. This represents a 38 percent reduction in the time required to achieve an optimal, ultimate total solids concentration. This point is of considerable importance when considering seasonal time constraints placed on sand drying bed use in some regions. Decreasing the sludge turn-over time from application to removal from drying beds would increase the total volume of sludge which could be dried during the time period when bed use was possible. Increasing the total volume of sludge passing through this drying process would reduce the volume of sludge storage required to carry treatment plant operations through severe winter months.



METEOROLOGICAL CONDITIONS DURING TEST

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TEMPERATURE (°F)																	
HIGH	101	98	89	80	77	85	93	93	86	82	77	80	83	84	88	90	76
LOW	62	61	55	48	52	52	56	54	49	56	46	48	51	56	49	57	54
RELATIVE HUMIDITY (%)	23	16	31	32	28	20	25	25	29	31	39	45	35	33	38	38	40
WIND SPEED (MPH)	8.2	10.8	11.0	9.6	6.6	6.8	6.4	8.5	6.4	9.7	8.1	3.8	6.5	12.5	7.0	9.2	8.7

FIGURE 24. Comparison Between Raw and Lime-Treated Sludge Drying Characteristics

GROWTH STUDIES

GENERAL

The phase of the program dealing with the effects of spreading lime stabilized sludges on land used for crop production involved both greenhouse studies and a larger scale outdoor plot study.

A small greenhouse, pictured in Figure 25, was constructed adjacent to the treatment plant for the conduct of growth studies. These greenhouse studies were designed to study the response of plants grown in various sludge-soil mixtures. The first of two greenhouse studies yielded information which was used in design of the outdoor plot study. This outdoor plot study was conducted during the summer of 1973 at the Washington State University Irrigated Agriculture Research and Extension Center in Prosser, Washington.

FIGURE 25. Greenhouse Used in Growth Studies

GREENHOUSE STUDIES

Two greenhouse studies were conducted to determine the effects of spreading lime treated sludge on soil to be used for crop production. In the first greenhouse study, the soil used was Ritzville silt loam while a Rupert sand was used in the second greenhouse study. Anaerobically digested sludge and lime-treated sludges (primary, humus, and mixed primary-humus) were applied to soils at five application rates ranging from 11 to 220 metric tons/hectare (5 to 100 tons dry solids/acre).

In the first greenhouse study, the sludges were dried prior to mixing with the soil. It was observed that the sludge contained a large amount of fibrous material which combined with the undissolved lime and formed a hard, crusty material after drying. This material had to be mechanically ground to form a product which could be mixed with the soil to produce a relatively homogeneous mixture. One disadvantage of dry application of the sludge was the loss of nutrient transport in the sludge liquid phase which normally percolates through the soil after sludge application. This problem was solved by the sludge application technique used in preparation for the second greenhouse study.

For the second greenhouse study, digested and lime stabilized sludges in liquid form were applied at the designated rates on small outdoor plots. The sludges were dewatered by the mechanisms of draining and evaporation and the sludge solids were left on the surface of the plots. After the sludge dried, the solids were spaded into the underlying soil to an approximate plow depth of 20 cm (8 inches). These sludge-soil mixtures were transferred to the pots and barley was grown as in the first greenhouse study. This sludge application technique very closely simulated conditions encountered in large scale sludge spreading operations.

In both greenhouse studies, four replicates were used to minimize the effects of random variations. The sludge-soil mixtures were placed in clay flower pots (18 cm top diameter, 11 cm bottom diameter, 17 cm height) and readied for use. Control pots were prepared for use in comparing plant growth characteristics and soil response to sludge application. The control set contained only soil with no sludge additions and received optimum additions of chemical fertilizer during the actual plant growth phase of the studies. The fertilizer requirements for the Ritzville silt loam used in the first greenhouse study were 100 lbs nitrogen/acre, 40 lbs P_2O_5/acre, and 2 lbs boron/acre. For the Rupert sand used in the second greenhouse study, the fertilizer requirements were 60 lbs nitrogen/acre, 150 lbs P_2O_5/acre, 100 lbs potash/acre, 40 lbs sulfur/acre, 5 lbs zinc/acre, and 1 lb boron/acre. Barley

(*Hordeum vulgare*) was sown in the pots and the growing plants maintained through a full growth cycle as indicated by the formation of grain heads.

After the full growth cycle of approximately 2.5 to 3 months, the plant material and sludge-soil mixtures were subjected to analyses. The plant tissue was weighed to determine the mass yield and then chemically analyzed for micro- and macronutrient content. The sludge-soil mixtures were analyzed both before and after plant growth for available micro- and macronutrient content, pH, permeability with water, hydraulic conductivity, and field capacity (a measure of the soil's ability to retain moisture). Available nutrient concentrations in the sludge-soil mixtures were determined by a commercial soil testing laboratory using techniques certified by the Washington State University Agricultural Extension Service. The techniques used for determining pH, permeability with water, hydraulic conductivity, and field capacity are described in *Methods of Soil Analysis*.[15]

Results From First Greenhouse Study

Figure 26 compares the barley growth for various sludges and application rates midway through the growth cycle during the first greenhouse study.

The results from analyses of physical characteristics of the sludge-soil mixtures used in the first greenhouse study are shown in Table 18. The only general trend that can be seen from the intrinsic permeability with water data is that permeability appears to increase after the soil has been used as a growth medium. This increase in permeability appeared in all the sludge-soil mixtures except in those with primary sludge. The mixtures of primary sludge and soil all showed a decrease in permeability after the barley growth cycle. The results also indicated that, in general, soil permeability is improved by the addition of sludge, but no general trend which would correlate permeability with sludge type and application rate seemed to exist.

In almost every case, the pH values of the sludge-soil mixtures were lowered during the growth study. This phenomenon is probably caused by CO_2 production during biological breakdown of organic matter and nitrification in the soil. Acid buildup in the soil results in a lower pH.

Field capacity of the mixtures decreased slightly during the growth studies. Results from analyses of sludge-soil mixtures for available macro- and micronutrients before and after the plant growth are shown in Table 19. No general trends were

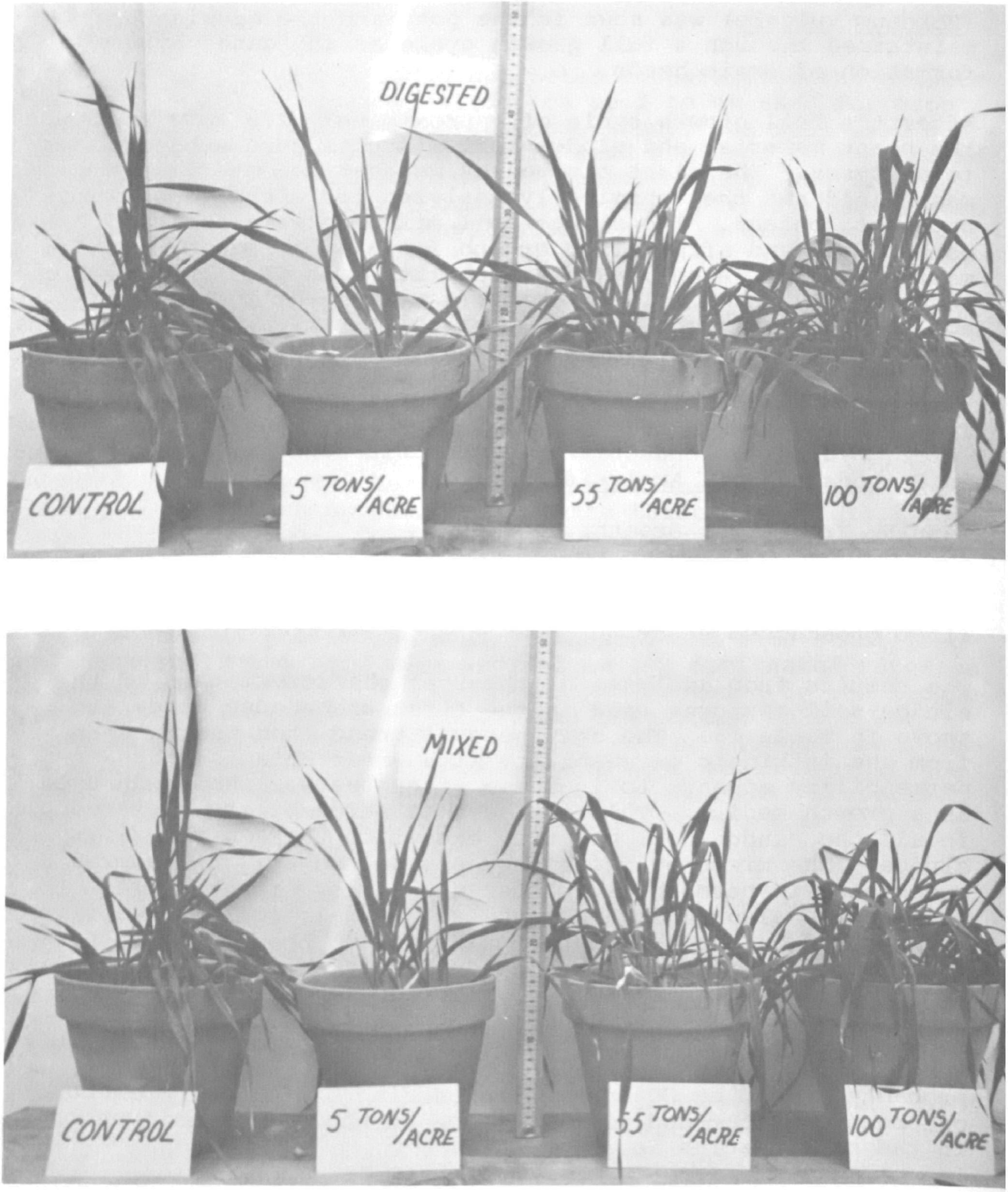


FIGURE 26. Barley Growth During First Greenhouse Study

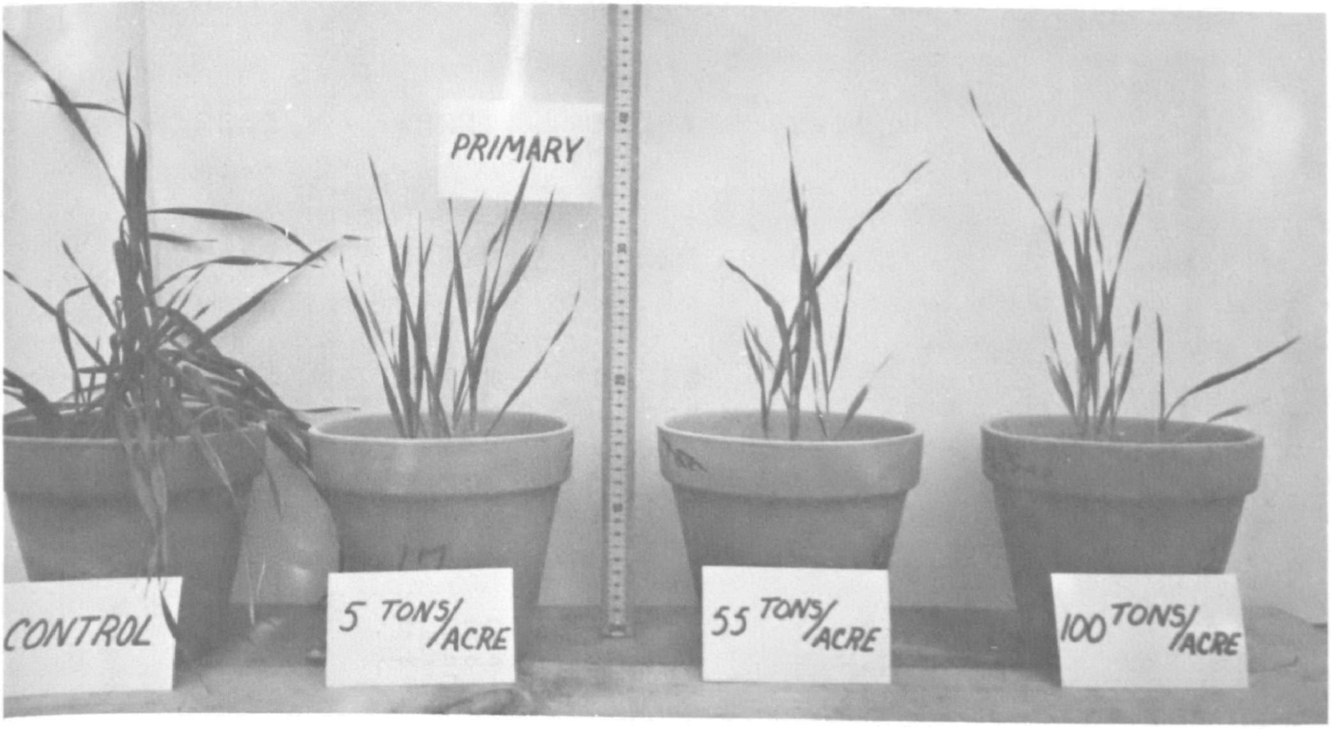


FIGURE 26 (continued)

TABLE 18. Physical Characteristics of Soils Before and After Barley Growth in the First Greenhouse Study

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Intrinsic Permeability with Water - K'_w (cm^2)		Hydraulic Conductivity - K (cm/sec)		K_m/K_c [1]		pH of Mixture[2]		Field Capacity of Mixture[3] (% of soil dry wt.)	
	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control										
100% Ritzville Silt Loam (RSL)	9.01×10^{-10}	1.03×10^{-9}	1.01×10^{-4}	1.16×10^{-4}	1.00	1.15	7.90	6.40	31	25
Mixed Primary and Secondary and RSL										
5	8.31×10^{-10}	9.05×10^{-10}	9.29×10^{-5}	1.01×10^{-4}	0.92	1.00	8.00	7.85	29	27
30	1.03×10^{-9}	4.89×10^{-9}	1.15×10^{-4}	5.47×10^{-4}	1.14	5.42	8.15	7.42	29	30
55	2.78×10^{-9}	6.99×10^{-9}	3.11×10^{-4}	7.82×10^{-4}	3.07	7.74	8.20	7.70	31	30
80	9.20×10^{-9}	1.51×10^{-8}	1.02×10^{-3}	1.69×10^{-3}	10.01	16.73	8.35	7.02	43	34
100	2.04×10^{-8}	1.65×10^{-8}	2.28×10^{-3}	1.85×10^{-3}	22.6	18.32	8.30	7.18	42	34
Digested Sludge and RSL										
5	1.01×10^{-9}	7.61×10^{-10}	1.13×10^{-4}	8.52×10^{-5}	1.11	0.84	7.80	7.80	28	26
30	9.23×10^{-9}	1.81×10^{-9}	1.03×10^{-4}	2.03×10^{-4}	1.03	2.01	7.60	7.55	27	22
55	6.37×10^{-10}	8.26×10^{-9}	7.12×10^{-5}	9.25×10^{-4}	0.70	9.16	7.10	7.02	29	27
80	5.29×10^{-10}	5.30×10^{-9}	5.92×10^{-5}	5.90×10^{-4}	0.59	5.84	6.90	7.10	30	29
100	6.67×10^{-10}	3.15×10^{-9}	7.48×10^{-5}	3.52×10^{-4}	0.74	3.48	6.90	7.10	30	29
Primary Sludge and RSL										
5	8.27×10^{-10}	2.05×10^{-10}	9.27×10^{-5}	2.29×10^{-5}	0.91	0.23	8.25	7.51	22	27
30	5.62×10^{-9}	8.05×10^{-10}	6.29×10^{-4}	9.02×10^{-5}	6.23	0.89	8.35	7.69	24	25
55	1.16×10^{-8}	9.44×10^{-9}	1.30×10^{-3}	1.05×10^{-3}	12.87	10.40	8.40	7.88	28	20
80	1.34×10^{-8}	4.10×10^{-9}	1.50×10^{-3}	4.58×10^{-4}	14.85	4.53	8.65	7.27	38	25
100	1.48×10^{-8}	1.26×10^{-9}	1.66×10^{-3}	1.42×10^{-4}	16.44	1.41	8.50	7.45	39	26
Secondary Sludge and RSL										
5	7.64×10^{-10}	1.50×10^{-9}	8.56×10^{-5}	1.69×10^{-4}	0.85	1.67	8.10	8.05	20	29
30	3.10×10^{-10}	2.95×10^{-9}	3.47×10^{-5}	3.03×10^{-4}	0.35	3.00	8.40	8.30	21	28
55	2.46×10^{-10}	5.80×10^{-10}	3.03×10^{-5}	6.50×10^{-5}	0.30	0.64	8.60	8.00	26	29
80	1.94×10^{-10}	1.03×10^{-10}	2.16×10^{-5}	1.15×10^{-4}	0.20	1.14	8.75	8.40	29	30
100	2.26×10^{-10}	1.06×10^{-9}	2.54×10^{-5}	1.18×10^{-4}	0.25	1.17	8.80	8.58	31	31

1. Ratio of the hydraulic conductivity of the sludge/soil mixture (K_m) to that of the control (K_c) before the growth cycle.
2. Soil pH measured in water.
3. 1/3 bar percentage.

TABLE 19. Macro- and Micronutrient Concentrations in Sludge-Soil Mixtures Before and After Barley Growth in the First Greenhouse Study

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Nitrate-N (ppm)		Phosphorus (ppm)		Potassium (ppm)		Sulfur (ppm)		Magnesium (ppm)		Calcium (ppm)	
	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control	2.0	28.0	250	170	260	110	7	7	444	384	6000	1640
100% Ritzville Silt Loam (RSL)												
Mixed Primary and Secondary Sludge and RSL												
5	0.23	16.0	130	25	200	190	104	16	300	324	2240	2440
30	0.23	77.0	175	90	190	190	112	39	300	324	3520	4240
55	2.0	12.0	230	130	300	130	120	83	320	348	3580	5000
80	1.1	63.2	245	240	280	230	132	104	348	336	3860	4680
100	0.45	18.5	245	270	380	240	146	118	384	360	4000	4740
Digested Sludge and RSL												
5	0.45	6.0	440	29	340	180	60	29	300	300	2040	2740
30	0.23	5.9	535	110	380	180	64	62	324	252	2600	3080
55	1.35	10.8	14	115	220	170	66	92	336	264	3140	3780
80	0.68	8.8	62	150	200	140	74	112	432	264	4300	3820
100	0.23	16.3	120	165	190	150	88	130	468	240	4400	4000
Primary Sludge and RSL												
5	1.6	0.23	20	44	200	200	18	6	324	240	1820	2960
30	1.6	8.6	33	80	240	170	24	6	324	240	2800	3280
55	0.68	29.0	290	140	420	180	24	48	336	327	2800	5000
80	1.1	17.2	130	200	260	170	62	36	384	264	4060	4240
100	0.45	27.1	370	230	320	180	62	44	420	276	4160	4360
Humus and RSL												
5	0.45	5.2	475	50	500	200	34	14	360	312	2760	2600
30	0.68	213.0	655	300	700	200	54	43	372	312	3040	4780
55	2.5	171.0	750	528	800	510	56	85	396	324	4740	5760
80	0.68	4.7	41	825	240	640	14	130	396	360	5000	4500
100	0.90	2.0	135	770	280	800	68	138	408	444	6080	5760

TABLE 19 (continued)

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Sodium (ppm)		Iron (ppm)		Manganese (ppm)		Boron (ppm)		Copper (ppm)		Zinc (ppm)	
	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control	81	23	70	85	45	30	1.0	0.6	13.0	4.5	55.0	1.7
100% Ritzville Silt Loam (RSL)												
Mixed Primary and Secondary Sludge and RSL												
5	46	35	210	28	102	85	1.0	0.7	6.5	5.5	155.0	5.7
30	92	46	220	90	85	100	1.1	1.0	4.8	13.0	185.0	50.0
55	104	46	230	130	140	120	0.4	1.5	2.8	15.5	65.0	65.0
80	115	115	70	285	90	80	0.3	1.2	3.5	4.5	9.5	120.0
100	138	115	145	320	120	135	0.2	0.5	2.0	5.5	50.0	12.0
Digested Sludge and RSL												
5	35	35	312	28	92	60	0.5	0.7	6.0	9.0	60.0	21.0
30	69	92	305	60	95	100	0.7	0.8	9.3	8.0	80.0	26.0
55	92	92	52	180	45	163	0.4	1.1	4.0	10.5	10.0	181.0
80	161	92	85	205	75	138	0.8	1.4	8.0	8.5	60.0	150.0
100	173	104	190	210	85	105	1.1	1.5	9.0	8.5	120.0	185.0
Primary Sludge and RSL												
5	46	69	40	50	27	110	0.4	0.6	4.5	2.5	1.0	4.0
30	35	69	60	52	60	100	0.5	0.7	3.6	3.6	3.5	10.0
55	127	69	114	110	85	140	0.3	1.2	1.5	14.5	37.0	65.0
80	69	104	130	78	120	90	0.5	1.1	6.3	8.0	16.0	26.5
100	138	115	350	78	110	90	0.6	0.9	3.6	8.0	50.0	40.0
Humus and RSL												
5		46	175	100	97	135	0.3	0.5	3.0	5.5	73	12.0
30		46	195	75	85	95	0.2	0.8	5.0	10.0	85	45.0
55		115	310	100	110	75	0.6	1.1	4.5	14.0	105	70.0
80		253	64	290	65	80	0.5	0.9	4.5	6.5	5.0	110.0
100		253	110	490	138	75	0.5	1.7	1.6	11.0	4.3	140.0

developed from this data since in many instances the available nutrient concentrations after plant growth exceeded that present in the mixture before germination of the barley. However, the results do show that no significant buildup of any macro- or micronutrient occurred. Variations in the soil data were unavoidable because sludge-soil mixtures are heterogeneous and it is difficult to get a sample that is representative of the whole pot.

The barley weight gains from the first greenhouse study are shown in Table 20. The maximum weight gains occurred in the sludge-soil mixtures containing lime-treated primary sludge and the mixture of primary sludge and trickling filter sludge. Weight gains from barley grown in these two mediums slightly exceeded that in the control which was 100 percent soil with optimum chemical fertilizer additions. The control pots with digested sludge applications equivalent to 220 metric tons/hectare (100 tons/acre) also produced a weight yield that exceeded that of controls which received only chemical fertilizer.

Results from analyses of macro- and micronutrient content of the barley are shown in Table 21. None of the nutrients appear to be significantly concentrated in the plant tissue except iron whose concentration was consistently higher in the plants grown in soils which received sludge treatment than in the control pots which received no sludge.

Results From Second Greenhouse Study

The results from analyses of the physical characteristics of the sludge-soil mixtures used in the second greenhouse study are shown in Table 22. In this study the soil used was classified as a Rupert sand which is very porous. Addition of sludge to the soil appears to have reduced the soil's permeability with water. This would be expected in a sandy soil since the sludge organic matter acts to retain moisture; whereas, in a silty or clay soil, the organic matter would tend to open the pore structure and cause an increase in permeability. Again, no well defined trend developed which would correlate permeability with the amount of sludge applied. In general, permeability appears to be reduced after plant growth. This could possibly be caused by biodegradation of the coarse organic components in the sludge to finer humus-like material which would fill pore spaces between larger sand particles.

The pH values in the sludge-soil mixtures were usually lower after plant growth than before. This same phenomenon was observed in the first greenhouse study and is believed to be caused by CO_2 buildups resulting from biological activity in the soil.

TABLE 20. Barley Weight Gains From the First Greenhouse Study

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Total Number Plants	Total Weight of All Plant Tissue Produced (grams)	Average Weight of Tissue in Each Plant (grams/plant)	Yield Ratio* (grams/gram)
Control				
100% Ritzville Silt Loam (RSL)	12	422.4	35.2	1.00
Mixed Primary Sludge and Humus and RSL				
5	16	120.8	7.6	0.21
30	16	276.2	17.3	0.49
55	12	347.3	23.2	0.66
80	15	426.5	28.4	0.81
100	13	476.6	36.7	1.04
Digested Sludge and RSL				
5	16	108.3	6.8	0.19
30	15	198.6	13.2	0.38
55	15	257.1	17.1	0.49
80	16	392.0	24.5	0.70
100	16	431.2	26.9	0.76
Primary Sludge and RSL				
5	15	83.3	5.6	0.16
30	16	151.2	9.5	0.27
55	12	232.4	19.4	0.55
80	16	486.7	30.4	0.86
100	17	617.9	36.4	1.03
Humus and RSL				
5	16	181.1	11.3	0.32
30	15	403.9	26.9	0.76
55	4	21.7	5.4	0.15
80	0	0.0	0.0	0.00
100	0	0.0	0.0	0.00

*Calculated as grams plant tissue from the sludge/soil mixtures per gram plant tissue from the control pots.

TABLE 21. Macro- and Micronutrients in Barley Tissue From the First Greenhouse Study (All Sludges Lime Treated Except the Digested Sludge)

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Total N (%)	Phosphorus (%)	Potassium (%)	Sulfur (%)	Magnesium (%)	Calcium (%)	Sodium (%)	Iron (ppm)	Manganese (ppm)	Boron (ppm)	Copper (ppm)	Zinc (ppm)
Control												
100% Ritzville Silt Loam (RSL)	1.82	0.34	0.40	0.16	0.25	0.32	0.12	740	115	6	12	330
Mixed Primary and Secondary Sludge and RSL												
5	0.99	0.36	1.35	0.18	0.22	0.45	0.10	2,000	77	15	11	27
30	1.30	0.50	1.53	0.28	0.32	1.07	0.17	6,000	165	10	23	86
55	2.07	0.68	1.05	0.33	0.25	3.94	0.21	6,010	225	10	80	260
80	1.89	0.70	1.17	0.40	0.35	1.40	0.37	3,500	110	17	19	70
100	1.62	0.57	0.93	0.40	0.32	1.34	0.37	4,000	118	25	70	120
Digested Sludge and RSL												
5	0.85	0.32	1.17	0.16	0.27	0.47	0.12	2,400	77	8	15	40
30	1.18	0.39	1.37	0.20	0.27	0.70	0.14	2,000	183	8	25	80
55	1.07	0.45	1.17	0.23	0.30	1.27	0.17	6,240	207	9	34	120
80	1.24	0.51	1.25	0.27	0.32	1.35	0.21	6,240	190	12	28	140
100	1.60	0.50	1.25	0.31	0.32	1.34	0.32	3,800	175	17	31	114
Primary Sludge and RSL												
5	0.19	0.32	1.05	0.19	0.22	0.80	0.08	5,040	140	7	28	54
30	0.24	0.50	1.42	0.24	0.25	0.87	0.10	3,800	110	11	22	176
55	1.87	0.83	1.00	0.33	0.32	2.15	0.32	10,560	218	14	35	210
80	0.28	0.66	1.90	0.28	0.25	1.00	0.29	3,000	70	10	25	80
100	0.25	0.66	1.45	0.25	0.27	1.22	0.17	4,240	107	9	15	86
Humus and RSL												
5	1.57	0.40	1.50	0.40	0.32	1.00	0.21	4,560	145	13	21	40
30	1.13	0.41	0.97	0.26	0.30	1.25	0.22	4,800	240	8	19	64
55	1.46	0.55	1.00		0.32	1.70	0.20	10,400	274	5	38	120
80						NO PLANTS						
100						NO PLANTS						

TABLE 22. Physical Characteristics of Soils Before and After Barley Growth in the Second Greenhouse Study

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Intrinsic Permeability with Water - K'_w (cm^2)		Hydraulic Conductivity - K (cm/sec)		K_m/K_c [1]		pH of Mixture[2]		Field Capacity of Mixture[3] (% of soil dry wt.)	
	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control										
100% Rupert Sand (RS)	$3.91x10^{-8}$	$1.44x10^{-8}$	$4.61x10^{-3}$	$1.74x10^{-3}$	1.00	0.38	7.6	6.1	5.5	4.6
Mixed Primary Humus and RS										
5	$3.36x10^{-8}$	$9.91x10^{-8}$	$3.96x10^{-3}$	$1.17x10^{-3}$	0.86	0.25	7.8	7.6	9.1	7.1
30	$1.91x10^{-8}$	$1.70x10^{-8}$	$2.25x10^{-3}$	$2.00x10^{-3}$	0.49	0.43	8.1	8.1	9.4	8.8
55	$3.67x10^{-8}$	$1.84x10^{-8}$	$4.34x10^{-3}$	$2.17x10^{-3}$	0.94	0.47	8.5	8.1	13.9	10.2
80	$2.33x10^{-8}$	$1.73x10^{-8}$	$2.75x10^{-3}$	$2.04x10^{-3}$	0.60	0.44	10.6	8.1	15.9	9.6
100	$4.82x10^{-8}$	$2.85x10^{-8}$	$5.69x10^{-3}$	$3.36x10^{-3}$	1.23	0.72	10.2	8.2	11.4	5.3
Digested Sludge and RS										
5	$2.45x10^{-8}$	$1.31x10^{-8}$	$2.90x10^{-3}$	$1.54x10^{-3}$	0.63	0.33	7.0	7.3	8.6	6.8
30	$1.51x10^{-8}$	$2.58x10^{-8}$	$1.78x10^{-3}$	$3.04x10^{-3}$	0.39	0.66	6.5	6.8	13.3	8.2
55	$1.57x10^{-8}$	$3.50x10^{-8}$	$1.85x10^{-3}$	$4.13x10^{-3}$	0.40	0.89	6.7	6.6	15.2	12.4
80	$1.91x10^{-8}$	$2.53x10^{-8}$	$2.25x10^{-3}$	$2.99x10^{-3}$	0.49	0.64	6.8	6.3	15.6	11.1
100	$3.97x10^{-8}$	$3.88x10^{-8}$	$4.69x10^{-3}$	$4.58x10^{-3}$	1.01	0.99	6.8	6.7	16.1	9.2
Primary Sludge and RS										
5	$2.05x10^{-8}$	$6.86x10^{-9}$	$2.42x10^{-3}$	$8.09x10^{-4}$	0.53	0.18	7.8	7.6	7.6	4.2
30	$2.46x10^{-8}$	$1.06x10^{-8}$	$2.90x10^{-3}$	$1.25x10^{-3}$	0.63	0.27	7.6	7.6	8.4	5.4
55	$2.77x10^{-8}$	$2.58x10^{-8}$	$3.27x10^{-3}$	$3.04x10^{-3}$	0.71	0.66	7.9	7.6	10.7	4.2
80	$4.30x10^{-8}$	$3.14x10^{-8}$	$5.07x10^{-3}$	$3.70x10^{-3}$	1.10	0.80	8.1	7.7	14.9	6.4
100	$2.68x10^{-8}$	$3.26x10^{-8}$	$3.16x10^{-3}$	$3.85x10^{-3}$	0.69	0.84	10.0	7.7	15.0	5.5
Humus and RS										
5	$2.60x10^{-8}$	$1.22x10^{-8}$	$3.07x10^{-3}$	$1.44x10^{-3}$	0.66	0.31	7.9	8.2	7.7	3.5
30	$2.32x10^{-8}$	$2.02x10^{-8}$	$2.74x10^{-3}$	$3.39x10^{-3}$	0.59	0.74	8.5	8.3	13.2	5.6
55	$5.09x10^{-8}$	$5.38x10^{-8}$	$6.01x10^{-3}$	$6.36x10^{-3}$	1.30	1.38	8.0	8.0	13.2	4.4
80	$4.42x10^{-8}$	$4.35x10^{-8}$	$5.22x10^{-3}$	$5.14x10^{-3}$	1.13	1.11	8.1	8.0	16.1	4.4
100	$2.22x10^{-8}$	$4.26x10^{-8}$	$2.62x10^{-3}$	$5.04x10^{-3}$	0.56	1.09	8.3	8.0	20.2	6.4

1. Ratio of the hydraulic conductivity of the sludge-soil mixture (K_m) to that of the control (K_c) before the growth cycle.
2. Soil pH measured in water.
3. 1/3 bar percentage.

The field capacities of the sludge-soil mixtures were lower in the samples taken after plant growth than in those taken before the barley was planted. The results obtained from analyses of sludge-soil mixtures for available macro- and micronutrients before and after the plant growth are shown in Table 23. In general, the results show increases in available nutrient concentrations in the sludge-soil mixtures as sludge application rates increased. A decrease in available nutrient concentrations apparently occurs during plant growth. This decrease is probably caused by nutrient uptake in the growing plants. Sludge application to the soil at rates as low as 11 metric tons dry solids per hectare (5 tons dry solids per acre) significantly increased the concentrations of available calcium and iron in the mixtures. The increase in calcium concentration was expected because of the lime added to the sludges. The increase in available iron was also observed in the results from the first greenhouse study. Application of moderate to high amounts of sludge caused significant increases in the concentrations of available phosphorus, sodium, manganese, and zinc.

Results from the study of barley weight gains in the second greenhouse study are shown in Table 24. The total weights of plant materials produced in this study were not as high as in the first greenhouse study but the growth patterns were more definite. The reduced overall yields probably resulted from using Rupert sand as the soil upon which sludges were applied. This type soil is not as good for crop production as is the Ritzville silt loam used in the first greenhouse study. The control pots which received only chemical fertilizer yielded plants which averaged only 4.7 grams each. However, the addition of sludge to the soils significantly affected the yield. The sludge-soil mixtures made from mixed primary sludge and humus, primary sludge alone, and humus alone, applied at the lowest rate of 11 metric tons dry solids per hectare (5 tons dry solids per acre) all yielded less plant material than the control pots which received only chemical fertilizer. The mixture made from Rupert sand and digested sludge applied at 11 metric tons dry solids per hectare (5 tons dry solids per acre) produced plants whose average weight exceeded that of the control by almost 2.5 times. The mixtures made from mixed sludge and digested sludge applied to Rupert sand all produced increasing plant material yields as the sludge application rates increased from 66 through 176 metric tons dry solids per hectare (30 through 80 tons dry solids per acre). Plant yield decreased for each of these sludge-soil types when the application rate reached 220 metric tons dry solids per hectare (100 tons dry solids per acre). The mixtures made from primary sludge and humus applied to

TABLE 23. Available Macro- and Micronutrient Concentrations in Sludge-Soil Mixtures Before and After Barley Growth in the Second Greenhouse Study

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Nitrate-N (ppm)		Phosphorus (ppm)		Potassium (ppm)		Sulfur (ppm)		Magnesium (ppm)		Calcium (ppm)	
	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control												
100% Rupert Sand (RS)	2	37	7	100	280	106	1	10	108	144	360	320
Mixed Primary and Secondary Sludge and RS												
5	13	3	9	13	200	150	9	5	120	120	520	720
30	43	2	88	41	210	110	50	26	132	96	2160	1900
55	25	2	125	60	190	120	48	33	120	108	2200	2400
80	2	2	175	78	210	150	0	0	120	132	3040	2800
100	2	3	275	50	240	120	0	24	132	132	3080	2300
Digested Sludge and RS												
5	19	2	18	11	240	150	44	12	120	120	460	420
30	35	1	40	56	240	80	140	23	132	96	540	520
55	3	7	85	104	240	100	150	120	120	96	560	560
80	1	23	46	110	190	80	200	185	120	120	680	600
100	1	4	116	122	190	80	210	120	132	96	720	600
Primary Sludge and RS												
5	11	1	16	20	170	120	0	3	120	120	600	460
30	36	14	60	104	210	110	46	25	120	120	1660	920
55	34	2	125	69	240	100	57	16	132	96	2100	1320
80	1	1	225	130	240	110	0	27	120	96	2760	1800
100	2	2	220	110	240	120	0	48	120	120	2640	2040
Humus and RS												
5	19	2	15	16	200	140	12	4	120	120	520	560
30	4	3	60	59	190	110	12	4	120	96	1120	1600
55	15	2	150	130	210	80	39	9	108	132	1460	1460
80	1	2	200	244	290	80	60	30	144	132	1660	2200
100	2	26	250	244	290	100	0	44	168	144	2000	2080

TABLE 23 (continued)

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Sodium (ppm)		Iron (ppm)		Manganese (ppm)		Boron (ppm)		Copper (ppm)		Zinc (ppm)	
	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control												
100% Rupert Sand (RS)	75	33	68	73	37	26	0.5	0.5	9	5	1	4
Mixed Primary and Secondary Sludge and RS												
5	50	44	197	42	95	102	0.4	0.6	8	6	2	7
30	87	55	210	106	70	63	0.6	0.7	10	7	27	21
55	110	67	217	117	180	140	0.6	1.0	9	12	26	26
80	112	112	245	103	85	70	0.5	0.8	11	10	50	37
100	142	105	177	208	137	133	0.5	0.5	12	9	68	26
Digested Sludge and RS												
5	27	23	288	56	84	52	0.8	0.6	7	10	8	15
30	80	95	310	60	90	86	1.1	0.7	11	12	46	38
55	90	85	211	187	76	102	1.4	1.1	10	6	68	88
80	145	77	214	210	66	140	1.7	1.3	9	8	33	125
100	160	93	186	200	83	92	1.3	1.5	13	12	172	105
Primary Sludge and RS												
5	52	67	53	47	40	105	0.8	0.4	11	6	3	7
30	30	63	70	57	65	88	0.9	1.0	9	11	30	27
55	140	85	93	100	93	115	0.9	0.5	12	7	26	20
80	76	112	112	60	130	105	0.8	0.9	10	9	70	30
100	126	107	312	94	100	95	0.5	0.6	14	12	48	40
Humus and RS												
5	28	43	108	85	85	110	0.4	0.5	9	8	2	5
30	33	40	88	96	97	62	0.7	1.2	12	7	10	10
55	122	113	96	105	83	105	0.9	0.6	11	12	22	18
80	207	86	300	80	70	72	1.0	0.8	10	12	40	36
100	237	120	420	106	100	55	1.1	0.9	12	9	37	34

TABLE 24. Barley Weight Gains From the Second Greenhouse Study

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Total Number Plants	Total Weight of All Plant Tissue Produced (grams)	Average Weight of Tissue in Each Plant (grams/plant)	Yield Ratio* (grams/gram)
Control				
100% Rupert Sand (RS)	16	74.8	4.7	1.00
Mixed Primary Sludge and Humus and RS				
5	16	67.0	4.2	0.89
30	16	158.6	9.9	2.12
55	15	200.1	13.3	2.83
80	15	252.6	16.8	3.57
100	16	206.5	12.9	2.74
Digested Sludge and RS				
5	14	162.1	11.6	2.47
30	15	211.6	14.1	3.00
55	17	253.2	14.9	3.17
80	16	309.4	19.4	4.13
100	15	219.2	14.6	3.11
Primary Sludge and RS				
5	16	36.1	2.3	0.49
30	14	122.8	8.8	1.87
55	16	144.5	9.0	1.91
80	17	122.2	7.2	1.53
100	17	176.4	10.4	2.21
Humus and RS				
5	15	41.2	2.8	0.60
30	16	122.2	7.6	1.62
55	16	175.6	11.0	2.34
80	14	238.6	17.0	3.62
100	16	297.2	18.6	3.96

*Calculated as grams plant tissue from the sludge/soil mixtures per gram plant tissue from the control pots.

Rupert sand produced increasing plant yields as sludge application rates increased through 220 metric tons per hectare (100 tons per acre).

These results indicate that sludge addition to poor soils would increase productivity and, therefore, would be beneficial. The addition of large amounts of lime to the sludges did not appear to produce any detrimental effects.

Results from analysis of macro- and micronutrient content of the barley grown in this study are shown in Table 25. The total nitrogen and phosphorus levels in the plants grown in the test pots which contained sludge-soil mixtures were consistently lower than in the plants grown in the control which contained only soil. These results cannot be interpreted as indicating a nitrogen or phosphorus deficiency in the soils which received sludge treatment since plant production in these pots generally exceeded that in the control pots. The calcium concentration in plant tissues from pots which received sludge applications was higher than in the plant tissue from the control pots. Zinc concentration was considerably higher in the tissue of plants grown in pots which received digested sludge than in any of the other plant tissues tested.

GROWTH STUDIES ON OUTDOOR PLOTS

In order to further evaluate the short term effects of spreading lime treated sludge on cropland, larger scale crop growth studies were conducted on outdoor plots. The site chosen for this study was located at the Washington State University Irrigated Agriculture Experiment and Extension Center in Prosser, Washington. The soil at the site was classified as Warden silt loam. The site had not been used for any agricultural experiments during the preceding year. Five 0.04 hectare (0.1 acre) plots were used: one control plot received no sludge (only application of 200 lbs nitrogen/acre, 5 lbs zinc/acre, and 1 lb boron/acre); two plots received applications of anaerobically digested sludges at rates equivalent to 22 and 88 metric tons dry solids per hectare (10 and 40 tons per acre); and two plots received lime-treated mixed primary sludge and humus at the same application rates used for the digested sludge. Buffer zones were provided between plots to assure individual plot integrity during sludge spreading operations, plant growth, and harvesting operations. The sludge was transported to the site by a contracted septic tank service. Even distribution of the sludge on the plots was accomplished by use of a splasher plate attached to the tank truck discharge port as shown in Figure 27. Figure 28 shows this spreading operation.

TABLE 25. Macro- and Micronutrients in Barley Tissue From the Second Greenhouse Study (all sludges lime treated except the digested sludge)

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Total N (%)	Phosphorus (%)	Potassium (%)	Sulfur (%)	Magnesium (%)	Calcium (%)	Sodium (%)	Iron (ppm)	Manganese (ppm)	Boron (ppm)	Copper (ppm)	Zinc (ppm)
Control												
100% Rupert Sand (RS)	4.1	1.14	3.10	0.32	0.98	0.75	0.58	478	36	31	11	31
Mixed Primary and Secondary Sludge and RS												
5	1.2	0.45	3.48	0.32	0.37	1.12	0.21	450	68	14	11	70
30	1.3	0.62	4.32	0.49	0.44	1.23	0.26	700	73	16	16	107
55	1.6	0.51	3.60	0.38	0.45	1.20	0.38	800	98	16	14	93
80	1.5	0.46	3.23	0.34	0.45	1.45	0.63	433	122	24	11	68
100	1.9	0.52	3.41	0.43	0.44	1.25	0.58	445	120	21	12	74
Digested Sludge and RS												
5	1.9	0.42	4.40	0.40	0.37	0.92	0.59	800	60	23	14	92
30	2.6	0.56	3.40	0.40	0.45	1.50	0.75	820	102	34	19	450
55	3.2	0.52	2.82	0.41	0.45	1.68	0.95	550	215	55	21	500
80	3.9	0.59	2.55	0.36	0.41	1.68	1.20	950	221	50	23	550
100	3.2	0.51	2.38	0.39	0.38	1.50	1.00	550	187	45	21	500
Primary Sludge and RS												
5	1.4	0.44	4.60	0.35	0.41	1.15	0.38	1250	55	16	13	70
30	2.1	0.39	3.75	0.39	0.41	1.20	0.70	428	44	19	13	77
55	2.1	0.39	3.41	0.48	0.37	1.37	0.85	475	60	14	11	84
80	2.0	0.55	3.87	0.50	0.37	1.12	0.70	415	53	13	14	110
100	2.7	0.42	3.05	0.49	0.38	1.25	1.00	500	65	15	14	90
Humus and RS												
5	1.2	0.50	4.00	0.31	0.38	0.87	0.38	650	44	20	9	57
30	2.6	0.45	3.60	0.36	0.37	1.20	0.75	950	97	27	15	62
55	2.5	0.70	3.55	0.40	0.40	1.55	0.85	550	145	31	15	84
80	3.0	0.54	3.23	0.40	0.43	1.55	0.95	600	138	25	16	95
100	3.2	0.42	3.00	0.40	0.43	1.75	1.00	700	135	21	16	79

FIGURE 27. Sludge Splasher Plate Showing Design and Distribution Pattern

FIGURE 28. Application of Sludge to Outdoor Plots

After sludge application, the plots were allowed to dry and then were prepared for planting. Samples for analyses of soil physical and chemical characteristics were taken at this time. Sudan grass, an annual pasture grass adapted to Eastern Washington State, was used as an indicator plant. Maintenance of the plots during plant growth mainly involved periodic application of irrigation water and was carried out by the staff of the WSU Experiment Center. In early autumn when danger from frost damage was imminent, the grass was harvested as shown in Figure 29. The yield from each plot was recorded and plant matter and soil samples were collected for analyses. These samples were subjected to the same tests as conducted on the plant tissue and soil samples from the greenhouse studies.

The results from analyses of physical characteristics of soils before and after Sudan grass cultivation are shown in Table 26. Intrinsic permeability with water slightly improved in the soils from all plots during the growth study. The greatest improvements occurred in the plots which received sludge applications of 88 metric tons dry solids per hectare.

TABLE 26. Physical Characteristics of Soils Before and After Sudan Grass Cultivation in the Outdoor Plot Studies

Sludge/Soil Type and Sludge Application Rate (tons dry solids/acre)	Intrinsic Permeability with Water - K'_w (cm^2)		Hydraulic Conductivity - K (cm/sec)		K_m/K_c [3]		pH of Mixture[4]		Field Capacity of Mixture[5] (% of soil dry wt.)	
	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control[1] 100% Warden Silt Loam (WSL)	7.25×10^{-9}	7.98×10^{-9}	8.56×10^{-4}	9.42×10^{-4}	1.0	1.1	6.7	6.5	22	23
Digested and WSL 10	8.70×10^{-9}	9.43×10^{-9}	1.02×10^{-3}	1.11×10^{-3}	1.2	1.3	6.6	6.3	25	24
Lime Treated[2] and WSL 10	1.81×10^{-8}	1.96×10^{-8}	2.14×10^{-3}	2.31×10^{-3}	2.5	2.7	7.3	6.8	28	30
Digested and WSL 40	4.57×10^{-8}	5.22×10^{-8}	5.39×10^{-3}	6.16×10^{-3}	6.3	7.2	6.6	6.7	28	26
Lime Treated[2] 40	5.95×10^{-8}	6.60×10^{-8}	7.02×10^{-3}	7.79×10^{-3}	8.2	9.1	8.0	6.8	32	34

1. Control plot received recommended chemical fertilizer application instead of sludge.
2. Lime treated sludge was a mixture of primary sludge and trickling filter humus.
3. Ratio of the hydraulic conductivity of the sludge/soil mixture (K_m) to that of the control (K_c) before the growth cycle.
4. Soil pH measured in water.
5. 1/3 bar percentage.

FIGURE 29. Sudan Grass Harvesting Operation

A slight decrease in soil pH was observed in the samples collected after the Sudan grass was harvested.

Field capacity varied slightly between the beginning and the end of the growth study. No general trend could be established and the variations in most cases were not significant.

The results from analysis of macro- and micronutrients in the outdoor plots before and after plant growth are shown in Table 27. Increases in the nutrient concentrations resulted from the application of sludges at the rate of 88 metric tons dry solids per hectare.

The average maximum plant heights and green tonnage yields of the Sudan grass grown in this study are summarized in Table 28.

TABLE 27. Macro- and Micronutrient Concentrations in Outdoor Plots Before and After the Outdoor Growth Study

Sludge Type and Application Rate (tons dry solids/acre)		Nitrate-N (ppm)		Phosphorus (ppm)		Potassium (ppm)		Sulfur (ppm)		Magnesium (ppm)		Calcium (ppm)	
		Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control[A]		2	12	26	29	340	300	5	6	216	168	1320	960
Digested	10	25	19	33	32	360	220	15	10	216	180	1280	960
Lime Treated[B]	10	84	6	43	26	280	180	22	7	228	180	1600	1140
Digested	40	63	7	56	132	460	270	58	16	252	192	1600	1240
Lime Treated[B]	40	87	15	104	180	460	300	54	17	216	180	2160	1560

Sludge Type and Application Rate (tons dry solids/acre)		Sodium (ppm)		Iron (ppm)		Manganese (ppm)		Boron (ppm)		Copper (ppm)		Zinc (ppm)	
		Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro	Pre-Gro	Post-Gro
Control[A]		66	33	21	40	9	16	0.3	0.5	10.0	1.1	18.5	4.2
Digested	10	66	40	28	52	13	49	0.4	0.5	1.5	2.5	11.5	16.5
Lime Treated[B]	10	88	33	32	54	14	82	0.4	0.4	1.7	2.6	12.0	14.8
Digested	40	110	40	44	73	27	93	0.6	0.7	2.9	8.8	30.0	68.0
Lime Treated[B]	40	110	40	45	70	23	110	0.5	0.7	1.5	6.0	15.0	50.0

[A]Control plot received optimum chemical fertilizer application instead of sludge.

[B]Lime treated sludge was a mixture of primary and secondary sludge.

TABLE 28. Average Maximum Plant Heights and Tonnage Yields of Sudan Grass Grown in Outdoor Plots

Test Plot	AVERAGE HEIGHT cm	AVERAGE HEIGHT in	YIELD m. tons/ hectare	YIELD tons/ acre
Control (no sludge)	66	26	11.77	5.35
Digested Sludge				
22 metric tons dry solids/hectare	117	46	20.35	9.25
88 metric tons dry solids/hectare	132	52	24.20	11.00
Lime Stabilized Sludge				
22 metric tons dry solids/hectare	89	35	17.16	7.80
88 metric tons dry solids/hectare	132	52	25.96	11.80

The Sudan grass growth on the plots which received sludge applications was more luxuriant than on the control plot which received only an optimum application of chemical fertilizer. Figures 30, 31, and 32 show the test plots 1 month into the growth cycle. On the plots which received 22 metric tons dry solids per hectare, the grass reached average heights of 117 cm (46 inches) with digested sludge applied and 89 cm (35 inches) with lime-stabilized sludge applied. The grass which received lime-treated sludge had a yellowish tinge while the grass in the digested sludge plot had a healthy dark green appearance. In each of the plots which received 88 metric tons dry solids per hectare of digested and lime-stabilized sludge, the grass grew to a height of 132 cm (52 inches). The plants in both of these plots appeared dark green and healthy.

Results from macro- and micronutrient content analyses of Sudan grass are shown in Table 29. These results indicate that the amount of nutrients concentrated in the plant tissue was independent of the amount or type of sludge applied to the land in which the plants were grown. Also, there were no indications of buildup of significant amounts of nutrients in the plant material with the exception of calcium and iron which did show concentration increases over those in the chemically fertilized control plot.

Control Plot - Chemical Fertilizer Only

Plot #2 - Digested Sludge Applied at 22 Metric Tons/Hectare

FIGURE 30. Sudan Grass After 1 Month Growth Period on Outdoor Plots

Lime-Stabilized Sludge Applied at 22 Metric Tons/Hectare

Digested Sludge Applied at 88 Metric Tons/Hectare

FIGURE 31. Sudan Grass After 1 Month Growth Period on Outdoor Plots

Lime Stabilized Sludge Applied at 88 Metric Tons/Hectare

FIGURE 32. Sudan Grass After 1 Month Growth Period on Outdoor Plots

TABLE 29. Macro- and Micronutrient Concentrations in Sudan Grass Tissue From Outdoor Growth Study

Sludge Type & Application Rate (tons dry solids/acre)		Nitrate Nitrogen ppm	P Phosphorus %	K Potassium %	S Sulphur %	Mg Magnesium %
Control[1]		800	.5	3.05	.24	.40
Digested	10	100	.47	3.20	.19	.41
Lime Treated[2]	10	0	.52	2.85	.14	.42
Digested	40	600	.48	2.75	.15	.44
Lime Treated[2]	40	500	.42	2.37	.16	.42

	Ca Calcium %	Na Sodium %	Fe Iron ppm	Mn Manganese ppm	B Boron ppm	Cu Copper ppm	Zn Zinc ppm
Control[1]	.52	.06	370	48	7.0	10.5	66
Digested	.77	.09	530	34	7.0	11.0	80
Lime Treated[2]	.80	.22	1800	55	9.5	8.5	50
Digested	1.00	.10	640	40	8.0	12.0	50
Lime Treated[2]	.95	.09	1850	38	7.5	6.5	34

1. Control plot received recommended chemical fertilizer application instead of sludge.
2. Lime-treated sludge was a mixture of primary and secondary sludge.

DESIGN AND COST CONSIDERATIONS

PROCESS DESIGN

Based upon this work, it appears that the two most important process variables which must be considered are pH and contact time. Results indicate that the lime dose to the raw sludge should be sufficiently high to initially attain pH≥12.0. Moreover, the lime dose should be high enough to prevent significant pH decay during storage. In the laboratory and pilot plant work conducted in this program, short term (1 hour) lime-sludge contact at pH≥12.0 provided excellent reductions in viable pathogenic bacteria, but upon storage pH was subject to decay. Therefore, in practice, excess lime should be added to maintain the desired pH level during storage.

The lime dose required to achieve and maintain high pH levels will vary considerably among different types of sludges, and even for the sludge produced at a specific treatment plant, the required dose will probably be subject to temporal variations. The quantity of lime required to achieve the desired condition in any particular sludge can be determined easily in the laboratory. Sludge samples of a known volume can be titrated with a lime slurry until the desired pH level is achieved. Sludge samples dosed with the minimum lime addition required to reach the desired pH and others dosed with increasing multiples of this amount could then be stored and pH decay observed over a period of time. By using this procedure a good indication of the lime dose required to attain and maintain the desired conditions could be obtained. A full scale process can be designed with automatic process control equipment.

A possible process flow scheme is shown in Figure 33. The process flow is basically the same as that used in the pilot plant operated for this study. The main variations are provisions for automatic process control and the capability for adding excess lime in the sludge-lime contactor.

Process operation consists of introducing sludge into a mixing vessel where lime slurry is added. The pH level of the sludge in this vessel is continuously monitored and lime slurry addition automatically altered when the pH deviates from the setpoint. Sludge whose pH had been elevated to the desired level is continuously passed from the mixing vessel to a sludge-lime contactor. This contactor is also mixed and the excess lime required to prevent pH decay is added at this point. The quantity of excess lime is a specified multiple of the dose being added in the sludge-lime mixing vessel. This lime feed system provides positive process control since

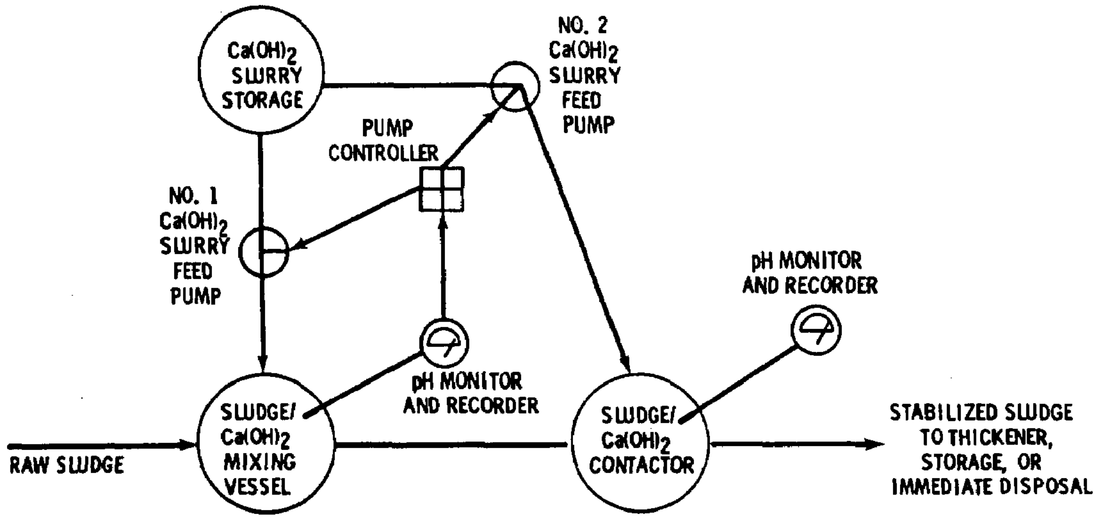


FIGURE 33. Lime Stabilization Process Conceptual Flowsheet

lime additions in the mixing vessel vary in accordance with temporal variations in sludge chemical demand. The addition of excess lime to maintain desired conditions is directly tied to the lime dose added in the mixing vessel.

Since an air agitation type mixing system was successfully used in pilot plant operations both in this study and in Farrell's work,[1] this type of mixing is recommended for further applications of the process. Air agitation provides adequate mixing without the blade or paddle fouling problems commonly encountered in mechanical sludge mixers. Also, air agitation avoids development of high shear forces which could tend to homogenize the sludge and cause dewatering problems. No efforts were made to optimize the air mixing technique in this program. Optimization of mixing may be an important part of future process development work.

Lime addition is best accomplished by slurry feed. Dry hydrated lime ($Ca(OH)_2$) is preferred over quicklime (CaO) for many reasons. Hydrated lime has superior storage characteristics to those of quicklime. With dry storage, hydrated lime may be kept for a period of up to 1 year without serious deterioration of chemical activity. Quicklime, however, has a great affinity for either carbon dioxide or water, and under improper conditions of storage and handling, quicklime will air slake. This phenomenon is caused by absorption of moisture and carbon dioxide from the atmosphere and results in physical swelling, decrepitation, and a marked loss of chemical activity. Because of gradual absorption of moisture from the atmosphere, 60 to 90 days is the usual limit for storage of quicklime in bags. In small treatment plants where operating manpower is limited, hydrated lime is the preferred form because of its ease of handling. Since its solubility in water is so low, lime is never fed in solution form. Instead a suspension of lime in water is made, and the lime is fed to the waste in slurry form. The obvious advantages of slurry feed are (1) easy transport to the point of application, (2) better dispersion of the lime in the waste when mixed, and (3) prewetting of the lime in the feeder where agitation assures that all the particles are wet thus preventing settling out in the reaction tank. Proportioning feed pumps of the diaphragm or piston type are capable of high accuracy and can be adapted to feed slurries. Proportioning pumps are also easily adapted for use with integrated instrumented control which is desirable since it provides optimum process performance and efficiency of chemical usage.

Another disadvantage of using quicklime is that it must be slaked (hydrated) before it is fed to the waste. Slaking is generally accomplished in special mechanical equipment operating at temperatures of from 180 to 210°F. The slaking operation may take 30 minutes or slightly more to reach completion. This extra operation will introduce additional capital and operating expenses into the overall treatment process. Hydrated lime may be added directly to the water in the lime slurry mixing tanks and no special processing steps are required when using hydrated lime.

PROCESS COSTS

Cost estimates for a lime stabilization process must be based on laboratory and pilot plant information. Lime costs may be easily and accurately estimated from chemical dose data from laboratory and pilot plant work. The chemical cost estimates made in this section were based on a hydrated lime cost of $22 per metric ton ($20 per short ton). Operating and maintenance (O&M) costs were estimated from a similar process at South Lake Tahoe which uses lime slurry feed.[16] A breakdown of those O&M costs is shown below:

	COSTS ($/Metric Ton Sludge Solids)
Electricity	$0.76
Operating labor	4.32
Maintenance labor	1.22
Repair materials	0.44
Other operating costs not included above	0.26
Total estimated O&M costs	$7.00

The $0.26 included under "other operating costs..." was added to account for sludge pumping and mixing costs which would have been excluded otherwise. For a 37,850 m^3/day (10 MGD) sewage treatment plant which produces a total sludge flow of approximately 255 m^3/day (67,000 gallons per day), the total capital cost of a lime stabilization process would probably be less than $8000. This cost includes tankage, piping, chemical feed system, and automatic control instrumentation. This cost is too small to be financed by a bond issue and would probably be paid directly from an account set to finance such low cost improvements of municipal facilities. Since capital costs are considered insignificant, the major cost of the lime stabilization process would be O&M costs which, as stated above, would amount to approximately $7.00 per metric ton of sludge solids treated.

From his work in Ohio, Farrell, et al.[1] estimated that lime addition to an alum-primary sludge cost an average of $4.95 per metric ton sludge solids. By adding the O&M costs developed previously to this chemical cost, a total O&M cost estimate of $11.95 per metric ton sludge solids was obtained Farrell, et al.[1] also found that iron primary sludges had an average lime cost of $2.50 per metric ton sludge solids. Therefore, total O&M in this case would be about $9.50 per metric ton sludge solids. The amount of lime applied to the sludges in this study was, in general, the minimum dose required to raise pH to 11.5. Excess lime to maintain pH above a specified level was not added.

O&M cost estimates based on the work done by Paulsrud and Eikum[12] were also developed for comparison purposes. The dose required and the estimated costs for lime stabilization of various types of sludges are summarized in Table 30. The recommended lime doses are those required to maintain pH≥11.0 in sludges stored for 14 days at 20°C. The total estimated O&M costs using these recommended lime doses range from $9 to $19 per metric ton sludge solids. These results indicate that treatment costs will be mainly dependent on chemical requirements which will vary with the type of sludge being treated and the chemical pretreatment history of the sludge.

Process costs developed from the results of this program agree with those developed from the results of the other investigators. Chemical cost estimates were based on an average lime dose of 150 g $Ca(OH)_2$/kg sludge total solids required to achieve pH≥12.0 and maintain that level for 1 hour. Lime costs in this case were found to be $3 per metric ton sludge solids, so that estimated total O&M costs would be $10 per metric ton sludge solids.

TABLE 30. O&M Costs for Lime Stabilization

Type of Sludge	(g $Ca(OH)_2$/kg SS)[1]	Lime Costs ($/metric ton)	Total[2] O&M Costs ($/per metric ton)
Primary sludge	100 - 150	2.00 - 3.00	9.00 - 10.00
Septic tank sludge	100 - 300	2.00 - 6.00	9.00 - 13.00
Biological sludge	300 - 500	6.00 - 10.00	13.00 - 17.00
Al-sludge (Secondary precipitation)	400 - 600	8.00 - 12.00	15.00 - 19.00
Al-sludge (Secondary precipitation + Prim. sludge (SS_{Al}:SS_{PRIM} = 1:1)[2]	250 - 400	5.00 - 8.00	12.00 - 15.00
Fe-sludge (Secondary precipitation)	350 - 600	7.00 - 12.00	14.00 - 19.00

[1] Multiply this number by 2 to get lime dose in lbs lime/ton dry sludge solids.

[2] Sum of lime cost and $7.00 O&M cost estimated previously.

[3] SS = suspended solids.

PROCESS APPLICATIONS

There are several situations where application of the lime stabilization process could be advantageous. Small treatment plants which do not produce large quantities of sludge and have access to land for disposal by spreading could certainly use a simple, reliable, and inexpensive sludge treatment process. Another possible strategy, as suggested by Paulsrud and Eikum,[12] is for small treatment plants to use lime stabilization as a prepatory step for sludge storage. The stored, lime-treated sludge would be periodically hauled away to larger facilities for further treatment and/or disposal.

For plants which utilize digestion and do not have excess digester capacity, lime treatment may provide a satisfactory means of stabilizing sludge prior to ultimate disposal. Sludge flows in excess of digester capacity could be bypassed to a separate lime treatment facility. Another option would be to use existing digesters to thicken lime-treated sludge prior to dewatering or disposal.

Lime stabilization could also be used as a stop-gap technique when digesters or other sludge treatment processes temporarily are not working. In this context, lime stabilization would be used as an emergency back-up process. A temporary lime treatment process could be set up using the basic flow scheme presented in Figure 6. In a temporary process, sludge pH could be manually monitored on a periodic basis and the lime dose adjusted as required. Alternatively, if sludge were being hauled away regularly by tank truck, lime could be injected into the sludge as it was pumped into the truck. This technique was tried during the course of this program and was found to work quite well. The septic tank truck used to haul and spread lime-treated sludge on the outdoor plots used a vacuum system for sludge loading. A vacuum was taken on the truck tank and sludge was pulled into the tank. The technique used to inject lime slurry into raw sludge as it was being loaded into the tank was quite simple. A suction line with a 1/2 inch ball valve for slurry metering was attached to an existing threaded opening in the tank sludge loading port. Then, when suction was applied, both sludge and lime slurry were pulled into the tank. Mixing occurred at the point of slurry injection and during transport to the outdoor plots. Composite samples were taken during sludge spreading operations and were found to be at a pH of 12.2. This technique of lime addition could easily be applied for lime stabilization during emergency operations.

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-670/2-75-012		

4. TITLE AND SUBTITLE	5. REPORT DATE / 6. PERFORMING ORGANIZATION CODE
LIME STABILIZED SLUDGE: ITS STABILITY AND EFFECT ON AGRICULTURAL LAND	5. April 1975; Issuing Date 6.
7. AUTHOR(S) Cary A. Counts and Alan J. Shuckrow	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Battelle Memorial Institute Pacific Northwest Laboratories P.O. Box 999 Richland, Washington 99352	10. PROGRAM ELEMENT NO. 1BB043;ROAP-21ASD;Task-16 11. CONTRACT/GRANT NO. 68-03-0203
12. SPONSORING AGENCY NAME AND ADDRESS National Environmental Research Center Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED Final 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

An optimum system for the lime stabilization of municipal sewage sludge was first developed and then evaluated. The primary objectives of this work were: (1) to determine the degree of stability induced in a sludge by lime addition and (2) to determine the effects of spreading lime-stabilized sludge on agricultural land. Lime doses and contact times required to eliminate the pathogenic bacteria and odors from a raw sludge were determined by laboratory studies, and the information obtained was translated into design and operational parameters for a pilot scale, continuous flow process. Physical, chemical, and biological characteristics of both the raw and stabilized sludges were measured. Soil and crop studies, both in a greenhouse and on controlled outdoor plots, were performed to determine the effects of spreading lime-stabilized sludge. Effective lime stabilization of sludge was accomplished by elevating the pH to 12.0 with lime additon and maintaining this pH level for at least 30 minutes. From 102 to 208 g of $Ca(OH)_2$ was needed to stabilize 1.0 kg of sludge solids. The average amount required was 150 g. Total O&M costs for lime stabilization were estimated to be $10 per metric ton.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Calcium hydroxides Sludge disposal Disinfection Odors Odor control	Sludge treatment Sludge stabilization Lime treatment Liquid phase lime demands Solid phase lime demands Agricultural land Crop response	13B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	98
	20. SECURITY CLASS *(This page)*	22. PRICE
	UNCLASSIFIED	

EPA Form 2220-1 (9-73)

☆ U. S. GOVERNMENT PRINTING OFFICE: 1975-657-592/5353 Region No. 5-11