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LANDFILL DISPOSAL OF SLUDGE DERIVED FROM THE LIME/SODA-ASH SOFTENING OF WATER

Eugene A. Glysson

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ABSTRACT

Landfill Disposal of Sludge Derived from the Lime/Soda-Ash Softening of Water

Eugene Andrus Glysson

Paul Walton Purdom, Sr.

The use of landfilling as a means of disposition of the sludge derived from the lime/soda-ash softening of water is investigated.

Those chemical and physical characteristics of the lime sludge, as removed from a storage lagoon, which affect its disposal into a landfill are determined. These include elemental analysis of the sludge and changes which occurred in selected non-organic solutions as a result of contact with the sludge under various conditions.

The parameters of the sludge which affect its use as a fill material are investigated. These include the determination of the permeability of the sludge, its consolidation characteristics and its sheer strength. As a result of these determinations the possibility of use of the sludge in embankments is considered as well as the extent of its consolidation when used as a fill material.

The incorporation of the sludge into a landfill in various ways and the costs thereof is discussed. The recommended method is to use the dried sludge in shallow layers (6 inches to one foot) as a part of the daily cover applied to the landfill.

The results of this study indicate that to the extent of this investigation the disposition of the lime sludge into landfill is economical and acceptable with no adverse environmental effects.

CHAPTER 1

INTRODUCTION, REVIEW OF LITERATURE, AND OUTLINE OF RESEARCH PERFORMED

I. INTRODUCTION

The lime/soda ash softening process is often used by municipalities for softening hard water. This process involves the formation of insoluble forms of calcium and magnesium by adding the proper amounts of slaked lime and soda ash. The fundamental chemical reactions involved (without regard to pH adjustment) are as follows:

$$\underset{\text{(carbonate hardness)}}{Ca(HCO_3)_2} + \underset{\text{(lime)}}{Ca(OH)_2} \rightarrow 2CaCO_3\downarrow + 2H_2O$$

$$\underset{\text{(carbonate hardness)}}{MgCO_3} + \underset{\text{(lime)}}{Ca(OH)_2} \rightarrow Mg(OH)_2\downarrow + CaCO_3\downarrow$$

$$\underset{\text{(non-carbonate hardness)}}{CaSO_4} + \underset{\text{(soda ash)}}{Na_2CO_3} \rightarrow CaCO_3\downarrow + Na_2SO_4$$

These reactions show that in the treatment process, the soluble compounds containing calcium and magnesium are converted to insoluble compounds that can be removed by sedimentation in settling basins.

Water-softening plants have been using the lime/soda-ash process for many years, and their problems of lime-sludge disposal are familiar. Recently, however, these problems have grown more serious because certain long-standing disposal methods have been rejected as unacceptable. For instance, the common practice of discharging the lime sludge into streams and lakes without treatment is now generally forbidden by water-pollution control agencies.

Many water-softening plants have been or are beginning to use lagoons in which the lime sludge can be stored for long periods. During storage, the solids are allowed to re-settle and the supernatent liquid is decanted. This liquid may be discharged into a receiving stream or may be returned to the treatment process. In general, lagoon storage has proved to be economical and satisfactory. The critical factor is limited storage capacity. In some cases, more volume is obtained by making the dikes higher; but sooner or later, every lagoon gets full. When a lagoon does get full, it must either be abandoned or cleaned out. When it is abandoned, a search must be made for a new site that is within an economic haul distance, and is suitable for long-term sludge storage. When a lagoon is cleaned out, all accumulated solids must somehow be removed.

Increased urbanization makes abandonment and relocation less and less feasible in most instances. The available land near cities is growing too scarce to be used for indefinite lime-sludge storage. The problem is aggravated by the increase in the number of softening plants now needed to treat municipal water supplies. As stated by Russell *et al*,(54) "The number of lime softening plants is large and the demand for softened water is so varied and increasingly large, that there is no reason to expect anything but a continual increase in the number of these plants and in the volume of their wastes." Popular demand is forcing more and more cities to adopt some water-softening process. Usually their choice is between the ion-exchange process and the lime/soda process. Largely because the waste brines resulting from the ion-exchange program are hard to dispose of, the lime/soda process is gaining in popularity. But at the same time, the lime sludge resulting from the latter process is being subjected to increasingly stringent disposal controls. For all these reasons, the removal of accumulated lime sludge from existing lagoons is now and will be of considerable interest in the future.

A. Purpose

The purpose of this study is to determine the feasibility of disposing of the lime sludge by depositing it in landfills. Emphasis is placed on a study of the lime-sludge characteristics that would affect such disposal to a marked degree. Included in the study is an evaluation of various physical parameters that are helpful in identifying sludge characteristics and in predicting some of its properties as a landfill material. Also included is an evaluation of some of the chemical changes that would result from disposing of lime sludge in landfills, particularly those that are used for general solid-waste disposal.

B. Hypotheses

In this study, six hypotheses are investigated:

1) The characteristics of the lime sludge are such that it will not pollute ground water or surface water through leaching.
2) In a landfill, the presence of the lime sludge in association with solid wastes will aid in reducing pollutional effects.
3) Under controlled conditions, the lime sludge will serve as a suitable landfill material.
4) Under controlled conditions, the lime sludge can be used for embankments and as a backfill material.
5) If the lime sludge is handled and prepared properly, its characteristics are such that it will permit a mechanized disposal method.
6) The system for lime-sludge disposal will be economically feasible.

C. Methodology

Four points of methodology are employed in this study:

1) The selected sludge characteristics are determined by various physical and chemical analyses.

2) The effects of the sludge characteristics on leachate* are evaluated, as is sludge workability.
3) Field observations for selected engineering methods of excavation and placement are conducted.
4) Excavation and placement costs are estimated from field observations and from other existing data.

D. Exclusions

Three areas are excluded from the study:

1) Other methods of lime-sludge disposal, and sludges other than lime sludge.
2) Analysis of transportation alternatives such as pipelines and rail haul.
3) Any optimization of site selection for sludge disposal.

E. Significance

It is anticipated that this study will help to solve the problem of lime-sludge disposal in a technologically

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[*] In this study, "leachate" refers to a synthetic liquid consisting of either (1) demineralized water, (2) low, non-organic mineral leachate, or (3) high-iron, non-organic leachate. None of these three embody all the characteristics of a natural leachate. No attempt has been made to include any organic constituents.

sound, economically feasible manner. This disposal method will pollute neither surface waters nor ground waters, and will not create any other environmental problems. Furthermore, it may reveal some beneficial uses for an otherwise wasted material.

II. REVIEW OF LITERATURE

The magnitude of the overall problem of sludge disposal from water treatment plants has been well stated by Hudson (32). According to him, about one million tons of waste material are generated from municipal water treatment plants annually. This includes all sludges from various water-treatment processes, and not just lime/soda-ash softening sludge. An inventory by the U.S. Public Health Service as of January 1, 1964(64) showed that in the United States, 124 plants were softening water for cities with a population of over 25,000. Waring (65) reports that in 1954, there were 450 municipal lime-softening plants in the United States.

Howson (31) states that more than 90 percent of all lime/soda-ash softening plants have to pay for lime-sludge disposal, and try to get rid of it as cheaply as they can. Usually they put it into lagoons or discharge it into a stream. (By 1972, however, the latter choice is much reduced if not altogether eliminated.)

Nelson(45) indicates the order of magnitude of lime-sludge production by figuring that approximately 2-1/2 pounds of dry softening sludge are produced for every pound of lime that is added during the softening process in the form of commercial quick-lime.

Unlike some water-treatment plant sludges – namely alum sludges ($Al(OH)_3$) – lime-softening sludge will dewater itself. In a properly operated lagoon (13,31), they will yield a consistency of about 50 percent moisture on a wet-weight basis, which means they can be handled as a semi-solid. Alum sludges, on the other hand, are reported(10) to have difficulty yielding a solid content of 20 percent, which means that they require further treatment before landfill disposal.

Howson(31) describes the proper operation of lime-sludge lagoons to produce maximum usage of available volume, so that the stored sludge will contain about 50 percent moisture on a wet-weight basis. In this method of operation, the supernatant liquid must be withdrawn continuously from the lagoon, and the sludge must be deposited in shallow rather than deep layers. (Sludge that contains 50 percent moisture by wet weight can readily be removed from the lagoon by drag-line quipment.) Howson also indicates that lime sludge appears to be readily susceptible to air-drying.

One of the general characteristics of lime sludge upon removal from the sedimentation tanks in the softening process is that it settles readily. Black(10) reports that the solids content of softening sludge as it leaves the settling tank will vary from as low as 2 percent to as high as 15 percent. Burgess and Niple(13) report an average of 4 percent solids in softening sludge at five Ohio plants. These solids do not represent a source of pollution in the traditional sense of large organic content or high potential for bacteriological contamination; instead, they present such undesirable characteristics as toxicity from alkaline materials, and turbidity and color which are esthetically objectionable and would interfere with light transmission to the photosynthetic organisms present in the receiving waters. Due to their rapid settling, the solids may present some problems in pumping. Moreover, when settling on the bottom of a receiving body of water, they may adversely affect the benthic growths present there, and end by upsetting the ecological cycle therein. When lime-sludge is discharged into receiving waters, they will usually undergo considerable hardening, since the solids will be returned to solution by contact with the receiving waters. The waters will also undergo an increase in alkalinity and pH.

Sheen and Lammers(58) report a means of characterizing sludge on the basis of its particle size; in their studies of dried sludge, the average particle size was 5-7 microns, and 96+ percent of the particles passed a 325 mesh screen. Pedersen(47) reports that in an accurate analysis of the dried sludge, 99.8 percent of the particles passed through a 325-mesh screen, whereas a study by Gordon(26) reports that 96 percent passed through a 325-mesh screen.

Black(11) characterizes lime sludge by its chemical composition, and reports that composition to range from 87.2-93 percent equivalent calcium carbonate; the other percentage is made up of magnesium oxide, silica, iron, and alumina. Russell(54) states that "A sludge produced by softening of water by the lime-soda ash process consists principally of calcium carbonate with various amounts of ferric, magnesium and aluminum hydroxides."

Russelman(55) states that "the impact of a waste may be far reaching and devastating or it may be localized and temporary, but in any case, knowledge of the waste and knowledge of the receiving environment is essential to establish whether pollution occurs, may occur, or is absent. It is precisely this knowledge which is lacking and therefore it is difficult to discuss characteristics of water treatment plant wastes when the 'state of the art' is so fragmentary and non-documented." The research reported here on the character of lime/soda-ash sludge and its disposal in a landfill was undertaken in response to statements of this kind.

III. OUTLINE OF RESEARCH PERFORMED

To carry out this study, several different parameters of the lime/soda-ash sludge were determined and evaluated. These parameters have been divided into two main classifications, according to chemical characteristics and physical characteristics.

The research dealing with the chemical characteristics is described in Chapter 2. The studies conducted were:

1. Elemental analysis of the sludge by
    a. electron microprobe
    b. x-ray diffraction
    c. wet chemical analysis
2. Determining change over time of pH of demineralized water in contact with the sludge.
3. Determining changes over time in pH, alkalinity, and hardness as a result of passing a low-mineral leachate and a demineralized water leachate over the sludge at a controlled rate.
4. Determining the results of putting a high-mineral (high-iron) leachate in contact with the sludge under aerobic conditions.
5. Determining the results of putting a high-iron leachate in contact with the sludge under anaerobic conditions.

6. Determining the polarity and magnitude of the charge on the lime sludge particle.
7. Establishing the rate of solution of the lime sludge in demineralized water with pH adjusted to 5.5 with H_2SO_4.

The research dealing with the physical characteristics is described in Chapter 3. These studies are subdivided into two subdivisions: the physical characteristics or index properties, and the engineering properties. The parameters evaluated to establish the index properties were:

1. Grain-size distribution by use of hydrometer and standard sieve analysis.
2. Particle morphology by means of the electron microscope.
3. Specific gravity and bulk density.
4. Plasticity and liquid limits by standard soil-testing procedures.
5. pH of the sludge.

The studies undertaken to establish the engineering properties were:

1. Permeability by direct measurement with a permeameter and by computation from data developed from the consolidation test.
2. Consolidation test for determining the coefficient of consolidation and the compression index.

3. Moisture-density behavior.
4. Shear strength as determined by the triaxial method of analysis.

On the basis of an evaluation of these parameters, the lime sludge is classified and the results of its use as a landfill material or as a possible embankment material are discussed.

Each phase of the study includes (a) a discussion of the results of the research as applicable to uses of the sludge for various purposes, and (b) the effects of the various parameters as well as a description of the test procedures and apparatus used.

Chapter 4 discusses the possible uses of the sludge and some of the methods for placing it in a landfill. These methods are based on information from this study.

Chapter 5 presents a cost analysis using a dragline to excavate the sludge from the lagoon and of using a truck to get it to a landfill and a bulldozer to place it there.

Chapter 6 presents a summary and the conclusions that can be derived from this study.

CHAPTER 2

THE CHEMICAL CHARACTERISTICS OF LIME SLUDGE AND THEIR EFFECTS ON ITS USE IN LANDFILL DISPOSAL

Lime soda-ash sludge that is placed in a landfill may come into contact with water in one of two ways — either as rainfall that has not previously come into contact with refuse, or as leachate that has passed through refuse. In order to evaluate and explain the results of such placement, the sludge itself was subjected to elemental analysis by three methods: the electron microprobe, X-ray diffraction, and wet chemical analysis (EDTA).

I. ELECTRON MICROPROBE

The samples to be analyzed by electron microprobe were first prepared by mounting them on a suitable support and coating them with chromium in a vacuum. [These were the same samples viewed by the electron microscope. Chromium is the standard material for coating samples to be viewed by the electron microscope, and since no chromium was expected to be found in the sludge, the same samples could be used.] A stream of electrons was directed at each sample by the electron microprobe (Applied Research Lab—ARL-MX), and the characteristic X-rays that were emitted by the sample were picked up by a proportional counter.

After the results were observed on an oscilloscope, the released X-rays were analyzed and transferred to a recorder for readout.

The characteristics of this analysis are such that only approximately quantitative values of the elements can be derived. The sensitivity is very great, however; the X-ray-excited spectograph can detect about 10^{-9} grams of an element. The results are given in Table 1.

The analysis shows that calcium predominates. Some magnesium appears, which can be expected due to the formation of magnesium hydroxide in the softening process. Elemental sulfur appears due to the presence of sulfates in the water. Silica appears due to the turbid condition of the surface water that is being treated in the softening process. As noted above, chromium appears due to the coating of the sludge for analysis. The extreme sensitivity of this method of analysis is indicated by the fact that neither sulfur nor silica were detected in alternative methods of analysis.

Photographs of the traces of the accumulated counts (peaks) are given in Figure 31, Appendix A.

II. X-RAY DIFFRACTION

As a further means of elemental analysis, several samples of lime sludge were analyzed by X-ray diffraction. The apparatus used was a Phillips Electronic Norelco X-ray Diffractometer with an incident radiation (copper k_α) of

TABLE 1

SLUDGE ANALYSIS BY ELECTRON MICROPROBE

(Applied Research Lab – ARL-MX)

Sample No.	Channel No.	Counts	Energy Level Electron Volt	Energy Level from Standard(46) e.v.	Element Line
1	50	279	1.276	1.297	Mg k_α
				1.257	
	166	86	2.290	2.31	S k_α
	315	408	3.622	3.69	Ca k_α
	351	64	3.95	4.01	Ca k_β
	506	233	5.31	5.41	Cr k_β
	563				
2	318	421	3.62		Ca k_α
	352	63	3.95		Ca k_β
	507	87	5.31		Cr k_α
	567	19	5.84		Cr k_β
3	52	53	1.27		Mg k_α
	104	43	1.72	1.74	Si k_α
	164	43	2.29	2.31	S k_α
	319	439			Ca k_α
	354	65			Ca k_β
	507	200			Cr k_α
	564	45			Cr k_β
4	49	216			Mg k_β
	104	100			Si k_α
	165	56			S k_α
	318	728			Ca k_α
	353	101			Ca k_β
	506	64			Cr k_α
	568	16			Cr k_β
0	47	150	1.25	1.27	Mg k_β
	99	100	1.715	1.77	Si k_β
	303	1390	3.63	3.69	Ca k_α
	336	215	3.96	4.01	Ca k_β

wave length 1.5405A°. The samples were presented as flat-plate specimens, and were positioned in the machine for rotation from 10° to ≈ 50. (2θ) at the rate of 1° per minute.

A typical diffraction pattern of samples analyzed by X-ray diffraction is shown in Figure 32, Appendix A. The "d" values were converted from the measured angles using the NBS X-ray Diffraction Tables.(43) The standards were taken for ASTM X-ray Diffraction Powder Index #5-0586. The results of these analyses are given in Table 2.

The results of the X-ray diffraction analyses showed the samples to be comprised entirely of calcium carbonate (calcite); no other material was detected by this method.

III. WET CHEMICAL ANALYSIS

To quantify the major elements in the sludge, the Ca and the Mg content was determined by wet chemical analysis. Approximately 0.4 grams of sludge were dissolved in hydrochloric acid and the resultant solution was analyzed using the standard EDTA test for Ca and Mg.(3) The results, shown in Table 3, confirm the conclusion that the sludge consists primarily of calcium carbonate.

As a result of this analysis, the lime/soda-ash sludge was determined to be predominately $CaCO_3$ (calcite), with a very small amount of $Mg(OH)_2$ and other miscellaneous substances. The analysis also made it possible to predict (and subsequently confirm) the effects of contact

TABLE 2

SLUDGE ANALYSIS BY X-RAY DIFFRACTION

Sample No.	d-spacings of Most Intense Peaks (A°)	Relative Intensity of Peaks (%)	Probable Minerals( )
10-A	3.019	100	$CaCO_3$ as calcite
	2.279	18	
	2.091	18	
	1.908	17	
	1.871	17	
	2.487	16	
11-A-1	3.033	100	$CaCO_3$ as calcite
	2.282	19	
	2.096	19	
	1.912	18	
	1.869	18	
	2.496	14	
12-A-2	3.025	100	$CaCO_3$ as calcite
	2.279	18	
	2.091	18	
	1.909	17	
	1.872	17	
	2.489	15	
13-A-1	3.032	100	$CaCO_3$ as calcite
	2.281	22	
	2.093	22	
	1.873	22	
	1.909	20	
	2.493	16	

TABLE 2 (CONT'D)

SLUDGE ANALYSIS BY X-RAY DIFFRACTION

Sample No.	d-spacings of Most Intense Peaks (A°)	Relative Intensity of Peaks (%)	Probable Minerals
PDT-3	3.036	100	
	2.285	21	
	2.095	19	$CaCO_3$ as Calcite
	1.875	19	
	2.495	18	
	1.913	15	
PDT-4	3.036	100	
	2.281	19	
	1.908	19	
	1.872	18	$CaCO_3$ as Calcite
	2.092	17	
	2.491	13	
PDT-0	3.030	100	
	2.281	23	
	2.094	18	$CaCO_3$ as Calcite
	1.910	18	
	1.873	18	
	2.491	16	
PDT-1	3.038	100	
	2.287	22	
	1.877	21	$CaCO_3$ as Calcite
	2.495	19	
	2.094	19	
	1.912	17	
ASTM	3.035	100	
Standard	2.285	18	
X-ray Diffraction	2.095	18	$CaCO_3$ as Calcite
Powder	1.913	17	
Index File	1.875	17	
#5-0586	2.495	14	

TABLE 3

WET CHEMICAL ANALYSIS OF LIME SODA-ASH SLUDGE

(≈ 0.4 gm of sludge/liter)

Sample No.	Total Solids (mg/1)	Dis-solved Solids (mg/1)	Sus-* pend. Solids (mg/1)	(mg/1) Ca as Ca	(mg/1) Mg as Mg	Ca as $CaCO_3$ (mg/ℓ)	Mg as $Mg(OH)_2$ (mg/ℓ)	% Ca (by wt)	% Mg (by wt)	% $CaCO_3$ (by wt)
1	360	357	3	129	16	323	39	35.8	4.4	90.0
2	399	383	16	151	8	378	19	37.8	2.0	94.6
3	401	384	17	148	8	370	19	36.9	2.0	92.4
4	398	381	17	147	10	368	24	36.9	2.5	92.5
5	395	370	25	144	10	360	24	36.5	2.5	91.1
6	401	368	33	146	9	365	23	36.5	2.2	91.1
7	399	388	11	129	19	323	46	32.3	4.8	81.0
8	400	395	5	140	9	350	23	35.0	2.3	87.5
9	402	396	6	138	10	345	25	34.3	2.5	86.1

*Suspended solids assumed to be activated carbon or other material not dissolved by acid.

between this material and the water that may pass over or through it. The buffering action of solid $CaCO_3$ is important in this system.

IV. TEST FOR pH VS. TIME

Weber(66) discusses the buffering effect of solid calcium carbonate in a heterogeneous system where the addition of acid leads to the dissolution of the solid material at equilibrium. He indicates that after being in content for a sufficient time, the pH, alkalinity, and hardness as measured by the presence of Ca and Mg ions in the liquid in contact with the sludge should reach an equilibrium. Water moves over landfill material at a relatively slow rate,(52) and percolation through the sludge itself is very slow. Therefore conditions could develop by which equilibrium conditions between the sludge and the solute solution are established.

Another test in the present study determined the time required for equilibrium to be reached between the sludge and distilled water. As shown in Figure 1, it proved to be a matter of from two to three hours. If this much contact time occurred in an actual landfill, an equilibrium would be established; otherwise a steady-state condition would develop reflecting the prevailing conditions.

This test was carried out using demineralized water with pH adjusted to ≈ 5.5. The change in pH was observed with time; in order to maximize the time to reach

Figure 1. pH Change Over Time as a Result of Lime Sludge in Contact with Distilled Water.

an equilibrium, no mixing was provided. It was readily assumed that in a landfill, leachate will be in contact with the sludge for at least two or three hours.

V. BASIC TESTS FOR LEACHATE-SLUDGE CONTACT

Another objective of the present study was to determine the effects of leachate-sludge contact. Specifically, the question was what would happen in a landfill when lime sludge that had been deposited in layers came into contact with refuse that is generating leachate. A series of trays containing sludge at a 30° slope was constructed. Two leachates of differing qualities (distilled water and low mineral content) were allowed to flow over the sludge at a controlled rate (25 mℓ/min). [A high-iron-bearing solution was also used, but a soxhlet apparatus was used to determine relationships; see Section VII below.] The low-mineral leachate contained 1000 mg/ℓ of NaCl and 1000 mg/ℓ of $CaCO_3$. pH was adjusted to 5.0 - 5.2 with H_2SO_4. By analyzing the effluent, the change in pH, hardness and alkalinity versus time could be determined.

Each tray was 3 inches wide, 12 inches long, and had 1/2 inch of sludge that was smoothed off so that the leachate would flow evenly over the entire surface. In these experiments, only surface reaction was studied; the sludge was much too impervious to allow for appreciable percolation. The apparatus used is pictured in Figure 33, Appendix B.

To determine any noticeable effect, a run was made with the unit continuously flushed with nitrogen gas to simulate anaerobic conditions. When no noticeable changes were observed, all subsequent tests were carried out within the enclosure of the unit. Evaporation was thereby avoided, but there was no provision to control the oxygen level. Samples of the leachate (100 mℓ each) were collected for analysis as the flow left the chamber.

The results of typical surface reactions with low-mineral leachate and demineralized water are shown in Figures 2 and 3. In essence, the pH levels off between pH 8 and 9 (or between 9 and 10 for demineralized water), and the alkalinity levels off at between 30 and 70 mg/ℓ as $CaCO_3$ (or between 50 and 80 for demineralized water). As a result of contact with the sludge, a leachate with a relatively high acid content (low pH) will be neutralized to an alkaline pH (8 - 10) and will not have as adverse an effect on the environment. The alkalinity will be modified to a level that is much more acceptable in the environment.

As shown in Figure 3, large peaks in alkalinity appear in the curves for the first portions of effluent. They can be attributed to the erosion of the finely divided sludge which is washed off the surface in the first flush. Thereafter, the solids are not eroded to any extent and the alkalinity more nearly reflects the effect of contact with the sludge.

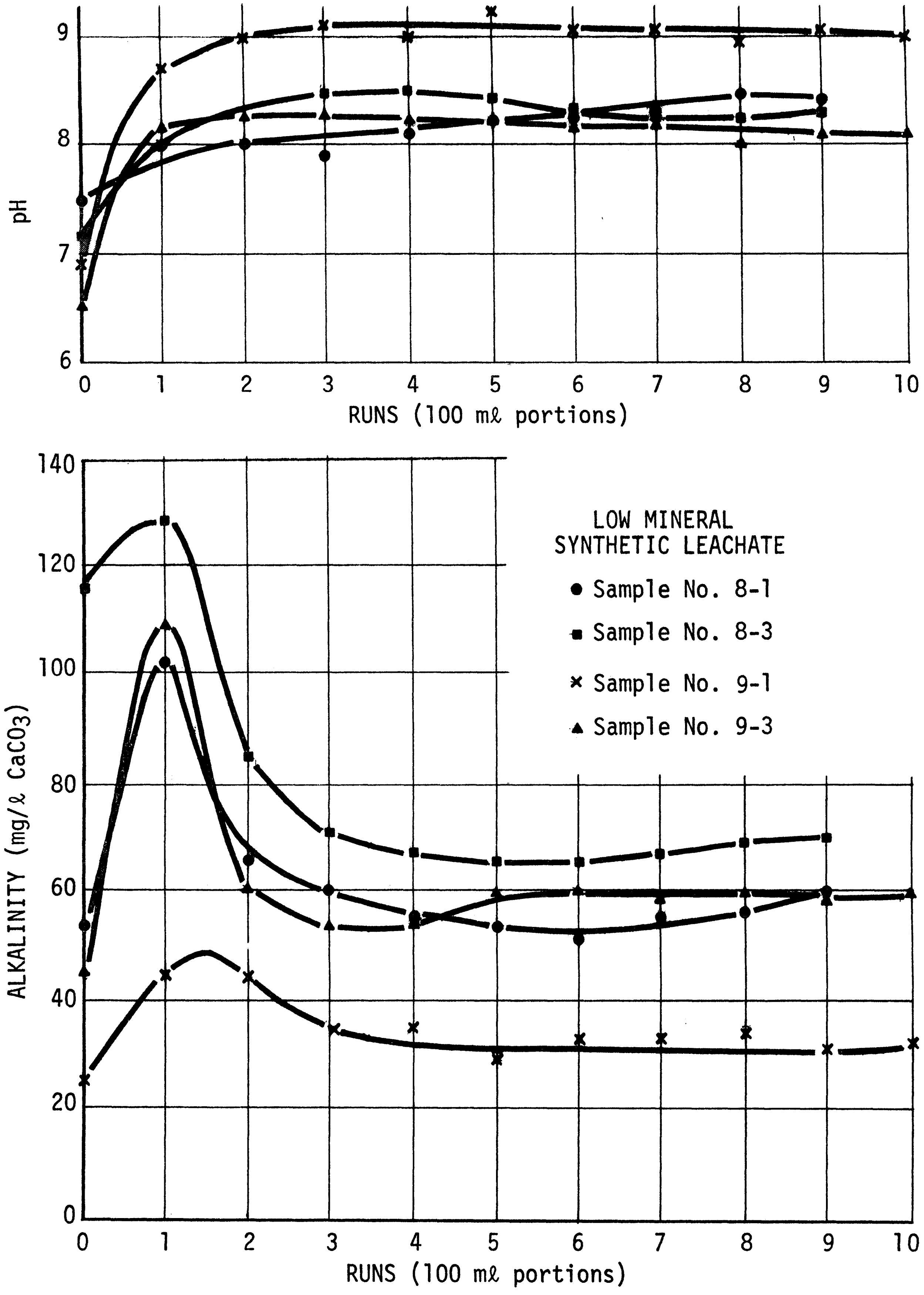


Figure 2. Changes in pH and Alkalinity with Flow of Low-Mineral Synthetic Leachate Over Lime Sludge.

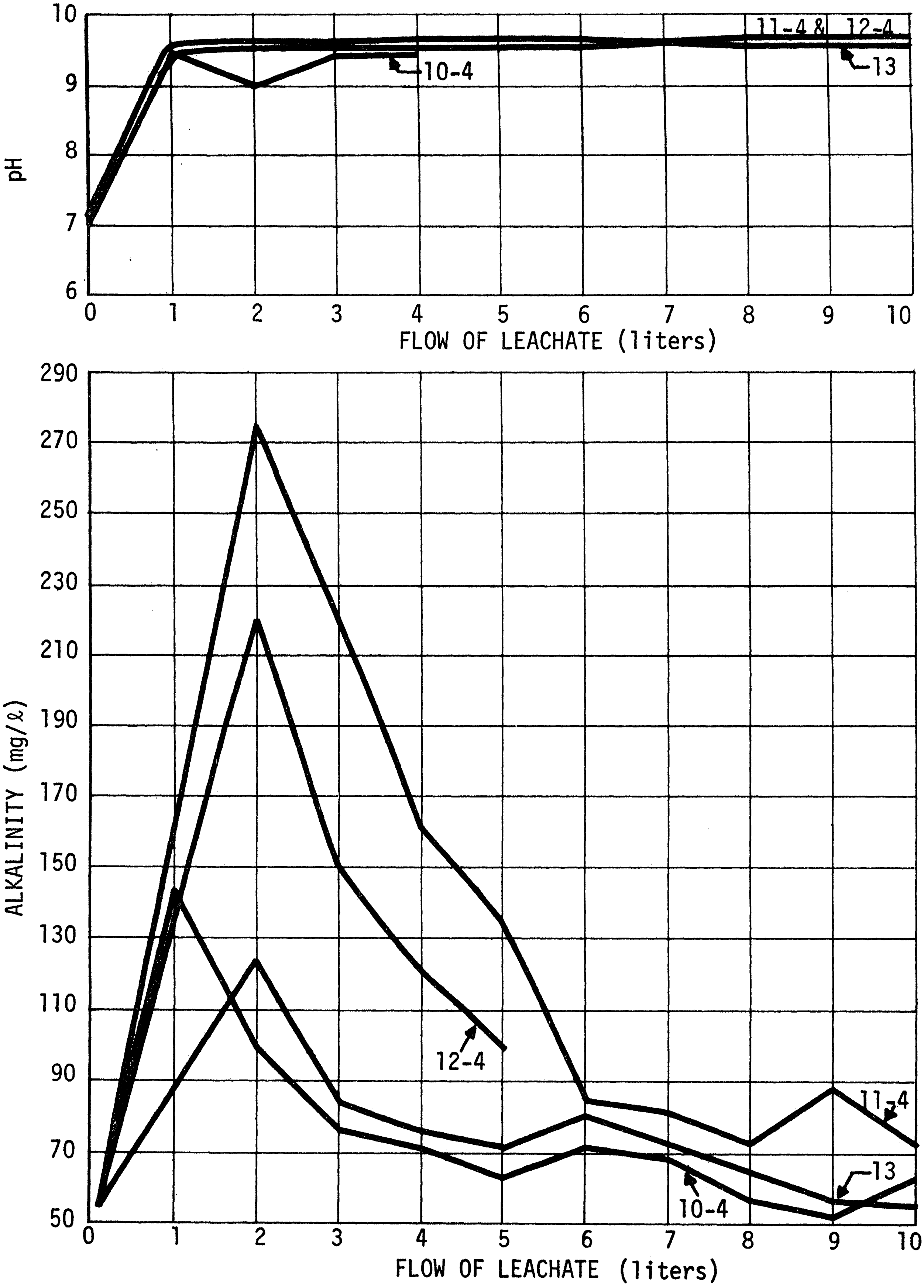


Figure 3. Changes in pH and Alkalinity with Flow of Demineralized Water Over Lime Sludge.

After flowing over the various sludge samples, the low-mineral leachate and demineralized water were also analyzed for total hardness. The observed results are tabulated in Tables 4 and 5.

TABLE 4

TOTAL HARDNESS (ppm as $CaCO_3$) – LOW MINERAL LEACHATE

	Sample		
Time	10-1	11-1	12-1
8	880	850	900
24	940	910	1020
40	930	920	940

TABLE 5

TOTAL HARDNESS (ppm as $CaCO_3$) – DEMINERALIZED WATER

	Sample			
Time	10-4	11-4	12-4	13-4
8	140	130	110	105
24	80	60	95	60
40	40	50	75	58

These results were such that an analysis of variance had to be carried out. First, it was necessary to determine whether there was any difference between samples; second, it was necessary to determine whether there was any significant difference in hardness with time. The results of the analysis of variance computations are given in Tables 6 and 7.

TABLE 6

ANALYSIS OF VARIANCE – TOTAL HARDNESS – LOW-MINERAL LEACHATE

Source	Sum of Squares	Degree of Freedom	Mean Square
Sample	.55	2	.275
Time	1.00	2	.50
Error	.24	4	.06
TOTAL	1.79	8	

$F_{Sample} = \frac{.275}{.06} = 4.6$ $\quad F_{.05_{DF_{2,4}}} = 6.9$

$F_{Time} = \frac{.50}{.06} = 8.33$ $\quad F_{.05_{DF_{2,4}}} = 6.9$

TABLE 7

ANALYSIS OF VARIANCE – TOTAL HARDNESS – DEMINERALIZED WATER

Source	Sum of Squares	Degree of Freedom	Mean Square
Sample	6.2	3	3.07
Time	91.9	2	45.9
Error	9.5	6 m	1.6
TOTAL	107.6	111	

$F_{Sample} = \frac{3.07}{1.6} = 1.92$ $\quad F_{.05_{DF_{3,6}}} = 4.76$

$F_{Time} = \frac{45.9}{1.6} = 28.7$ $\quad F_{.05_{DF_{2,6}}} = 5.14$

The computations in Table 6 show no difference between samples, but show a significant difference in hardness with time at the five percent level. This indicates that the hardness will increase with time of leachate exposure to the sludge, and that the increase reaches an equilibrium which is established by the solubility of the calcium carbonate (calcite). In this case, the equilibrium solubility is at approximately 950 mg/ℓ (as $CaCO_3$) total hardness.

The computations in Table 7 show no significant difference between sludge samples, but show a significant difference in hardness with time, with 5 percent chance of error. The initial increase in hardness is caused by the erosion of the finely divided materials; when they are removed, the increase falls to approximately 50 mg/ℓ (as $CaCO_3$) total hardness.

VI. TESTS FOR EQUILIBRIUM CONDITIONS

Two other tests were designed and conducted to study the effects of the contact between the lime sludge and demineralized water (pH adjusted to $\approx$ 5.0).

One test was designed so that equilibrium conditions between the demineralized water and the sludge would be assured. This was accomplished by grinding the sludge to a fine powder, putting an excess of the powder (one gram) into an Erlenmeyer flask containing 500 milliliters of solute solution, and shaking vigorously for varying amounts of time. After being shaken, the mixture in each case was centrifuged for 5 minutes and the supernatant was analyzed for pH and total hardness. [Total hardness was measured by the standard EDTA method, using the Hach water analysis apparatus.]

The results are shown in Table 8 and plotted in Figure 4. It is evident that equilibrium conditions were developed at pH 9.6 to 9.8 and total hardness of 50 - 55 mg/ℓ as $CaCO_3$. The chemical relationships which justify this conclusion are as follows: The solubility product of calcium carbonate is $10^{-8.3}$, i.e. $[Ca^{2+}][CO_3^{2-}] = 10^{-8.3}$. At pH 10.4 or above ($pK_2$ of H_2CO_3) $[Ca^{2+}] \approx [CO_3^{2-}]$ if dissolution of $CaCO_3$ is the only source of Ca^{2+}, while at a pH of 9.5, i.e. $[Ca^{2+}] \approx [CO_3^{2-}] + [HCO_3^-]$ and $[HCO_3^-] \approx 10[CO_3^{2-}]$ then $[Ca^{2+}] \approx .1[CO_3^{2-}]$.(66) The observed calcium content of 50 mg Ca^{2+}/ℓ as $CaCO_3$ is equal to $.5 \times 10^{-3}$ moles Ca^{2+}/ℓ. The resultant solubility product computation is $[.5 \times 10^{-3}]$ $.1[.5 \times 10^{-3}] = .25 \times 10^{-7}$ which indicates that the solution contains slightly more calcium carbonate in solution than would theoretically occur at equilibrium.

Since equilibrium conditions developed in a very short time (less than 5 minutes) with vigorous shaking, the reaction is not considered time-dependent. In a landfill, with the character of the sludge causing a slow rate of percolation, it is reasonable to expect that equilibrium conditions will prevail and that similar effects will occur.

TABLE 8

FINELY DIVIDED SLUDGE IN CONTACT WITH DEMINERALIZED WATER

(Water @ pH = 5.0, Zero Hardness)

Shaking Time (minutes)	Amount of Sludge (grams)	pH	Total Hardness (mg/ℓ as $CaCO_3$)
5	1	9.6	50
10	1	9.8	50
20	1	9.8	50
10	2	9.8	55

TABLE 9

RESULTS OF SURFACE CONTACT IN SOXHLET, DEMINERALIZED WATER AND SLUDGE

(Water @ pH = 4.0, Zero Hardness, Applied at the Rate of 1 Liter per Hour)

	Leachate Passed (mℓ)	Total Hardness (mg/ℓ as $CaCO_3$)	pH pH
Soxhlet #1	300	180	9.8
86.79	600	120	9.65
grams of sludge	900	105	9.7
	1400	70	9.8
	2050	65	9.7
	2500	55	9.8
	2900	65	9.6
Soxhlet #2	300	220	9.8
82.84	600	115	9.7
grams of sludge	900	90	9.7
	1500	65	9.8
	2150	60	9.6
	2700	55	9.6
	3000	55	9.6

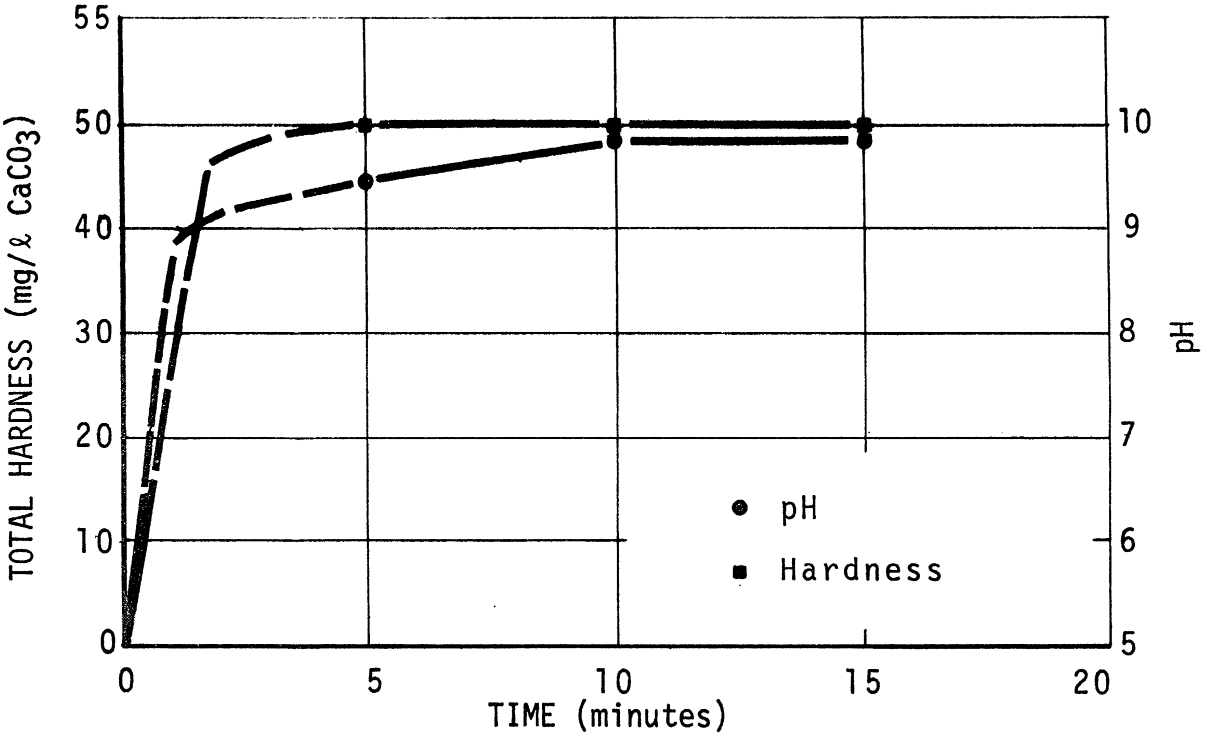


Figure 4. Changes in pH and Hardness with Time as a Result of Contact Between Finely Divided Lime Sludge and Demineralized Water.

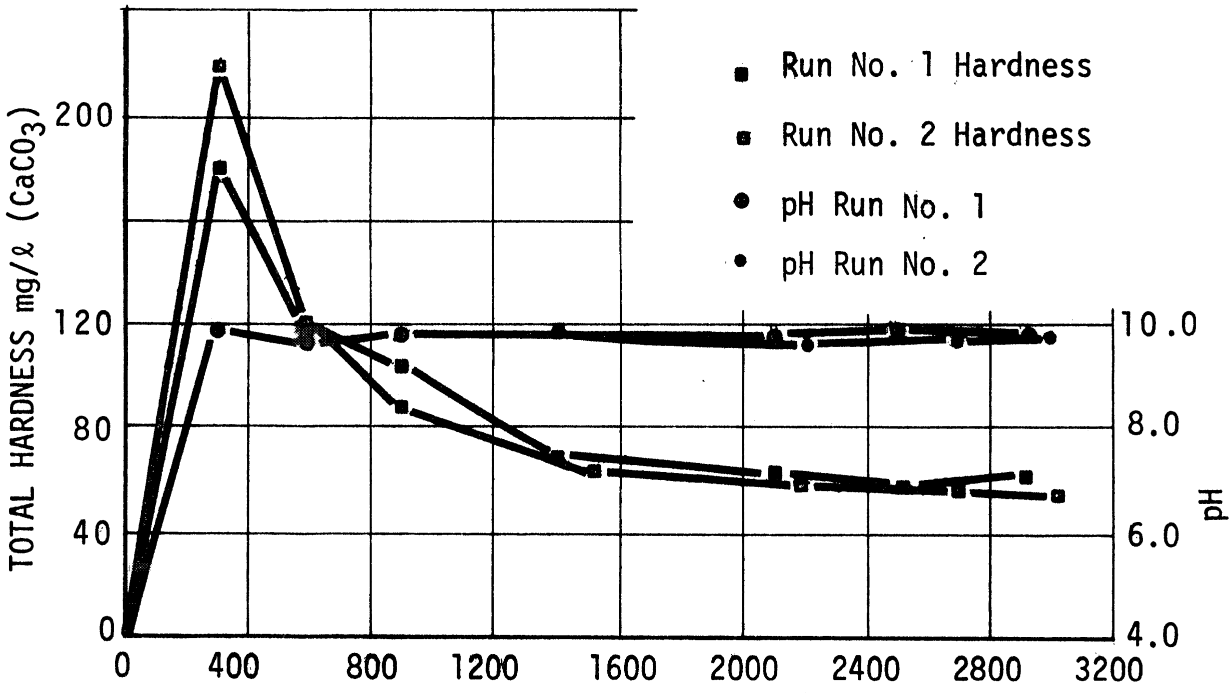


Figure 5. Changes in pH and Hardness with Flow of Demineralized Water Over Lime Sludge.

VII. TESTS WITH SOXHLET APPARATUS

The results of contact between the sludge and demineralized water were further tested by use of the soxhlet apparatus. The soxhlet flask was filled with dried sludge in lumps that were 1/4 inch in diameter or smaller. Glass beads and a plastic mesh screen served as an underdrain system. With this arrangement (which was identical to that used in the high-iron-solution tests) the liquid could be passed over the sludge at a controlled rate (1 liter per hour), and a saturated condition could be maintained in the sludge. Samples of the leachate after passing over the sludge were taken and analyzed for total hardness and pH. As shown in Table 9 and Figure 5, the pH of the leachate before entering the soxhlet was 4.0, and the leachate had 0 hardness. The first few hundred milliliters of leachate that left the apparatus had a high value of hardness; this was caused by a washing out of the very finely divided sludge present in the soxhlet. Thereafter, the total hardness was between 55 and 65 mg/ℓ as $CaCO_3$, and pH was 9.6 to 9.8.

These conditions were nearly the same as those prevailing when the samples had been shaken together in the previous analysis. Such conditions are more akin to field conditions than others, and because of the large particle size, equilibrium conditions may take somewhat longer to develop. Even so, an apparent equilibrium is developed well within the time of contact that would be expected to occur in a landfill. From the results it is very evident that lime sludge will act as an effective neutralizing media in a landfill, and with one exception will not contribute significantly to any pollutional effects. That exception is in raising the hardness approximately 50 mg/ℓ as $CaCO_3$. The amount of sludge taken into solution by a leachate will be affected by its pH and mineral content, which in turn determine its equilibrium concentration.

VIII. TESTS WITH HIGH-IRON-CONTENT SOLUTION

To determine the results of a high-mineral (high-iron) solution in contact with lime/soda-ash sludge, a series of tests were developed and conducted using dried sludge and soxhlet extraction apparatus and a high-iron-content solution. A solution with 300 mg/ℓ of ferrous iron was prepared with pH of 4.6. [Due to the solubility characteristics of iron, a low pH was needed to develop a high iron content.] A known weight of dried sludge in random lumps ranging in size from very small to approximately 1/2 inch diameter was placed in a soxhlet extractor. Glass beads and a piece of plastic screen served as an underdrain system. To aid in distributing the incoming solution, a fine-mesh, nickle-wire screen was placed over the sludge layer. A regulated syphon system was established to allow the solution to enter at a given rate (1 liter/hour), and samples were taken from the end of each liter after the solution passed over the sludge in the soxhlet. The soxhlet apparatus was selected so that a saturated condition could develop intermittently in the sludge. The soxhlet extraction apparatus (shown in Figure 34, Appendix B) is equipped with a self-starting syphon which floods the contents intermittently before they are discharged from the apparatus.

The solution leaving the soxhlet was analyzed for total iron by the 1,10 Phenanthroline Method (Hach-water analysis apparatus) and pH. Furthermore, a sample of the solution before entering the soxhlet was taken at each liter interval to monitor any change that may have occurred during storage.

The results of the various series of tests are as given in the Table 10 and are plotted in Figure 6, 7, and 8.

The results show that iron was removed in two ways, basically:

1. Precipitation after contact with the alkaline sludge resulted in an increase of pH up to 6 or 7. Iron precipitates in this pH range are most likely in the form of $Fe(OH)_3$ or $FeCO_3$ and possibly $Fe(OH)_2$, depending on the oxidizing state of the iron. From the observed leveling off of pH at 6+ to 7.0 it can be assumed that the iron in solution is reacting in this situation in one of the following two reactions.(67)

TABLE 10

CHANGES IN pH AND IRON CONTENT BETWEEN A HIGH-IRON-BEARING SOLUTION AND LIME SLUDGE

(Fe as total iron)

	Liters of leachate over sample 1 l/hr. (hours)	Fe conc. before mg/ℓ	Fe conc. after mg/ℓ	Fe retained mg/ℓ	Fe retained per gram sludge mg/ℓ/gm	ΣFe retained mg/ℓ/gm	pH
Series #1	1	270	200	70	.89	.89	5.6
78.25 gm	2	180	150	30	.38	1.27	5.6
Sludge	3	190	150	40	.51	1.78	6.0
	4	230	125	105	1.34	3.12	6.4
	6	280	190	90	1.15	4.27	6.2
	8	300	250	50	.64	4.91	6.4
	10	244	194	50	.64	5.55	6.3
	12	180	126	54	.69	6.24	6.4
Series #2	1	300	185	115	1.54	1.54	-
74.6 gm	2	300	230	70	.94	2.48	6.0
Sludge	3	300	210	90	1.21	3.69	5.7
	4	300	205	95	1.27	4.96	5.6
	5	300	230	70	.94	5.90	5.5
Series #3	1	300	93	207	1.95	1.95	7.4
106.18 gm	2	300	166	134	1.26	3.21	6.9
Sludge	3	300	190	110	1.03	4.24	6.6
	4	280	160	120	1.13	5.37	6.6
	5	270	178	92	.87	6.24	6.3
Series #4	1	300	140	160	1.75	1.75	6.7
91.47 gm	2	300	170	130	1.42	3.17	6.7
Sludge	3	300	180	120	1.31	4.48	6.3
	4	300	170	130	1.42	5.50	6.0
	5	300	180	120	1.31	7.21	5.9

TABLE 10 (CONT'D)

CHANGES IN pH AND IRON CONTENT BETWEEN A HIGH-IRON-BEARING SOLUTION AND LIME SLUDGE

(Fe as total iron)

	Liters of leachate over sample 1 l/hr. (hours)	Fe conc. before mg/ℓ	Fe conc. after mg/ℓ	Fe retained mg/ℓ	Fe retained per gram sludge mg/ℓ/gm	ΣFe retained mg/ℓ/gm	pH
Series #5	1	425	268	157	2.02	2.02	-
77.59 gm	2	420	288	132	1.70	3.72	6.1
Sludge	3	432	335	97	1.25	4.97	6.1
	4	448	340	108	1.39	6.36	6.1
	5	450	360	90	1.16	7.52	6.1
Series #6	2	290	196	94	1.25	1.25	6.3
75.15 gm	6	284	236	48	.64	1.89	6.2
Sludge	7	276	166	110	1.46	3.35	6.0
	8	290	222	68	.905	4.25	5.8
	9	298	230	68	.905	5.16	5.9
	10	300	240	60	.80	5.96	5.8
Series #7	2	290	250	40	.66	.66	6.1
61.18 gm	6	284	206	78	1.28	1.94	6.1
Sludge	7	276	188	88	1.44	3.38	6.0
	8	290	240	50	.82	4.20	5.6
	9	298	238	60	.98	5.18	5.7
	10	300	236	64	1.05	6.23	5.9

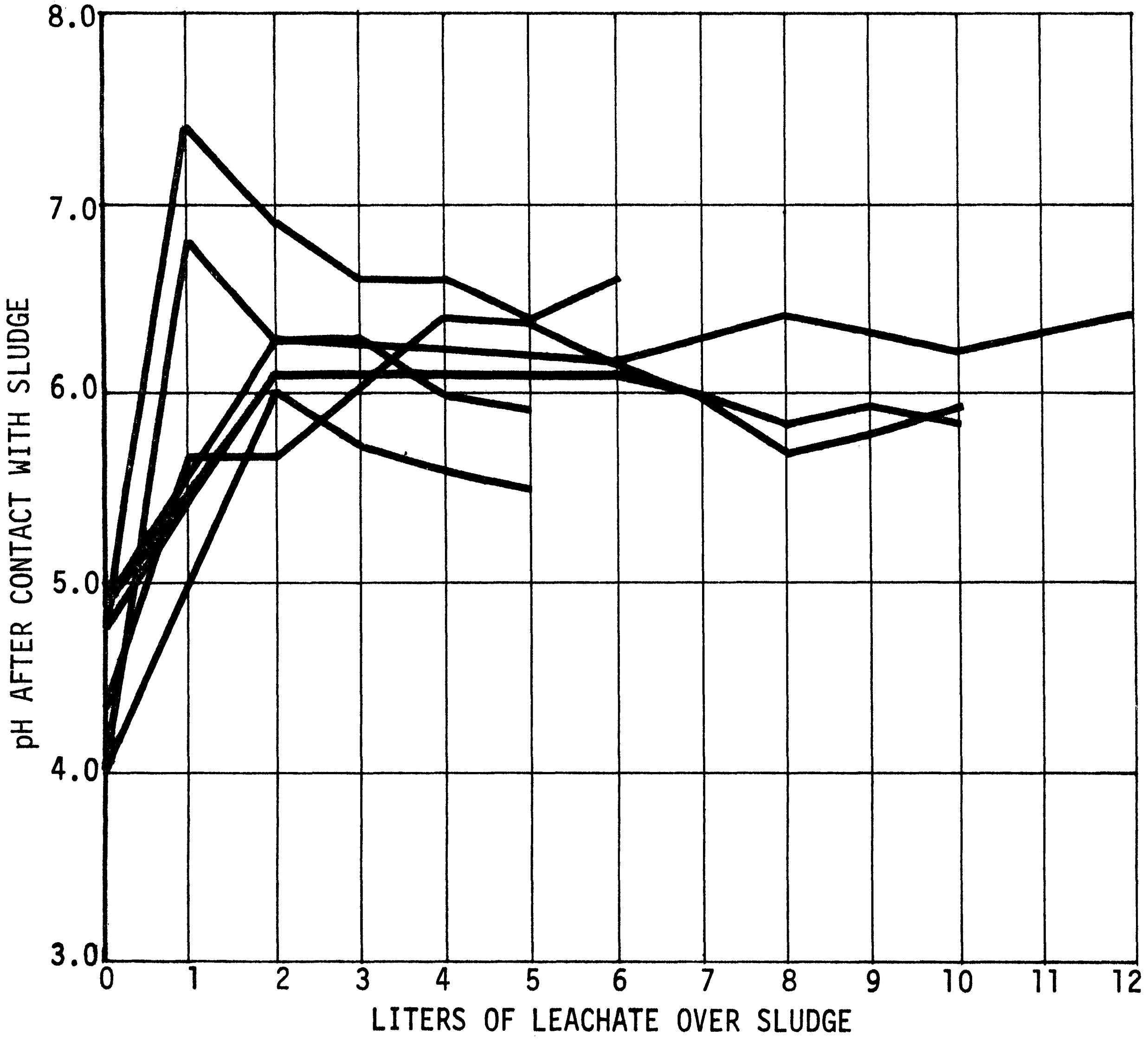


Figure 6. Change in pH With Flow of High-Iron-Bearing Solution Over Lime Sludge.

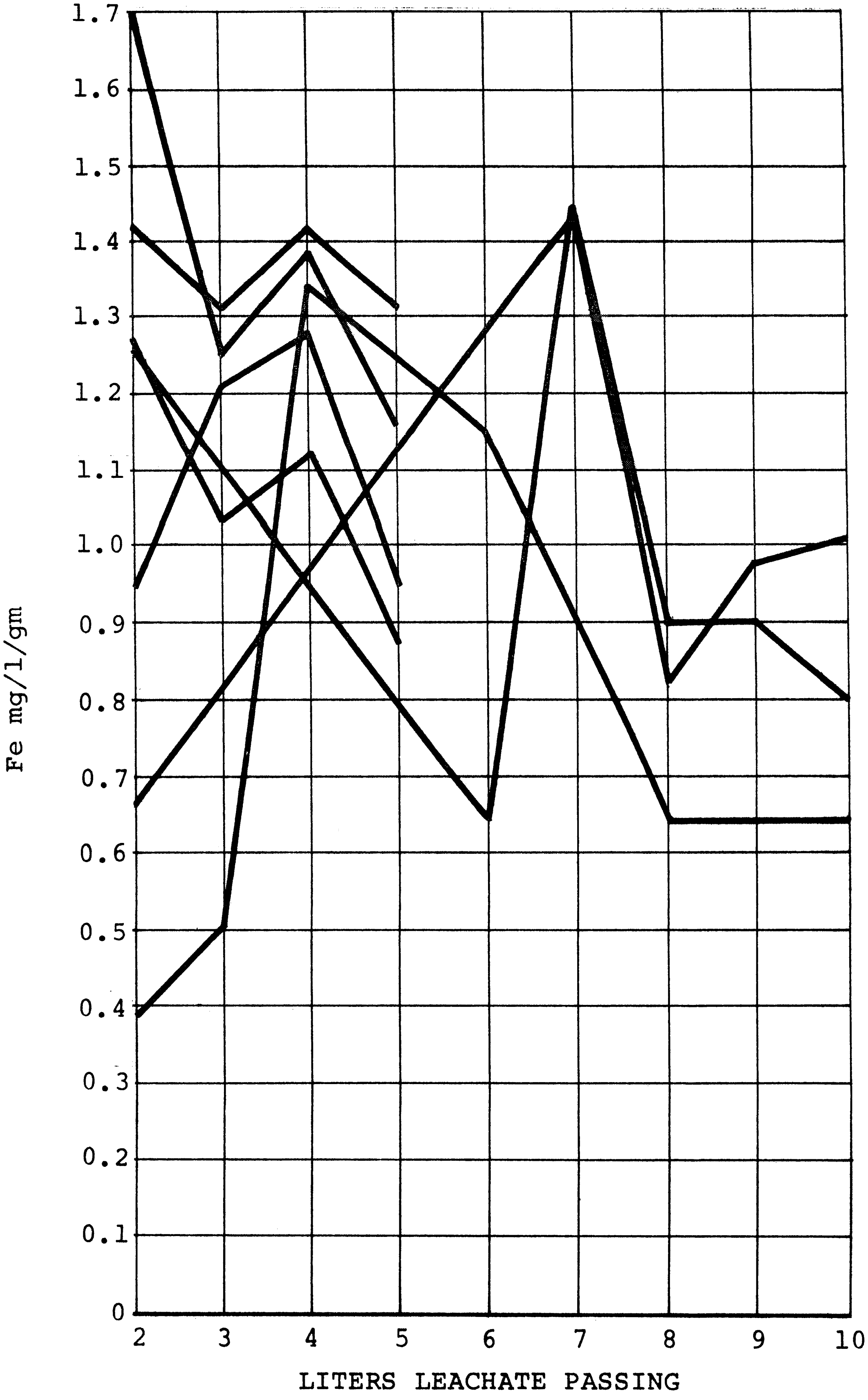


Figure 7. Iron Retained per Gram of Sludge with Flow of High-Iron-Bearing Solution and Lime Sludge.

$Fe^{2+} + H_2O \rightleftarrows Fe(OH)^+ + H^+$

$Fe^{3+} + 2H_2O \rightleftarrows Fe(OH)_{2+} + 2H^+$

and, depending upon pH, higher order hydrolysis reactions.

The released H^+ then reacts as follows;

$CO_3{}^{2-} + H^+ \rightleftarrows HCO_3{}^-$

$HCO_3{}^- + H^+ \rightleftarrows H_2CO_3$

$H_2CO_3 + H_2O \rightleftarrows HCO_3{}^- + H_3O^+$

The pk value of the latter reaction is 6.3-6.4 which is considered to represent the observed condition since the observed pH is 6.0+ (it is well to note that the carbonate system is a well buffered system at about pH of 6.4 as indicated by Weber(66)).

2. Some oxidation of the ferrous iron to ferric iron was a result of oxygen being available from the atmosphere. This supply would not be available in an anaerobic situation.

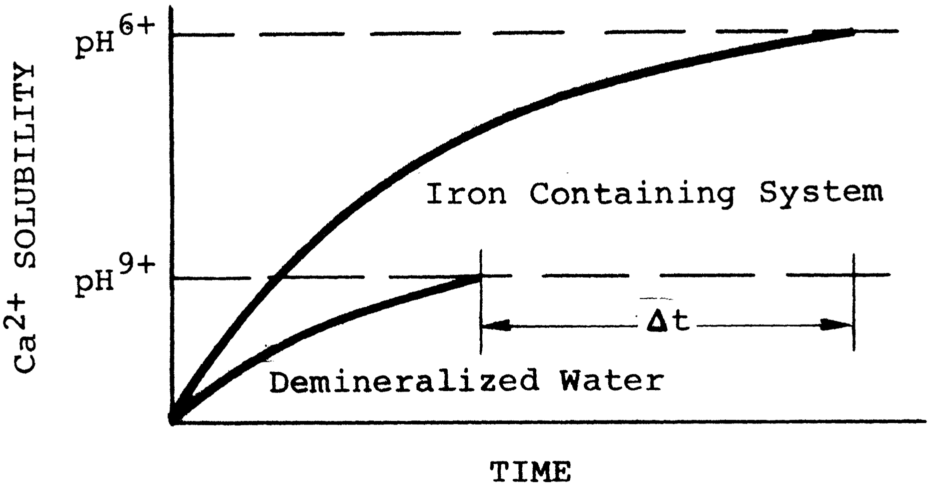
One result of the formation of insoluble precipitation of iron was its continued precipitation in the discharge tubing of the soxhlet apparatus and in the effluent containers. To account for the passage of iron into and out of the system, a materials balance of the system was attempted. It failed, however, due to the fact that an unknown amount of very fine sludge developed during the drying process was also removed. It is significant that soluble iron was converted to an insoluble form by contact with the lime sludge; this would reduce the amount of soluble iron appearing in a leachate from a landfill in which lime sludge has been incorporated. The conversion also indicates that any treatment to reduce the pollutional potential of leachate should include some form of lime treatment to reduce the iron content.

The rate of iron removal decreased but did not go to 0 because a certain amount of unreacted lime-sludge surface remained present. A compromise has to be made here between particle size and porosity, since smaller particles increase the capacity of the sludge as a contact media, but at the same time decrease the ability of leachate to pass over the sludge. The results of the contact of high-iron solution and sludge are shown in Table 10.

The iron-test results led to two key interpretations:

1. There was a loss of weight from the soxhlet. This was due to:
    a. erosion caused by dried sludge which pulverized and washed away with leachate;
    b. solution of calcium. At a pH of approximately 6 very little carbonate as such is available to precipitate calcium so that the solution of calcium would be

quite high if equilibrium conditions pretained. Based on the observed results steady state conditions are considered to prevail accounting for the leveling off of the pH at 6.0+ noted in the data rather than equilibrium conditions. Due to the low pH the solubility of calcium is increased and the system is therefore farther removed from equilibrium. The time required to reach the more remote equilibrium thus may be anticipated to be longer. This is shown schematically in the accompanying sketch which illustrates that more time is needed to reach an equilibrium condition in the high iron containing, low pH, system.



Since the residence time in the soxhlet apparatus is relatively short at the rate of application used (1 liter/hr) it is apparent that steady state rather than equilibrium conditions are most likely to occur. These deductions can be drawn from the discussion of carbonate equilibrium after Weber.(66)

[The conclusion is that most of the loss was due to flushing out of fines by leachate.]

2. The iron concentration was decreased. This was due to:
   a. precipate of iron as the carbonate and hydroxide resulting from an increase in pH due to the reaction between the acid leachate and the alkaline sludge;
   b. precipitate of iron resulting from the formation of $Fe(OH)_3$ due to contact with oxygen from the air;
   c. physical retention of iron on the sludge particles by adsorption.

Solubility of ferrous carbonate ($FeCO_3$) at 20°C is 65 mg/ℓ as $FeCO_3$, and the solubility of ferrous hydroxide is 7 mg/ℓ as $Fe(OH)_2$.(63) As the source of iron in the solution, iron in the form of ferrous ammonium sulfate was used. This is Mohr's salt, commonly used as a source of ferrous ions because it is much more resistant to atmospheric oxidation than ferrous sulfate alone. It was made up to 300 mg/ℓ as ferrous iron with a pH of 4.4 to 4.6.

The precipitate formed as a result of contact with the lime sludge was $Fe(OH)_2$. It was green due to contact with air; otherwise it would be white.(15) The green precipitate that was first observed converted to reddish brown, signifying that the ferrous iron had oxidized to ferric. Therefore $Fe(OH)_3$ was assumed to be the precipitate.

IX. TESTS TO DETERMINE PARAMETERS UNDER ANAEROBIC CONDITIONS

Anaerobic conditions predominate within a landfill, but aerobic conditions also exist either prior to or simultaneously with anaerobic conditions.(51) To determine the parameters under anaerobic conditions, a series of tests were run with nitrogen replacing air in closed bottles.

In order to establish the iron-retaining capacity of the sludge, a series of tests were developed. In this series, a known amount of dried sludge, finely divided, was placed in a known volume and concentration of high-iron solution ($\approx$ 300 - 450 mg/ℓ Fe). Then the mixture was shaken for various lengths of time in an anaerobic environment.

In each series, a measured amount of dried lime sludge and the known amount of solution were placed in a closed glass container and the air replaced with nitrogen. The solution itself was not deaired. The mixture was shaken constantly at 180 cycles/second for various lengths of time. It soon became apparent that the reactions were not time-dependent, since the results were the same at all times exceeding 2-3 minutes. For all tests, therefore, a 2-hour time was decided upon. This was long enough for all potential reactions to take place, and yet was less than the expected time of contact within a landfill between the sludge and any leachate.

After shaking, a 25-milliliter sample of the mixture was centrifuged for 5 minutes to separate the solids from solution; then the iron remaining in solution was determined using the same technique used in all the iron determinations (1,10- Phenanthroline method and the Hach water analysis apparatus).

X. TESTS WITH HIGH-IRON SOLUTION

The first series were conducted using from 1-15 grams of dried sludge and 500 ml of the high-iron (300 mg/ℓ) solution in a 1.5-liter flask. This proved to be an insufficient supply of iron, since the iron was completely exhausted by the 15 grams of sludge. The result was an inconclusive evaluation of the total capability of the lime sludge to react with the iron in the solution under anaerobic conditions.

Therefore a subsequent series of tests was set up, making a much greater amount of total iron available (2200 mg or more) in five liters of solution (450 mg/ℓ or more as Fe^{2+}) at a temperature of 20°C. The results of these runs are given in Table 11 and shown in Figure 8.

TABLE 11

HIGH-IRON SOLUTION IN CONTACT WITH SLUDGE UNDER ANAEROBIC CONDITIONS

Series	Iron in Leachate mg/ℓ	Grams of Sludge	pH	Iron Remaining mg/ℓ	Iron Removed mg/ℓ	Total Iron Removed mg
#4	450	2.5	6.1	364	86	430
5 liter	450	5.0	6.2	368	82	410
	450	7.5	6.6	324	126	630
#5	450	8	6.3	346	104	520
5 liter	450	9	6.4	330	120	600
	700	20	6.5	490	210	1050
#6	450	10	6.4	328	122	610
5 liter	450	13	6.4	318	132	660
	450	16	6.5	254	196	980
	450	20	6.5	204	240	1230

The results of this investigation show that the sludge has a great ability (a) to react with a high-iron solution, and (b) to produce an insoluble complex that will remove much of the iron from the solution. [In these determinations, the pH of the mixture was consistently found to be above 6 so that the iron could be assumed to have a negative charge as well.](35)

The relationship of iron removed by lime (finely divided) in an anaerobic environment is shown in Figure 8. A straight line has been fitted to this data by the method of least squares, and the equation of the resultant line has been determined. The equation is:

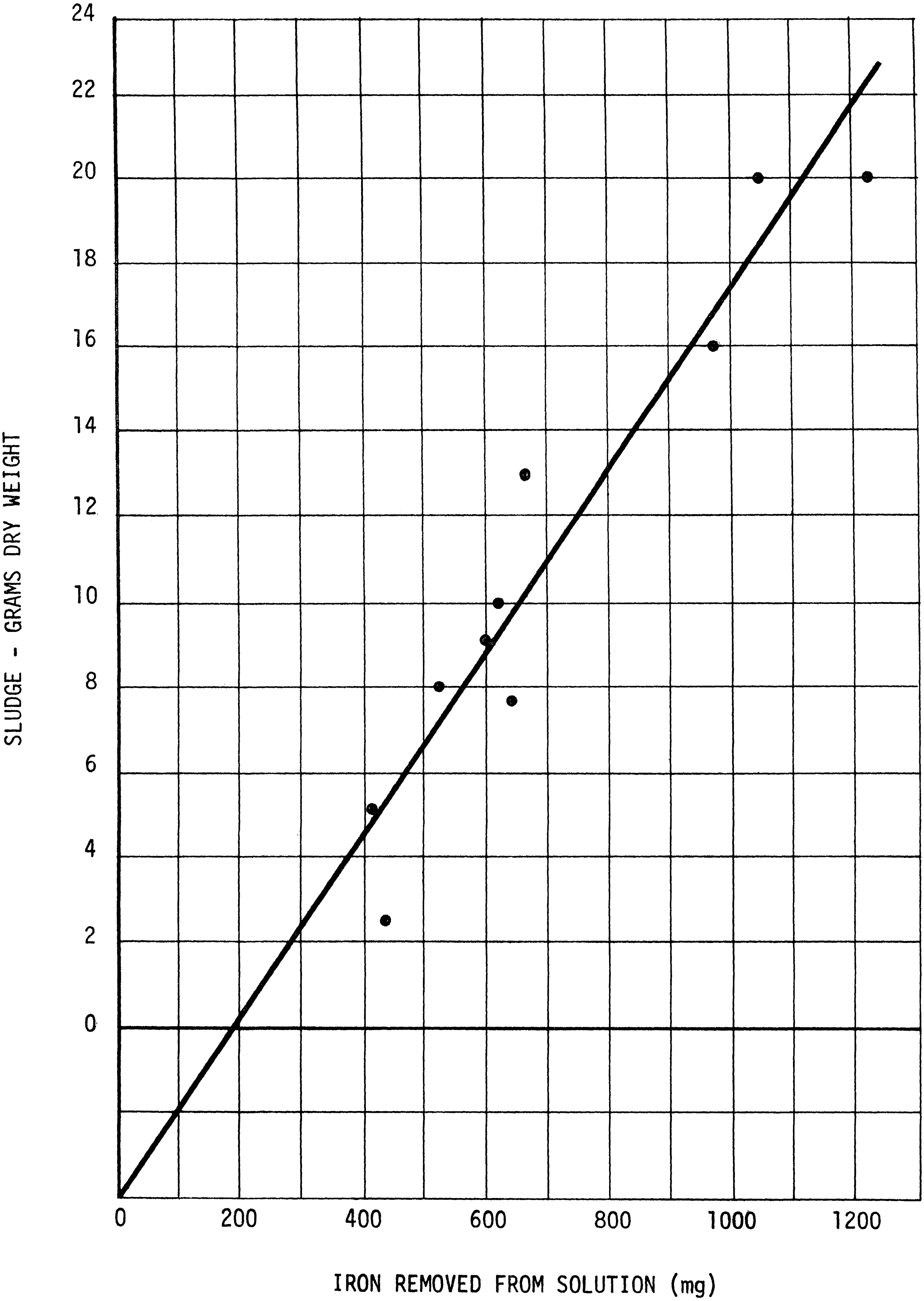


Figure 8. Iron Removal (milligrams) vs Amount of Lime Sludge (grams).

$$y = -4.1 + .0214\ x$$

y = the grams of finely divided dry lime sludge

x = the milligrams of iron (as Fe^{++}) removed.

The standard error of estimate for this relationship is 1.73 grams and the coefficient of correlation is .955. It should be noted that this relationship applies only for ≈ 200 mg of iron or more. The fact that the curve does not pass through the origin is attributed to the small amount of iron absorbed on the surface of the glass and to the presence of dissolved oxygen in the solution.

By means of the empirical relationship derived, it is possible to estimate (a) the amount of iron that can be complexed when lime sludge is used in the finely divided state in an anaerobic environment, or (b) the amount of lime that is needed to remove a given amount of iron. The estimate is not directly applicable to actual landfill situations because the sludge in the landfill will not be finely divided, as in this test, but rather in lumps and in a mass. Although the leaching tests described earlier are more typical of the actual situation, this relationship may be helpful in using lime sludge as a means of leachate treatment.

Since the size of the sludge particles was determined by use of the electron microscope to be $< 5\mu$, the surface area per gram of sludge could be estimated. The assumptions made: sludge particles are spherical (Area = πD^2, Volume = $1/6\ \pi D^3$); and specific gravity = 2.35.

The results: If the diameter is assumed to be 3µ, area/gram = .85 m^2/gram; if the diameter is assumed to be 5µ, the area = .51 m^2/gram.

From the curve (Figure 8), it can be computed that 10 grams of sludge will remove 660 mg of Fe. If the surface area per gram is assumed to be .5 m^2, then 10 grams will have an area of 5 m^2. Assuming that the reaction taking place is a surface phenomenon, for every gram of sludge of this size, 660/5 = 132 mg of Fe will be removed per square meter of surface area. Although this computation has little real value, it does indicate that under the stated conditions, considerable iron will be retained in the sludge.

To establish the rate of solution of the lime sludge in contact with a leachate that has an assured ability to dissolve it, distilled water was adjusted to a pH of 5.0 with H_2SO_4 and an excess of sludge was placed in it. The changes in dissolved solids in the water and pH of the solution were measured over a considerable period of time. No mixing was provided; the temperature was 20°C and saturation was assumed to have occurred after 4 hours. Weyl(68) states that 3-1/2 hours produced 50 percent saturation in a solution with CO_2. Figure 1 shows the change in pH with time of contact, and is the basis for establishing both the time of saturation and the pH which will occur after prolonged contact (equilibrium) with the sludge.

The increase in dissolved solids is shown in Table 12:

TABLE 12

INCREASE IN DISSOLVED SOLIDS

Sample	mg/ℓ/4 hr.
1	80.0
2	56.0
3	92.0

An average value is 76 mg/ℓ/4 hr. If it is assumed that this saturated water was replaced with unsaturated water six times during a day, then .304 gm/day will be removed per liter.

XI. CHARGE ON SLUDGE PARTICLE

To better explain the reaction with iron contained in leachate as affected by contact with lime sludge, the charge on the sludge particles was determined using the method called metachromasy described by Kawamura and Tanaka.(35)

A positive-charged colloid was supplied by using methyl glycol chitosan (MGC), and a negative-charged colloid was supplied by potassium polyvinyl alcohol sulfate (PVSK). The indicator, toluidine blue (TB), served to indicate the stoichiometric point.

Specifically, 100 mℓ of a solution containing ≈ 300 mg/ℓ of sludge dissolved in distilled water was placed in a beaker. The pH was adjusted to 10 with HCl, and 5 mℓ of MGC was added. A few drops of TB was added, turning the mixture blue; then titration to a purple endpoint was done with .001N PVSK. After establishing the relationship needed in distilled water (4.10 mℓ of .001N PVSK was needed to back titrate 5 mℓ of MGC), the polarity of the charge and its magnitude were calculated, with results as shown in Table 13.

TABLE 13

CHARGE ON PARTICLE OF LIME SLUDGE

(5 mℓ of MGC was added to each solution and then titrated with .001N PVSK to TB endpoint (purple))

Solution	Conc.of Sludge mg/ℓ	mℓ of PVSK	Excess Needed Over Distilled Water	Polarity of Charge	Charge Magnitude meg/ℓ
Distilled Water	0	4.10	0		
1	300	4.89	.79	+	7.9×10^{-4}
2	306	4.90	.80	+	8.0×10^{-4}
3	301	4.92	.82	+	8.2×10^{-4}
4	301	4.82	.72	+	7.2×10^{-4}

The pH of this lime sludge was determined to be 10.1, using the standard procedure employed in soil analysis.(12) Knowledge of this parameter is important in considering use of the lime sludge as a soil sweetener or for other uses which require a high-pH material.

XII. CONCLUSIONS

The decided iron removal noted in preceding sections can be explained chiefly by three mechanisms.

1. The charge attraction between the positively-charged sludge particles and negatively-charged iron particles. As stated in (35), ferric hydroxide is negatively charged only above a pH of 6; below that pH value, it has a positive charge. The high-iron-contining solution in contact with the sludge with even a very short time of contact reaches pH of 6 to 6.5, and remains at a pH of near 6 or slightly above 6 as the solution continues to pass over the sludge (see Figure 6). Since this would result in a negative charge being present on the ferric hydroxide, the iron would be removed on the sludge which has a positive charge.
2. Hem(30) states that waters containing more than 1.0 ppm of iron are only going to retain that amount of iron in solution if the pH is low. As the pH of the leachate is increased due to contact with the lime sludge, the soluble iron will be converted to $Fe(OH)_3$ which will precipitate.

3. If the leachate containing a reduced form of iron is allowed to remain in an aerobic environment, it may be oxidized to the Fe(III) form and precipitate from solution.(60)

The results of passing a high-iron-containing solution over lime sludge so that iron will be retained by the sludge is shown in Figure 7. This curve indicates a gradual reduction in the retentative capacity of the sludge, but shows that even after a large quantity of solution has passed over the sludge (as much as 10 liters), the sludge still has a retentative capacity in excess of .6 mg/ℓ/gram. These results along with the results from the anaerobic experiments show the lime sludge's great capacity to remove iron from a leachate in a landfill. They are the basis for the conclusion that if treatment of such a leachate is contemplated, the use of lime (perhaps lime sludge) should be an essential part of the treatment.

CHAPTER 3

THE PHYSICAL CHARACTERISTICS OF LIME SLUDGE AND THEIR EFFECTS ON ITS USE IN LANDFILL DISPOSAL

As previously discussed, the lime/soda-ash sludge excavated from storage lagoons has value as a soil additive and as a sweetener to reduce soil pH. The sludge also has potential as an additive to the soils of strip mines to counteract highly acid conditions. These uses are based on the chemical characteristics of the sludge. Other uses are based on its physical characteristics, and these are investigated in the present chapter. Prominent among the latter uses is disposal of the sludge in embankments, structural fills, sub-bases, and backfills. If the sludge is to be used in any of these ways, however, its properties must first be identified and characterized so that suitable conditions can be determined.

In the field of soil mechanics, the physcial characteristics of a material are separated from its engineering properties insofar as it is used as a construction or foundation material. The following list separates the various parameters evaluated in this study of lime-soda ash sludge:

PHYSICAL CHARACTERISTICS (index properties)		ENGINEERING PROPERTIES
Grain size distribution		Shear strength
Particle morphology		Moisture-density behavior
Specific gravity		Compressibility
Composition	chemical mineralogical	Permeability
Plasticity		
pH		

Once the material is classified and identified according to the physical properties listed above, one can predict (on the basis of experience and empirical relationships) the likely engineering properties of the material or its suitability for given engineering applications.(70)

Few of these parameters are known for lime sludge as it is found in a lagoon. In this study, therefore, the sludge was evaluated and the resultant properties were used as a basis for classifying and determining its suitability for various applications.

I. SIEVE ANALYSIS

The sludge was subjected to sieve analysis followed by hydrometer analysis (ASTM D422-63)(5), with results that are shown in Figure 9. According to the ASTM Particle Identification System, these results indicate that the material is of silt size.

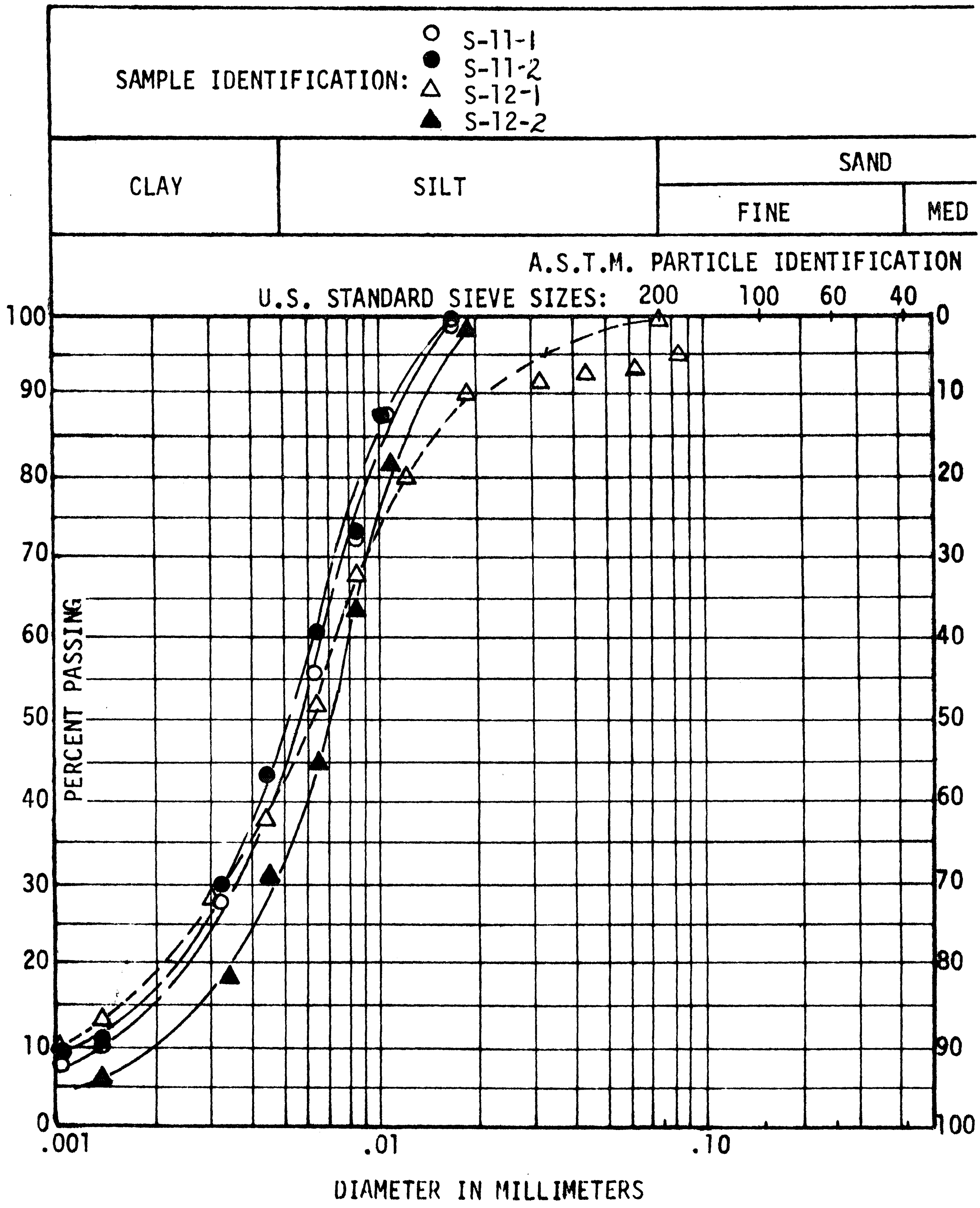


Figure 9. Sludge-Particle Size Analysis.

II. TESTS FOR ATTERBERG LIMITS

To determine the ASTM soil classification of the sludge, the Atterberg limit tests (liquid and plastic limits) were conducted on several sludge samples, with results that are shown in Table 14.

TABLE 14

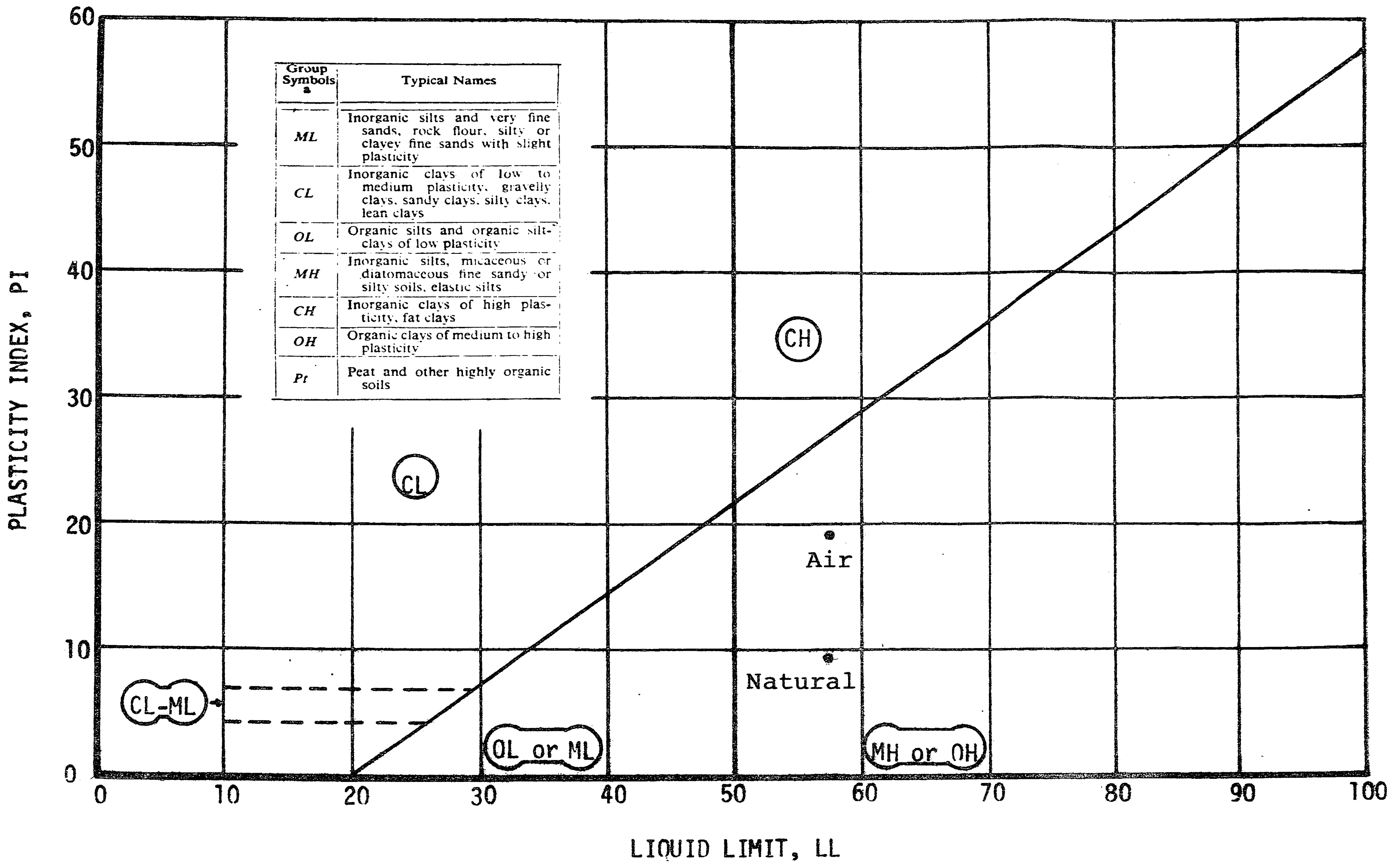
ATTERBERG LIMITS OF LIME SLUDGE

Sample	Liquid Limit	Plastic Limit	Plasticity Index	ASTM Classification
#1 (Oven dried)	41.8	35.0	6.8	0 (Liquid limit after oven drying is less than 3/4 of the original sample before drying)
#2 (Air dried)	57.7	38.8	18.9	MH
#3 Natural (as sampled)	57.5	48.2	9.3	MH

The locations of these samples on a plasticity chart is shown in Figure 10. The Atterberg limit tests were conducted according to standard ASTM procedures D423 and D424.(5) A typical data sheet is shown in Appendix D.

III. TESTS FOR COMPACTION

Knowledge of the moisture-density relationships or compaction characteristics of the lime sludge is required if it is to provide for reasonable stability in a



Group Symbols a	Typical Names
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
OL	Organic silts and organic silt-clays of low plasticity
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
CH	Inorganic clays of high plasticity, fat clays
OH	Organic clays of medium to high plasticity
Pt	Peat and other highly organic soils

Figure 10. Plasticity Chart.

rolled embankment or a compacted landfill by itself. These parameters were determined on air-dried sludge, using compactive effort equivalent to the modified AASHO compaction method. As shown later in this study (see the section on Triaxial Testing), the results gave an optimum moisture content of 32 percent (dry weight basis) and a maximum dry density of 81 pcf. It should be noted that as the moisture content of this material increases, the dry density decreases rather rapidly, impairing its usefulness as a landfill material.

IV. PERMEAMETER TESTING

To further define the engineering properties of the lime sludge and to establish the possible rate of movement of water through it, the coefficient of permeability was evaluated. The evaluation was carried out in two ways; one by use of the permeameter described in this section, the other by means of the consolidation test described in the section following.

The permeameters used for measuring the sludges coefficient of permeability were of the variable-head type, and consisted of a plexiglas cylinder with an effective length of 10.59 cm and an inside diameter of 5.00 cm. The cross-sectional area of the permeameter was 19.635 cm^2. The inside diameter of the burette from which the water was delivered was 1.04 cm. To assure drainage, porous stones .70 cm thick were used at each end of the permeameter. Filter paper was inserted between the sample and the stones.

The sludge samples to be tested were placed in the permeameters. No attempt was made to measure the permeability of completely disturbed samples, but the physical placement of the sludge in the permeameter required considerable remolding. The coefficients of permeability obtained by these tests were compared with those calculated from the consolidation tests where the samples were completely distorted. The comparison showed that the method of placing the samples had very little effect. A sketch of the apparatus and the equation used are given in Figure 11.

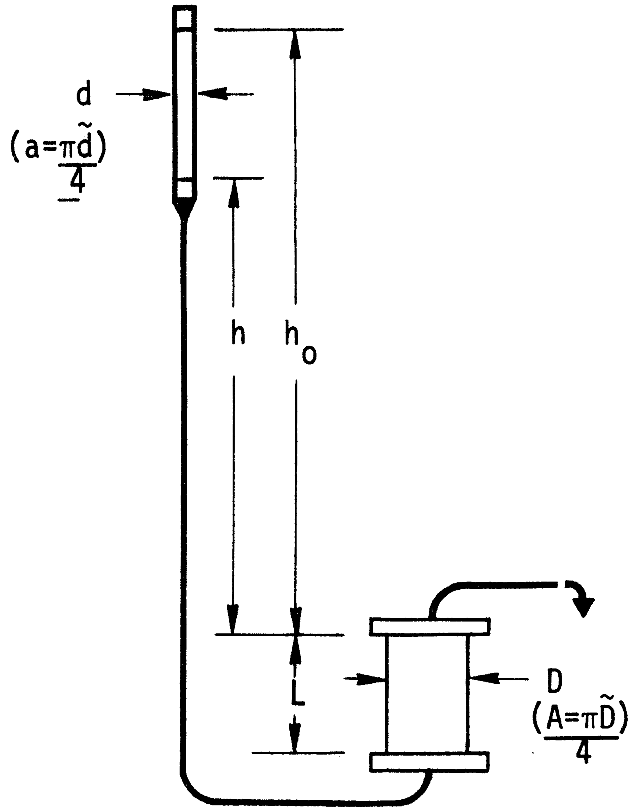


Figure 11. Variable-Head Permeameter

The equation used is:

$$k = 2.3 \frac{a\ L}{A(t_1 - t_o)} \log_{10} \left(\frac{h_o}{h_1}\right)$$

a = cross-sectional area of stand pipe (.85cm^{-2})

L = length of soil sample in permeameter (10.59cm)

A = cross-sectional area of permeameter (19.635cm^{-2})

t_o = time when water level in the standpipe is at h_o

t_1 = time when the water level in the standpipe is at h_1

h_o, h_1 = the heads between which the permeability is determined

The results of evaluating the coefficient of permeability by the use of the falling-head permeameter are given in Table 15.

Lambe and Whitman(38) have suggested that soils be classified according to their coefficients of permeability as follows:

Degree of Permeability	k (cm/sec)
High	over 10^{-1}
Medium	10^{-1} - 10^{-3}
Low	10^{-3} - 10^{-5}
Very low	10^{-5} - 10^{-7}
Practically impermeable	less than 10^{-7}

TABLE 15

PERMEABILITY BY DIRECT MEASUREMENT WITH A PERMEAMETER AND DISTILLED WATER

Test No.	Permeameter No. 1	Permeameter No. 2
	Permeability cm/sec	Permeability cm/sec
1 - R1	4.0E-6	2.3E-6
1 - R2	2.1E-6	4.0E-6
1 - R3	2.9E-6	2.3E-6
1 - R4	5.1E-6	2.6E-6
1 - R5	4.4E-6	2.4E-6
2 - R1	4.7E-6	2.8E-6
2 - R2	5.0E-6	3.1E-6
2 - R3	4.7E-6	3.1E-6
2 - R4	4.1E-6	2.4E-6
2 - R5	4.2E-6	2.4E-6
2 - R6	5.4E-6	3.3E-6
2 - R7	4.7E-6	2.8E-6
2 - R8	4.9E-6	3.0E-6
2 - R9	4.8E-6	2.9E-6
3 - R1	5.8E-6	3.7E-6
3 - R2	5.0E-6	3.0E-6
3 - R3	5.9E-6	3.9E-6
3 - R4	4.5E-6	2.8E-6
3 - R5	6.0E-6	4.1E-6
3 - R6	4.7E-6	3.7E-6

As discussed by Wu(69), the permeability coefficient is dependent to a very large extent on the size of the voids in a material, and the size of the voids is in turn largely dependent on the particle-size distribution of the soil.

Typical values of permeability coefficients from Terzaghi and Peck(61) are as follows:

Soil Types	Permeability Coefficient k (cm/sec)
Clean gravel	$1 - 10^2$
Clean sand; sand and gravel	$10^{-3} - 1$
Very fine sand; silts; mixture of sand, silt and clay; stratified clay deposits	$10^{-6} - 10^{-3}$
Homogeneous clay	10^{-7}

All indications are that the lime/soda-ash sludge has a permeability of $10^{-5} - 10^{-7}$ cm/sec, which is comparable to the range of a silt or silty clay and would be classified as having a very low degree of permeability.

V. CONSOLIDATION TESTING

The consolidation test was conducted to determine the coefficient of consolidation (c_v), and to permit the calculation of the compression index (C_c). These two coefficients are essential for use in calculations dealing with the amount and rate of settlement that can be expected from the lime/soda-ash sludge. An integral part of the consolidation test is the determination of void ratios; to further evaluate this parameter and also to confirm the coefficient of permeability as measured by the permeameter, the coefficient of permeability was calculated from this test.

The test was run on three types of samples. One consisted of the natural sludge alone, one contained 20 percent by weight of 20-30 Ottawa sand, and the third contained 40 percent by weight 20-30 Ottawa sand.

Each of the three samples was tested in the same manner. The apparatus used was a standard Karol-Warner constant-stress-load frame with a 2.5-inch floating consolidation ring. The sample to be tested was pressed into the ring, and the weight of the sample was determined. Porous stones were inserted at the top and bottom of the specimen to provide for vertical drainage of the pore water when the load was applied. Then the specimen unit was placed in the load frame, and the chamber was filled to the proper level with water. Loads of 2, 4, 8, 16, 32, and 64 psi were applied in that order. Each load was applied for 12-16 minutes, during which the changes in sample volume were recorded. This length of time was considered adequate for the completion of all primary consolidation; secondary consolidation was considered negligible.

In each of the samples containing sand, the dry weight was calculated according to known moisture content; on this basis, 20 percent and 40 percent sand was added, respectively. Then the samples were thoroughly remolded and set into the consolidation ring. Small voids were quite possibly embedded in the sample, accounting for the percentage of saturation exceeding 100 percent.

In calculating the consolidation coefficient (c_v), both the t_{50} and t_{90} values were determined, with results that appear as Method 2 (t_{50}) and Method 1 (t_{90}). A sample of the data collected and the calculation involved are included as Appendix F.

The results of the consolidation test were plotted by the square-root-fitting method and also by the log-fitting method, so that values of the time for 50 percent (t_{50}) and 90 percent (t_{90}) consolidation could be determined. The actual calculations leading to the values of the consolidation coefficient and coefficient of permeability were done on a computer. The summary data and computer printout are included as Appendix G. Data from this printout are the basis for the curves in figures 12, 13, 14, and 15, which show the relationship between the void ratio (e) and the log of the applied pressure (log p) for the different types of sludge samples.

The void ratio (e) versus log of permeability (log k) was plotted as shown in Figures 16, 17, and 18. In samples that included sand of varying amounts (Figures

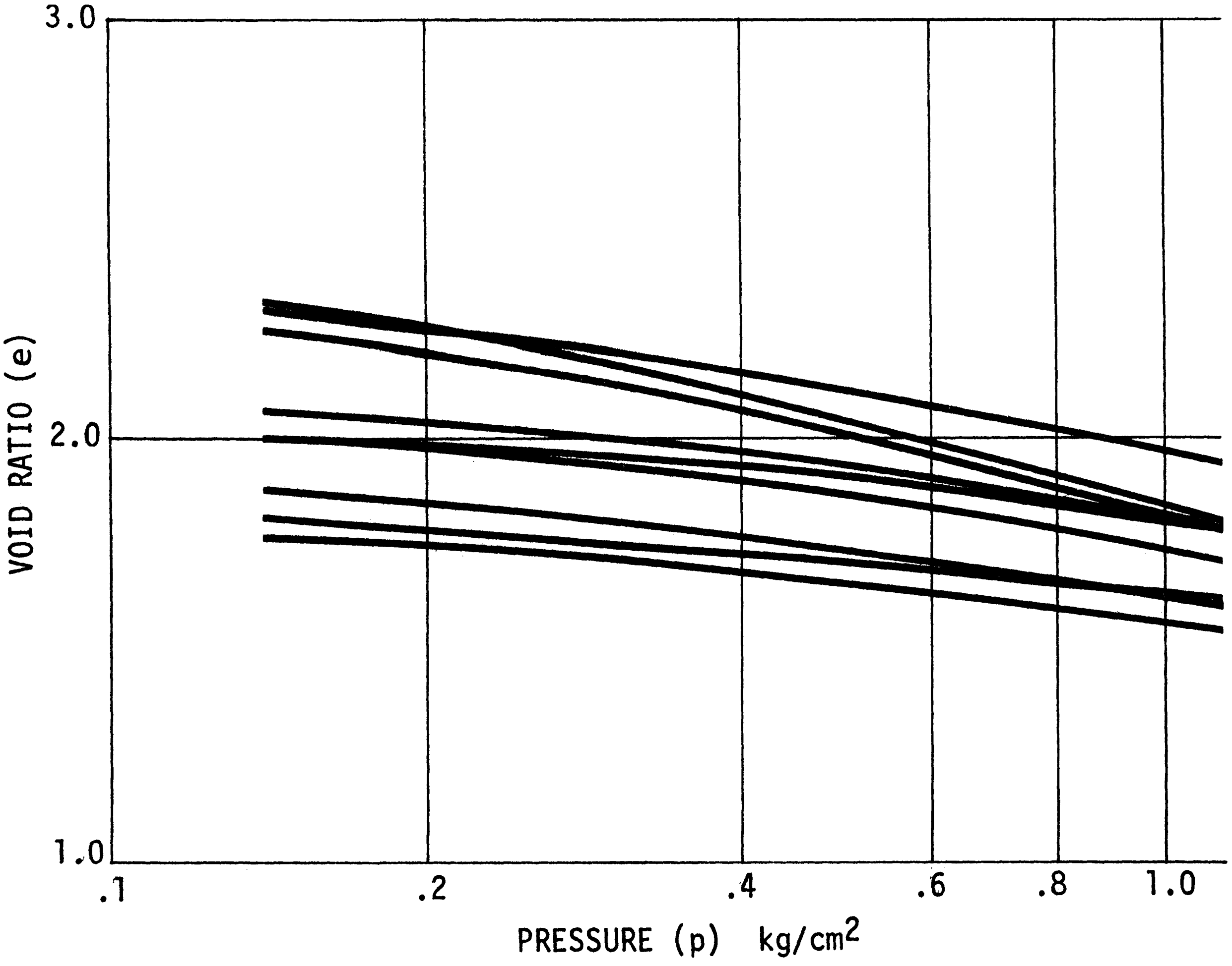


Figure 12. Void Ratio vs Applied Pressure (100% Sludge, 1st Series)

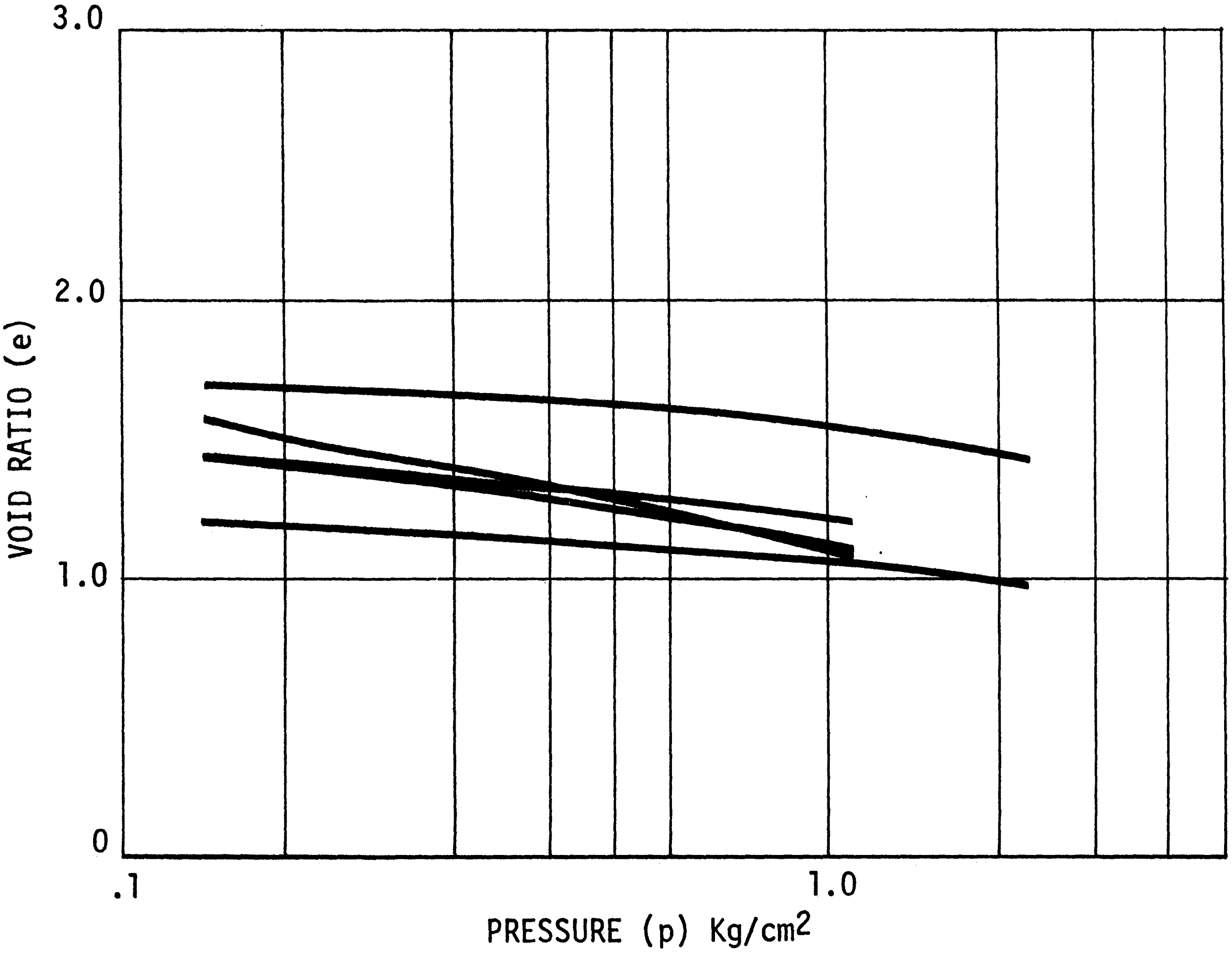


Figure 13. Void Ratio vs Applied Pressure
(20% Sand)

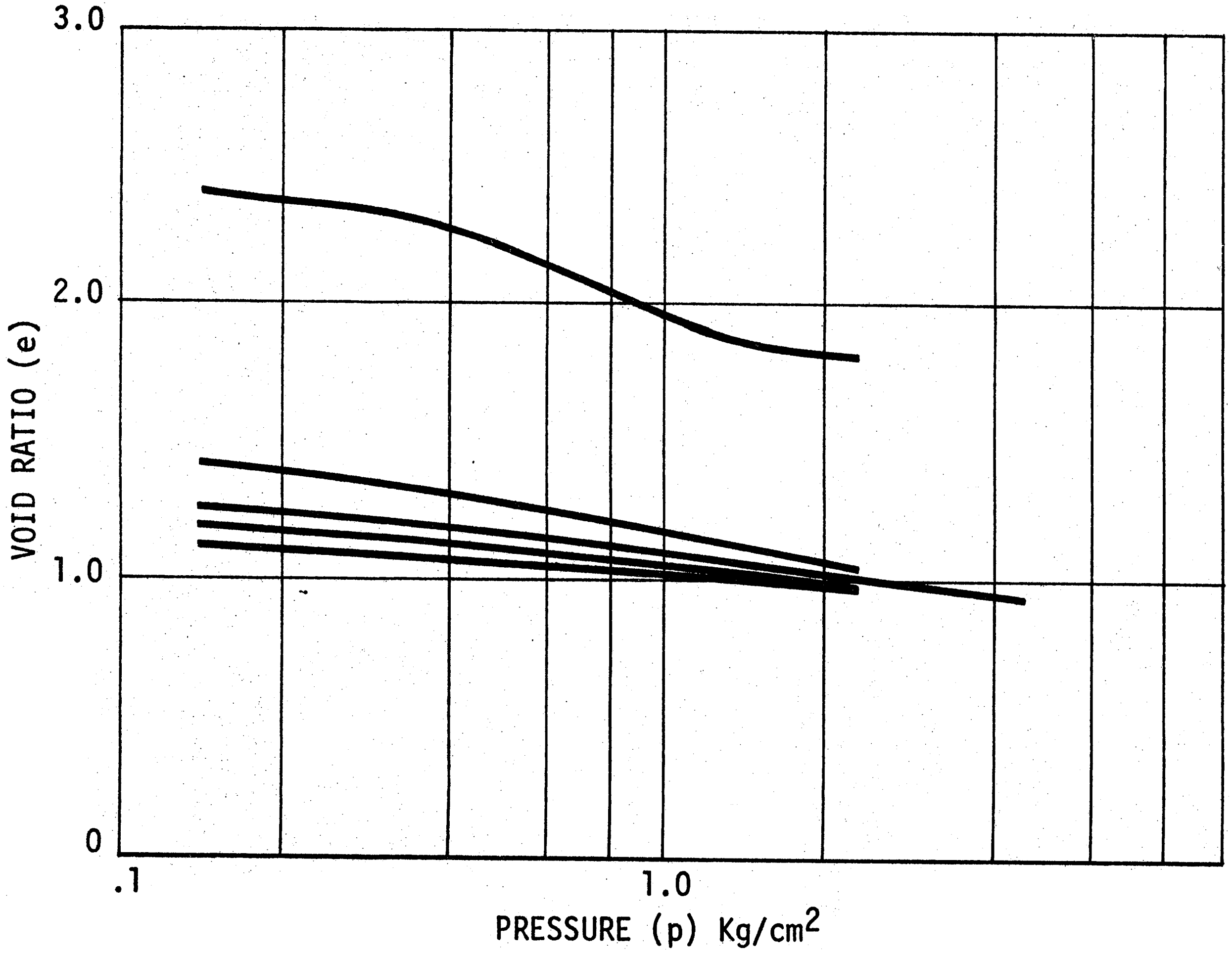


Figure 14. Void Ratio vs Applied Pressure
(40% Sand)

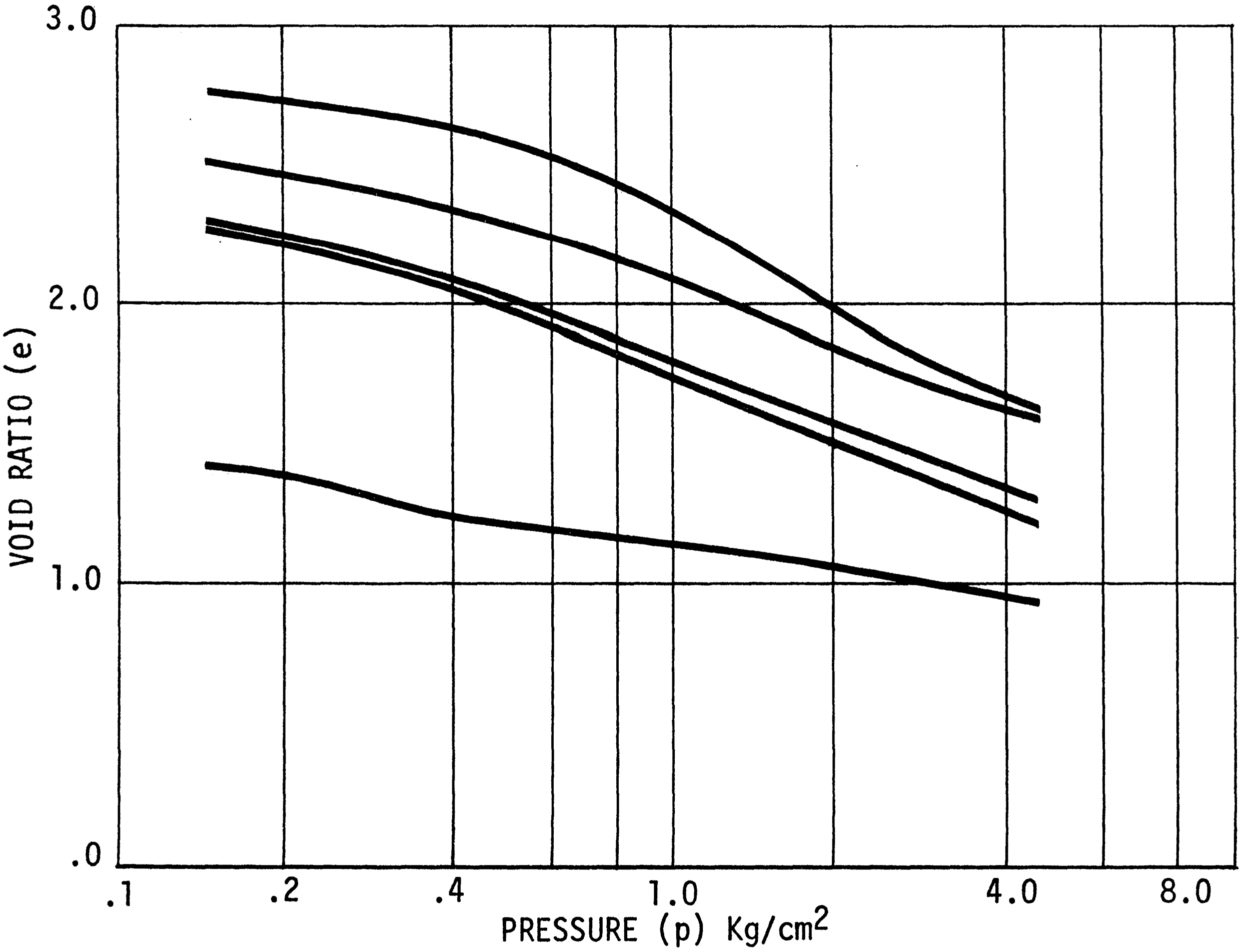


Figure 15. Void Ratio vs Applied Pressure (100% Sludge, 2nd Series)

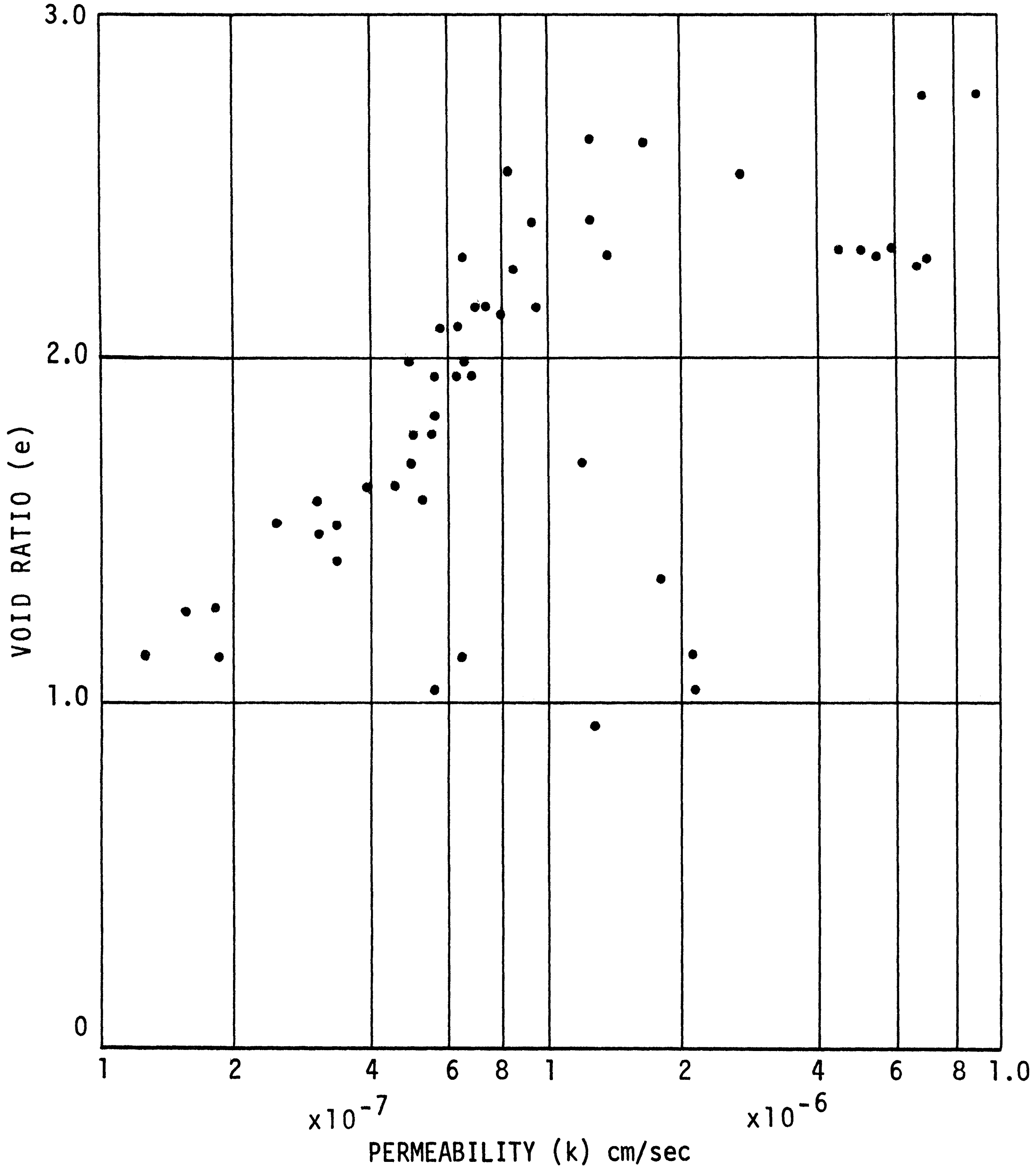


Figure 16. Void Ratio vs Permeability
(100% sludge).

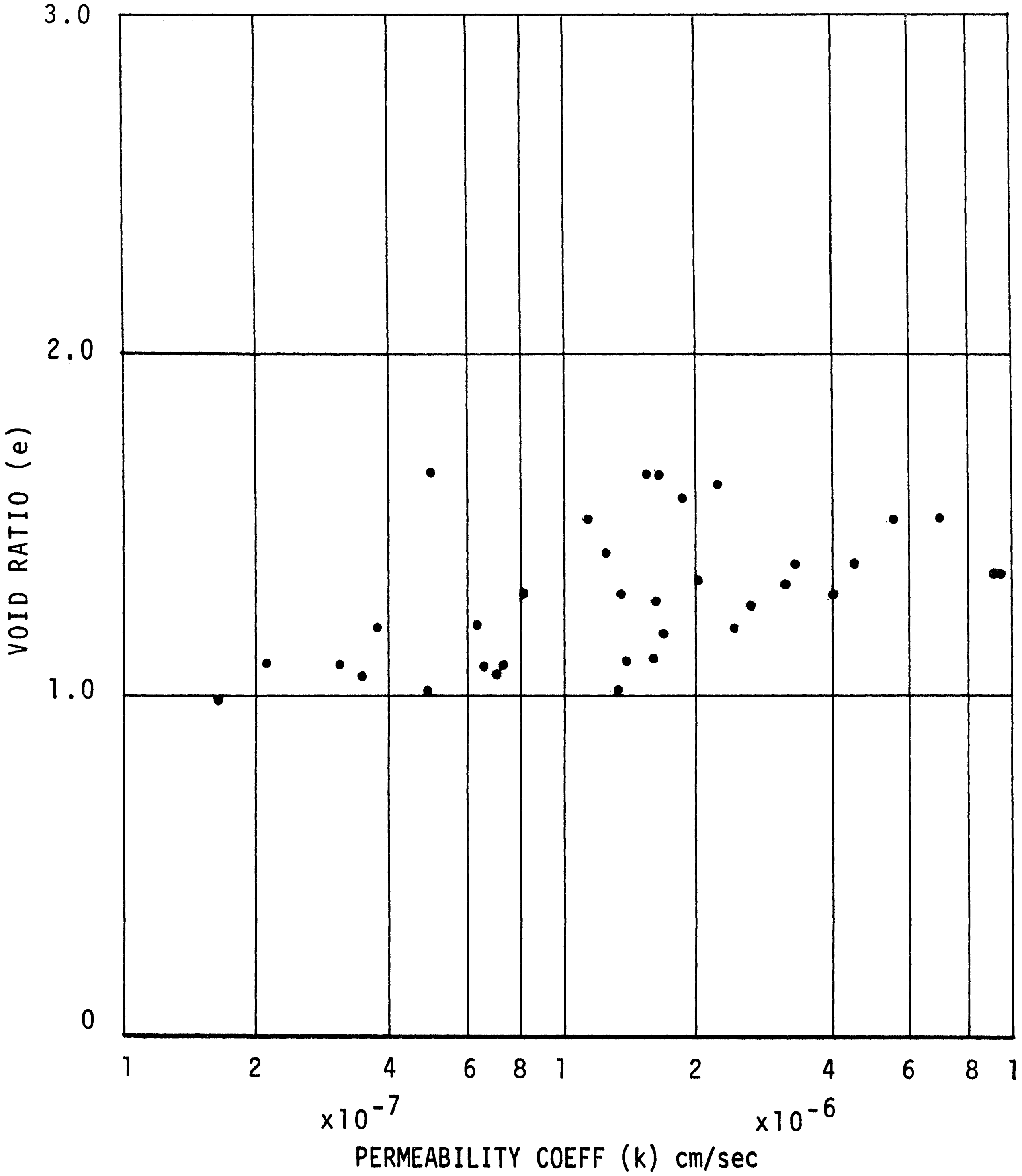


Figure 17. Void Ratio vs Permeability (20% sand).

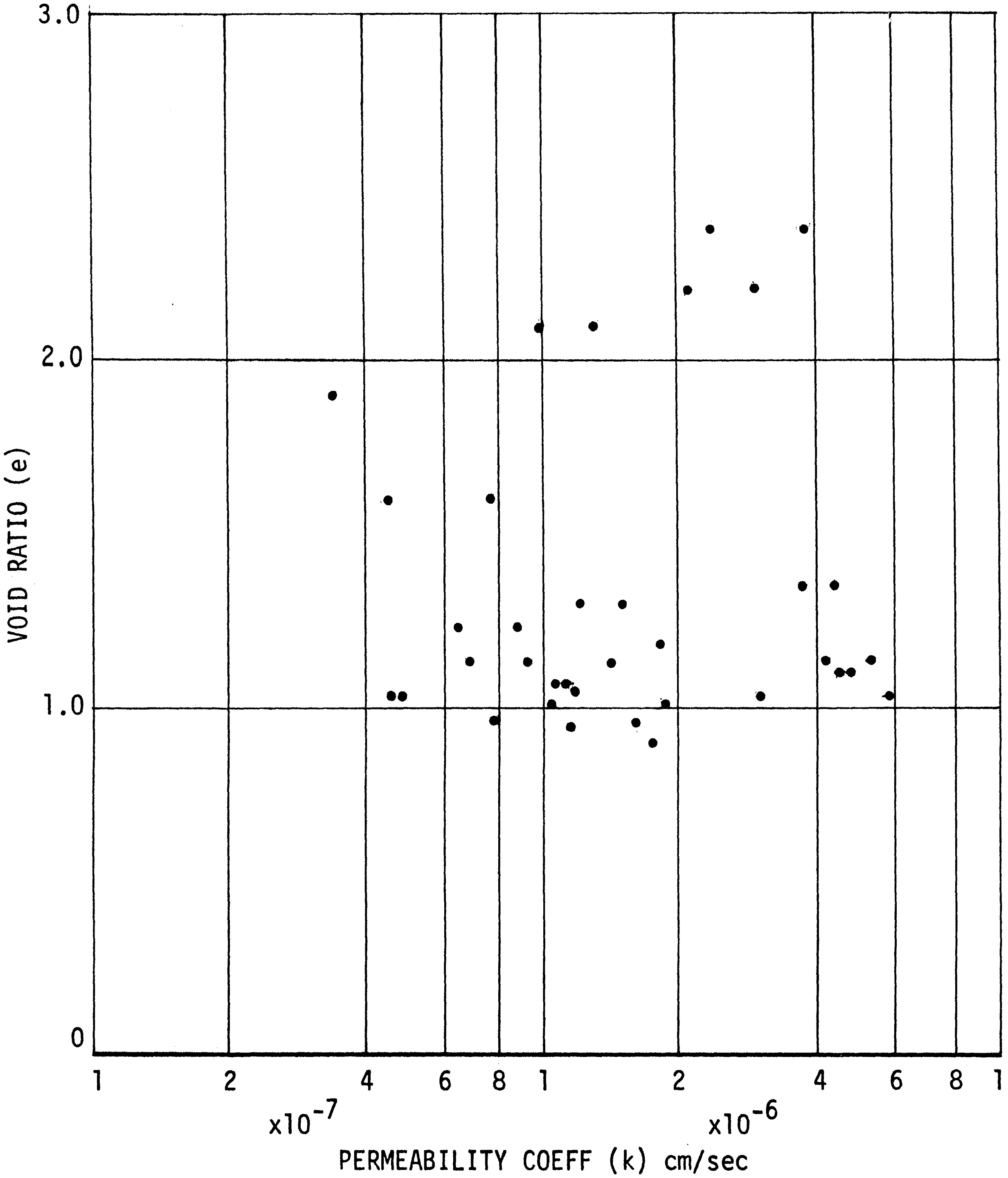


Figure 18. Void Ratio vs Permeability (40% sand).

17 and 18) there was no relationship between "e" and "log k"; and the results indicate that other factors besides the void ratio affected the permeability as different sizes of particles were combined. These other factors were particle size, composition, fabric, and degree of saturation.(38)

In the case of the pure sludge samples (Figure 16) the particle sizes were more nearly uniform, and the relationship between "e" and "log k" improved. From Figure 16, a trend develops indicating that the permeability increases as the void ratio increases.

In any material, the permeability coefficient (k) is dependent to a large extent on the size of the voids in the material. This can be carried further to say, as Wu(69) does, that the permeability coefficient is governed by the shape and size of the voids and the flow path that the water particles follow while moving through the material. By means of the Kozeny-Carmen equation, Wu relates the coefficient of permeability (k) to the void ratio (e) as follows:

$$K = C \frac{e^3}{1+e}$$

"C" is a lumped parameter which is a function of particle shape, tortuosity, and specific surface area for a given soil. Since these do not change with the void ratio, "C" is a constant.

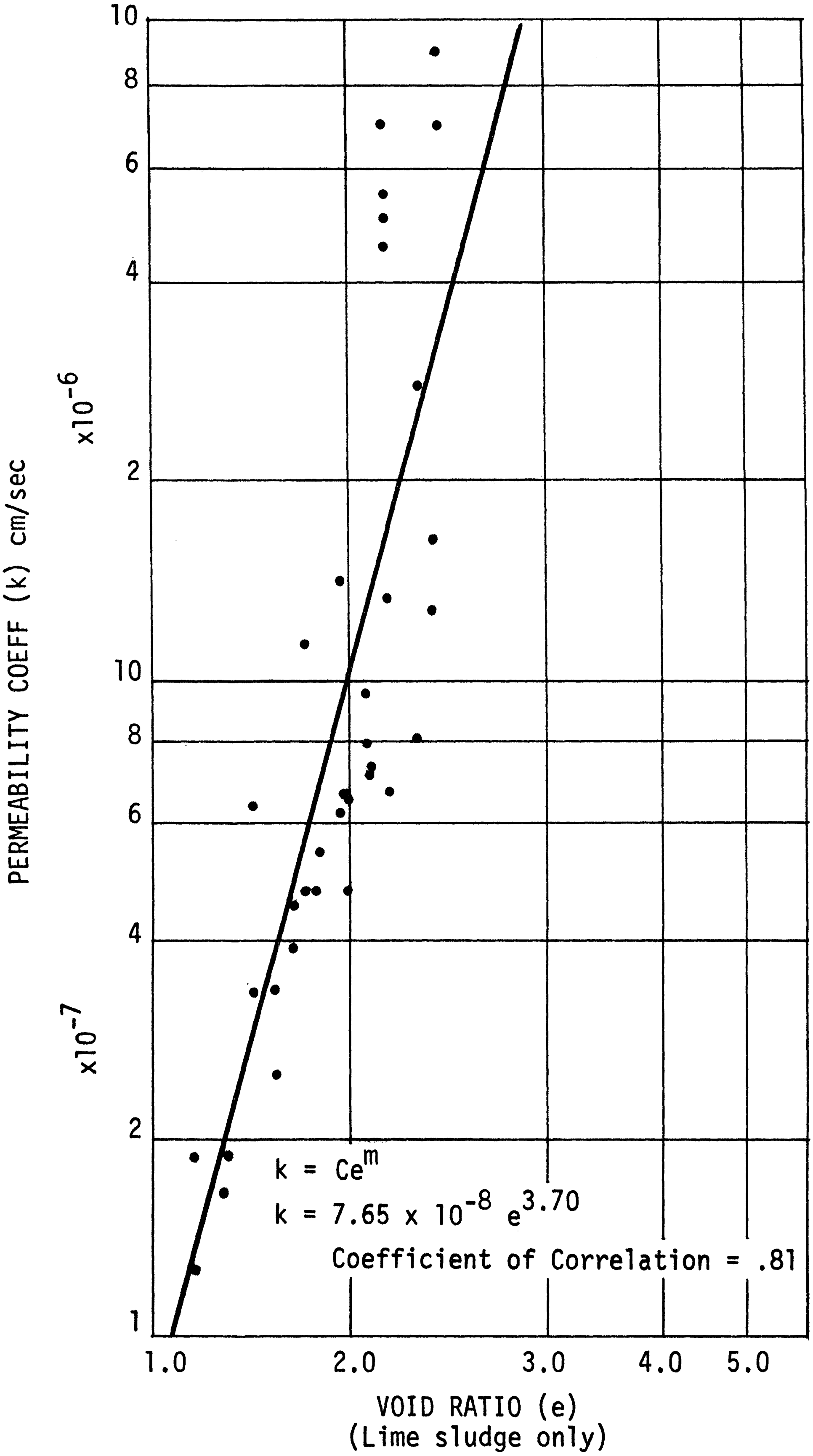


Figure 19. Relationship Between Permeability Coefficient and Void Ratio of Lime Sludge.

In order to determine "C", it is convenient to plot a linear relationship; i.e., if $e^3/1+e \simeq e^M$ then $k = C\ e^M$ and $\log k = \log C + M \log e$, which is a linear function.

To establish the relationship of the permeability coefficient (k) and the void ratio (e) in the sample of lime sludge analyzed by the consolidation test, the values of k vs e were plotted on log-log paper as shown in Figure 19. The straight line fitted to the data was determined by the least squares method, and the value of C and M are shown on the curve as well as the correlation coefficient. ($C=7.65 \times 10^{-8}$, $M=3.70$) By means of this curve, it is possible to estimate the permeability coefficient by determining the void ratio.

Pedersen(47) states that the compression index (C_c) can be computed using the relation $C_c = \frac{\Delta e}{\Delta p}$ where $\frac{\Delta e}{\Delta p}$ = change in void ratio per logarithmic cycle of stress "p".

Values of $\frac{\Delta e}{\Delta p}$ from Figures 12 through 15 result in the following:

Sample	C_c
1 (sludge only)	.280
2 (40% sand)	.0413
3 (20% sand)	.0856
4 (sludge only)	.224

Lambe and Whitman(38) list several soil types along with their compression indexes. Lime/soda-ash sludge compares with a kaolinite (C_c = .21 to .26); the more plastic soils have higher compression indexes and higher void ratios.

In the present study, when sand was added to the lime sludge, the compression index was lowered quite markedly, and the void ratio was reduced to some extent. The lime sludge alone is highly compressible—a fact that can be deduced from its small particle size, its high initial void ratio, its high natural water content, and (as shown in the consolidation test) the large change in its void ratio which occurs with loading. The high primary consolidation observed is due largely to the fact that the applied load causes pore water to be removed from the sludge.

VI. CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

Because of the compressibility of the sludge, it will consolidate when placed in a landfill. To determine the amount of consolidation expected when the sludge is deposited in a series of layers one foot thick to a total depth of six feet, with a 100 psf surcharge placed after the sludge is in place, the following numerical method is employed.

The theory of one-dimensional consolidation by vertical drainage of water is used. In this theory the primary assumptions are (a) that the soil is initially saturated, (b) the consolidation process is time dependent because of the flow of water out of the soil, (c) the water is considered incompressible as are the solid particles of the soil, (d) the coefficient of permeability and the coefficient of consolidation c_v are considered to be constant throughout the consolidation process, and (e) the soil is assumed to compress only in the vertical direction with no lateral motion of soil particles and no lateral flow of water. These assumptions are enumerated by Terzaghi.(62)

The numerical procedure is a means of substituting difference equations for the governing differential equation for consolidation as established by Terzaghi.(62) The basic ground rules for the difference equation substitution are given by Richart.(53) In this computation the value of A = 1/2 was used which provides the fastest convergence of the solution.(53)

$$A = \frac{c_r \Delta t}{\Delta Z^2}$$

Z = distance below the top surface of a layer

t = time

Each layer was considered to be placed in its one foot thickness instantaneously and to be saturated instantaneously. When these conditions were met then the time rate of consolidation was calculated by the numerical procedure. Thus the initial pore pressure distribution in each layer varied from 0 at the top surface to 24 lbs/sq.ft. at the bottom surface. (Bouyant weight of sludge equals 24 pcf.) The first layer placed was considered to rest upon sand which provided a drainage surface. Therefore this layer drains both top and bottom and H = 1/2 ft. The second layer is assumed to be added instantaneously to the first layer at the end of one day. The second layer eliminates a drainage surface at elevation of 1 foot and now the two drainage surfaces are at elevation 0 and elevation 2ft. Therefore H = 1 ft. for this part of the problem. Initial pore pressure for the 2 ft. total thickness is now 0 at the top varying to 24 lbs/sq.ft. at elevation of 1 ft. and varying in the bottom 1 ft. by 24 lbs. plus whatever residual pore pressure was left at the end of one day. Each succeeding layer added 24 lbs/sq.ft. to the entire thickness of soil below and the top layer had a pressure variation from 0 to 24.

The numerical procedure permits a change in pressure conditions within a given layer at any instant of time and it also permits a change in total thickness of all the layers at any instant of time. Therefore it is quite applicable to this problem of superposing layers of saturated material. After the six layers and the 100 lb/sq.ft. surcharge have finally been applied, then of course the numerical procedure permits calculation of the dissipation of pore pressure with time. The time required for 90% consolidation under the final condition should be quite similar to the time determined from the trapezoidal loading [T_v = .85.$^{(44)}$]

The calculations necessary to determine the consolidation of 6-1 foot layers of sludge each deposited on the other at the end of one day with a final surcharge of 100 psf put in place at the end of six days as described above were carried out. All the steps of the calculations and the resulting curves are provided in Appendix H.

The results were as follows:

All calculations are based on the sludge having the following characteristics:

Moisture content $w = 120\%$ on dry weight basis
Specific gravity $G_s = 2.35$
Initial void ratio $e_o = 2.80$
Compression index $C_c = 0.28$
Consolidation coefficient $c_v = 5.0 \times 10^{-3} cm^2/sec$
Wet weight of sludge = 85 pcf
Bouyant weight of sludge = 24 pcf

Note: c_v for all samples were within one order of magnitude of one another with a typical value of 5.0×10^{-3} cm/sec (1.93×10^{-2} ft^2/hr)

TABLE 16

CONSOLIDATION OF LAYERED SYSTEM

No. of the one foot layer placed at end of 24 hr.*	Pore Pressures σ avg $\#/ft^2$	Pore Pressures σ avg Kg/cm^2	Compression Δ(inches)
VI	10.9	.055	1.17
V	127.8	.064	1.23
IV	148.8	.074	1.29
III	172.8	.086	1.36
II	199.8	.100	1.45
I	229.0	.115	1.55
			8.05"

*100 psf surcharge placed 24 hours after the sixth sludge layer was placed.

The method and calculations used in this method along with the resultant curves showing the pore pressures in the increasingly deeper sludge as each additional layer is placed are shown in Appendix H.

As formulated by Richart(53)

$\Delta T_v = A\ (\Delta\xi)^2 \qquad A = 1/2$

$\Delta T_v = 1/2\ (\Delta\xi)^2$ for 6 foot depth $\Delta\xi = 1/3$

$\Delta T_v = .0555$

The number of .0555 time intervals "n" required to result in 90% consolidation in the six layered sludge was found to be 19

$$n\Delta T_v = T_v \quad = \quad 19 \times .0555 = 1.05$$

Solving for "n" in the equation as stated by Richart$^{(53)}$)

$$n = \frac{C_v \cdot t_{24}}{H^2 \quad \Delta T_v}$$

$$n = \frac{.019 \times 24}{3^2 \times .0555} \quad = \quad .915 \text{ days/increment}$$

.915 x 19 increments = 17 days plus 6 for placement, a total of 23 days to achieve 90% consolidation. As a means of relating consolidation of the 6 feet of layered sledge with time, Figure 21 was compiled using average values.

Considering the 6 feet of saturated sludge to be placed in a trench all at once and then loaded with a surcharge equal to 100 psf the following consolidation calculations would result.

γ' = bouyant weight of sludge = 24 pcf

H = 3 feet

P_o = 3 x 24 = 72 psf plus 100 psf = 172 psf

= .086 kg/cm^2

from Figure 20 e = 2.36

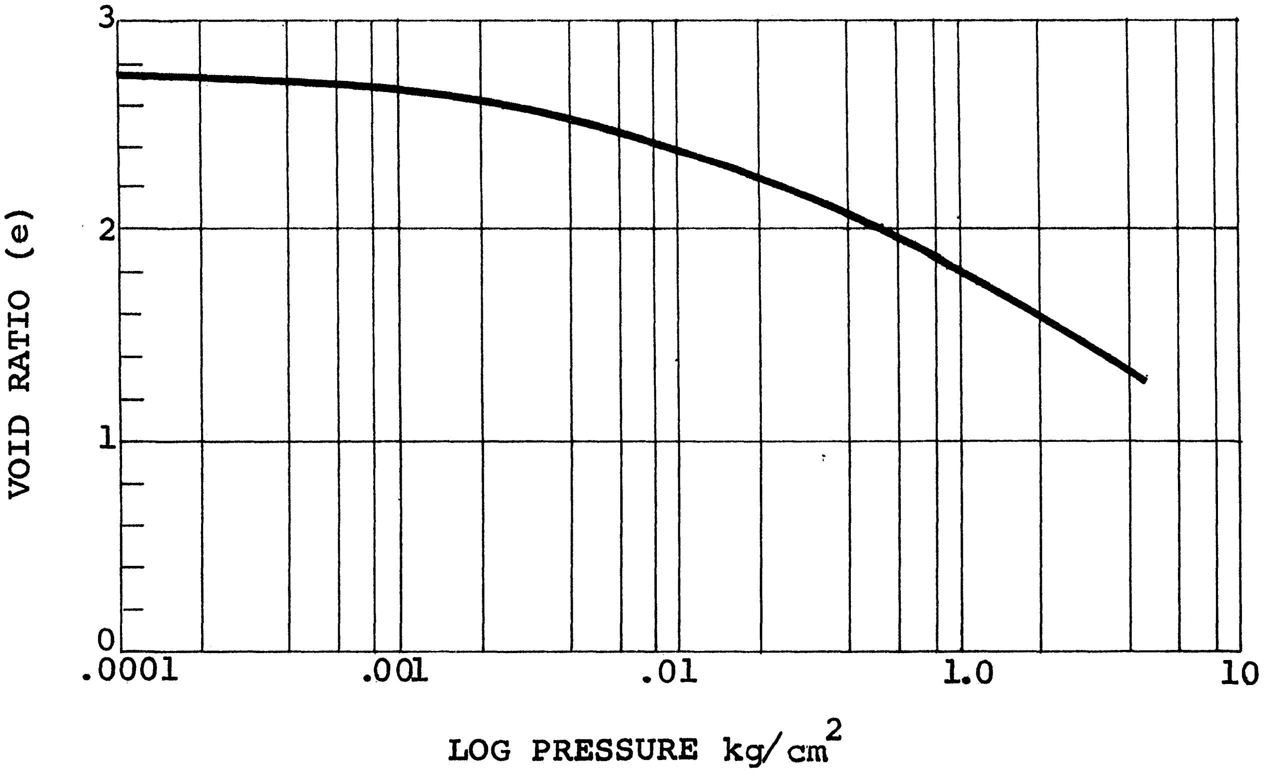


Figure 20. Typical Void Ratio vs. Pressure (100% sludge)

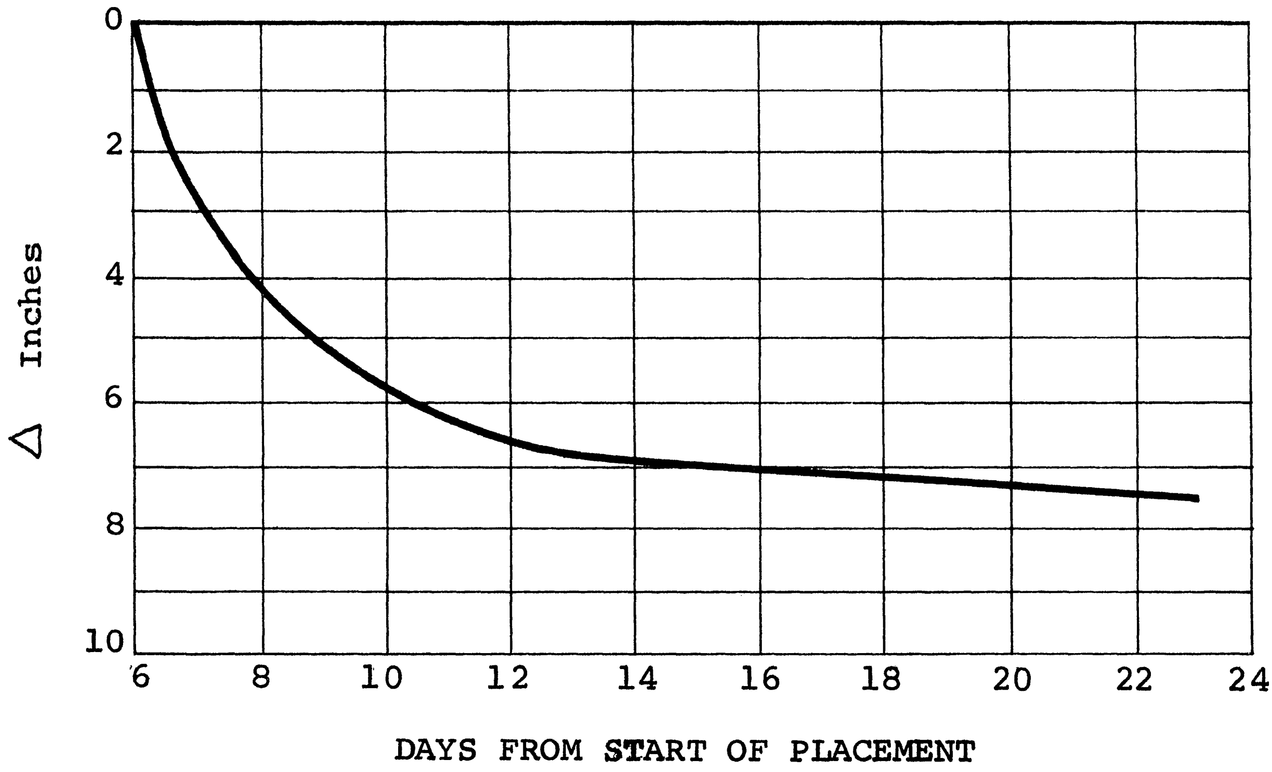


Figure 21. Consolidation vs. Time for 6 Feet of Sludge in One Foot Layers w/100 psf Surcharge

$$\Delta = \frac{\Delta e}{1+e_o} \text{ x } 2H \qquad \frac{2.80-2.36}{3.80} \text{ x } 72 = \underline{8.15}$$

which compares well with that calculated by the layered method. Time required for 90% consolidation assuming two way vertical drainage [T_v = .85 from (44)]

$$t = \frac{T_v \cdot H^2}{C_v \cdot 24} = \frac{.85\text{x}9}{.019\text{x}24} = \underline{17 \text{ days}}$$

The settlement which does occur will take place within a relatively short time. This means that most of the settlement will be accomplished while the landfill is still being worked so that regrading can be carried out if necessary.

VII. THE TRIAXIAL TEST

The same method is used for preparing sludge samples for the triaxial test and for determining the relationship between moisture content and density. The samples were compacted by impact compaction,the compactive effort used was equivalent to that in the modified AASHO test. This differed from the standard method only in the use of a smaller compaction mold and a smaller number of lifts. The mold used was 1-3/8 inches in diameter and 2-3/4 inches long. Each sample was compacted in three lifts with 25 blows of the hammer per lift. Sludge samples with various moisture contents were compacted following this standard procedure and their weight and moisture content determined.

The resulting curve in Figure 22 shows the relationship of the dry density vs moisture content, and indicates the optimum moisture content (corresponding to maximum density) of the sludge. [All moisture contents are figured on a dry-weight basis.] Sample data from this test are given in Appendix E.

The same steps described above are used to prepare samples with known moisture content for use in the triaxial test. Compacted material was used for this test because any sludge material to be used for an embankment will require compaction; it cannot be simply received and dumped.

The samples were tested in a Geonor-AS triaxial testing apparatus. As the tests were being conducted, the samples were consolidated and drained. A porous stone placed at the base of the sample helped to provide for drainage. Lateral drainage through the sides of the specimen was provided for by a slotted filter paper enclosure which completely encircled the specimen. Two very thin rubber membranes lubricated by stopcork grease were placed over the package (sample plus drainage provisions), and were held in place by rubber "O" rings. [Two membranes were used instead of one so as to avoid rupture.] After the membranes had been sealed in place, the triaxial chamber was closed, filled with water, and put under the desired confining pressure. This provided for pre-consolidation of the sample.

Modified American Association of State Highway Officials

Description: Light Gray Silt
Optimum Water Content: 32.0%
Maximum Density: 81.0 pcf

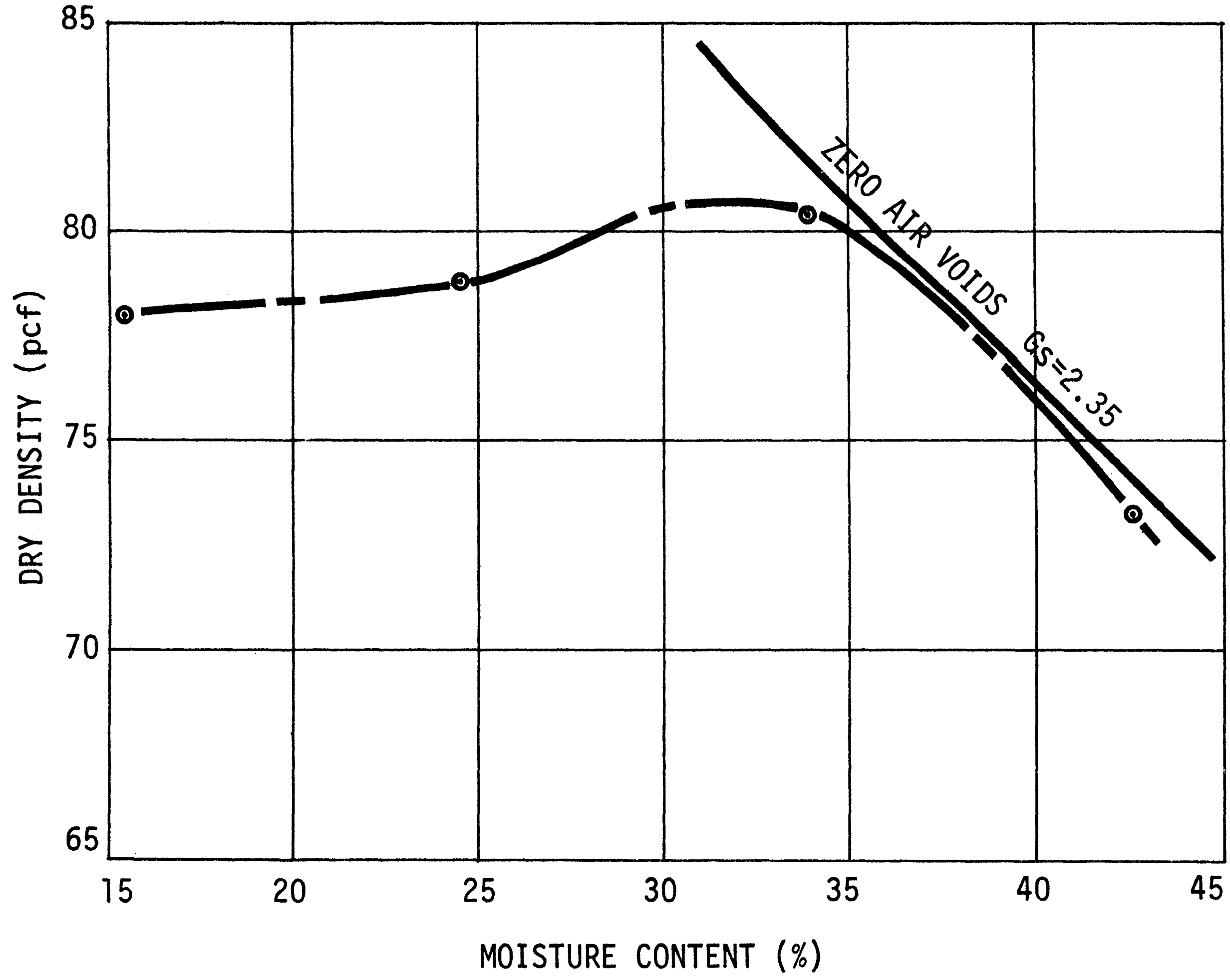


Figure 22. Dry Density of Sludge vs Moisture Content

On the basis of the results of the consolidation test, the time required for complete primary consolidation was less than 1/4 hour. To insure complete pre-consolidation under triaxial test conditions, the samples were subjected to the various confining pressures and held for 1 hour before the triaxial test was started. The confining pressures of 10, 20, and 30 psi were chosen because they compare roughly to 10, 20, and 30 feet of normal soil, and the lime sludge is likely to be subject to them in an embankment or a trench. After the pre-consolidation was completed, the triaxial test was carried out on each of the specimens.

Following the working rule stated by Bishop and Henkel(9), the strain rate (application of load) was set such that at failure at least 95% degree of consolidation would have developed. Readings were taken of the deflection and the load applied to failure. These data are also included in Appendix I.

Six different triaxial tests were conducted. Two different moisture contents (≈21% and ≈31%) were used; determinations for samples of this sludge showed optimum moisture to be ≈32%. Three confining pressures were used for each of the two levels of moisture content. After the tests were completed, the sample was observed for failure characteristics, and its moisture content was determined for use in subsequent calculations.

VIII. DETERMINATION OF COHESION AND ANGLE OF INTERNAL FRICTION

The p-q diagram described by Lambe and Whitman(38) was used to plot the results of the triaxial test. The points give a value for p and q corresponding to the peak values of maximum stress sustained before failure. The required calculations are as follows:

$$q = \frac{\sigma_1 - \sigma_3}{2}$$

$\sigma_1 = \sigma_3$ + stress difference as measured from the results of the triaxial test. It is the dial load converted to stress.

σ_3 = confining pressure.

$\sigma_1 - \sigma_3$ = stress difference, some times referred to as the normal stress.

$$p = \frac{\sigma_1 + \sigma_3}{2} = \frac{\text{stress difference plus } 2\sigma_3}{2}$$

$$= \frac{(\sigma_1 - \sigma_3) + 2\sigma_3}{2}$$

σ_3 varies according to values of confining pressure

10 psi = .703 kg/cm^2

20 psi = 1.406 kg/cm^2

30 psi = 2.109 kg/cm^2

Moisture Content ≈21%

Sample No.	σ_3 (kg/cm^2)	(Dial reading at failure converted to) Stress difference $(\sigma_1-\sigma_3)$	(q) $(\frac{\sigma_1-\sigma_3}{2})$	$(\sigma_1-\sigma_3)+2\sigma_3$	(p) $\frac{(\sigma_1-\sigma_3)+2\sigma_3}{2}$
7	.703	5.56	2.78	6.966	3.483
1	1.406	8.095	4.05	10.907	5.453
2	2.109	9.306	4.65	13.524	6.762

Moisture Content ≈31%

Sample No.	σ_3 (kg/cm^2)	(Dial Reading) Stress difference $(\sigma_1-\sigma_3)$	(q) $(\frac{\sigma_1-\sigma_3}{2})$	$(\sigma_1-\sigma_3)+2\;_3$	(p) $\frac{\sigma_1+\sigma_3}{2}$
5	.703	6.25	3.13	7.656	3.828
6	1.406	7.41	3.70	10.222	5.111
4	2.109	8.37	4.18	12.588	6.294

The data in these calculations are plotted in Figures 23 and 24.

These calculations allow the values of c (cohesion) and Φ (angle internal of friction) to be computed as shown, giving values for:

21% moisture (below optimum moisture) c = 1.595 kg/cm^2
Φ = 28.6°

31% moisture (approx. optimum moisture) c = 1.645 kg/cm^2
Φ = 24.3°

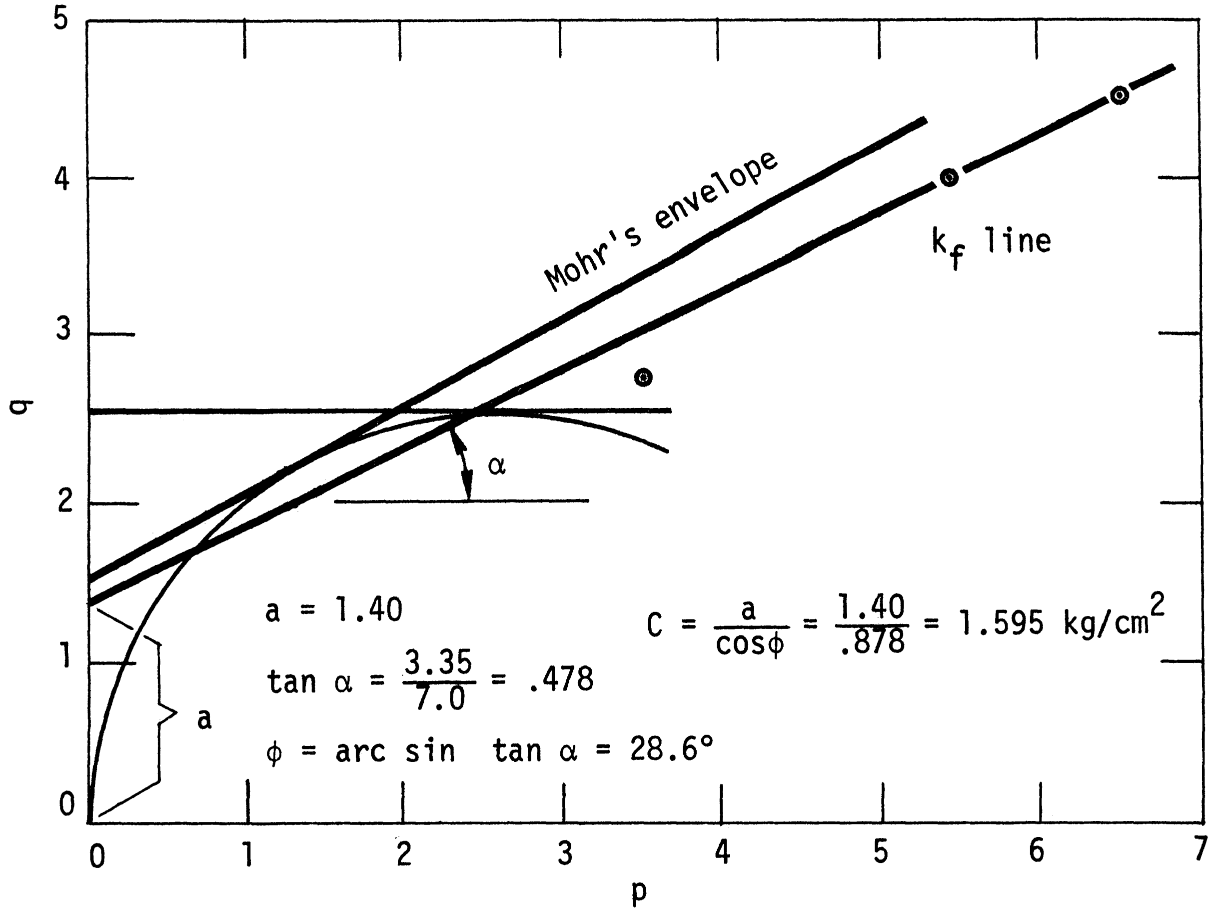


Figure 23. q vs p Diagram Showing Mohr's Envelope (21% moisture).

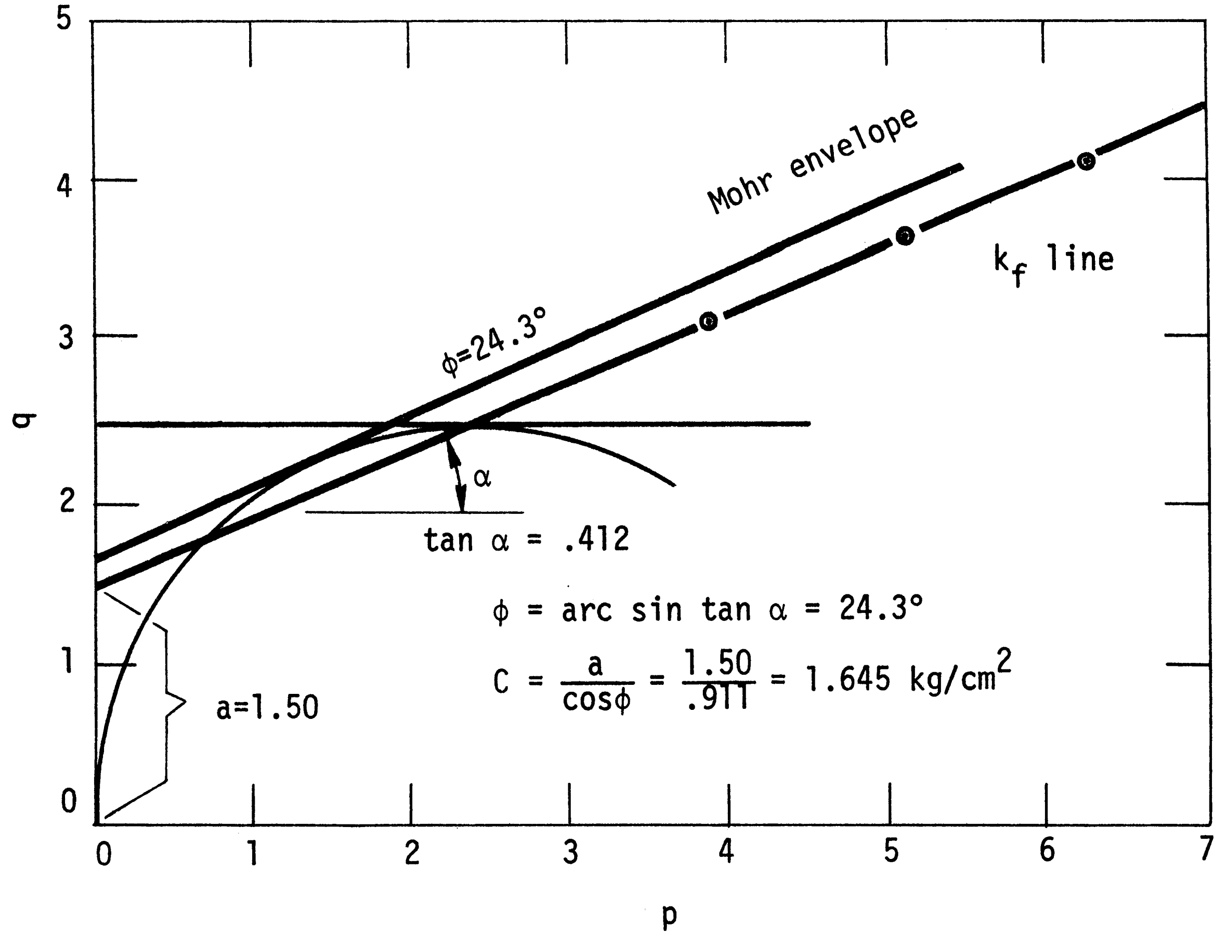


Figure 24. q vs p Diagram Showing Mohr's Envelope (31% Moisture).

Lambe & Whitman(38) summarize friction angles for various soil classifications and show that for design purposes, silt (non-plastic) has a Φ ranging from 26° - 30° at ultimate strength. The values determined from the present research compare very well with these observed values.

It should be noted that the strength parameter obtained from the triaxial test was obtained at nearly optimum moisture content and maximum dry density. Values developed in the field would be somewhat lower, with an upper limit being a relative compaction of perhaps 90% of maximum dry density. As seen in Figure 22, at moisture contents below optimum, the dry density is relatively insensitive to moisture content. At moisture contents above optimum, however, the density falls off rather sharply. In the triaxial test, shear-strength parameters were developed for samples molded at or near the optimum moisture content and on the dry side of optimum. Since the shear strength of sludge on the wet side of optimum was clearly low, samples were molded at 31% and ≈21% moisture figures cited earlier.

IX. EMBANKMENT CALCULATIONS

Lambe(38) suggests as a rule of thumb that it is unwise to use material for diking purposes at a slope (angle of inclination) higher than the effective angle of internal friction. (Assuming no cohesion.) In the case of lime sludge (assuming no cohesion and no seepage), this would limit an embankment to something less than a slope of 24°. But the lime sludge overcomes these limitations because it shows considerable cohesion. The following computations illustrate the slope stability of this material, and indicate possible slope heights when it is used as an embankment.

These computations are based on the results of the triaxial tests, which showed the lime sludge to have an angle of internal friction (Φ) of from 24° to 28° and a cohesion value of about 1.6 kg/cm^2 (3260 psf). The wet density of the sludge was 107 pcf (γ_w).

The stability factor N_s is a function of β the slope angle and Φ the angle of internal friction.(61) It is calculated according to the equation:

$$N_s = \frac{\gamma H_c}{c}$$

where γ = unit weight
H_c = critical slope height
c = cohesion

On the bases of curves from Terzaghi and Peck(61), these results are obtained:

$\Phi = 25°$
C = 3260 psf
γ_a = 107 pcf
F.S. = 1

$$H_c = \frac{N_s C}{\gamma}$$

$\Phi = 20°$
C = 3260 psf
γ_w = 107 pcf
F.S. = 1

β	N_s	H_c
50°	15	460
60°	12	360
70°	9.5	290
80°	7.5	230

β	N_s	H_c
50°	13.5	410
60°	10	300
70°	8.5	260
80°	6.5	200

It should be noted that at a safety factor of one, the heights H_c cited above are critical (impending failure). In practice, a safety factor of more than one should be used. A safety factor of two on the cohesion would reduce the H_c by 1/2. Since the above values are based on compacted sludge with nearly optimum moisture content, they are somewhat higher than the values resulting from the usual degrees of compaction in the field.

Another consideration is relative to the use of lime/soda-ash as an embankment: that is the performance of the material upon sudden drawdown or seepage. According to Lambe(38), for dry or completely submerged slopes in cohesionless soils, the factor of safety is

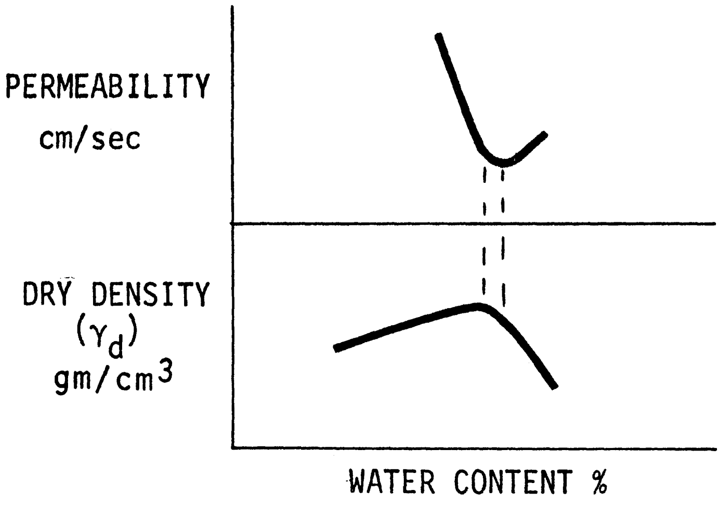
$$(F.S.) = \frac{\tan \Phi}{\tan \beta}$$

where Φ is the effective angle of internal friction and β is the angle of inclination of the slope of the embankment.

If sudden drawdown occurs, the safety-factor equation is modified by the ratio of the buoyant unit we weight over the total unit weight

$F.S. = \frac{\gamma b}{\gamma t} \frac{\tan \Phi}{\tan \beta}$. For most soils $\frac{\gamma b}{\gamma t} = 1/2$; but for lime sludge, $\frac{\gamma b}{\gamma t} = \approx 2/5$. The foregoing is cited merely to show how pore water pressure and seepage will reduce the safety factor in stability analysis. Due to small particle size, the surface of the sludge should be protected from erosion if this material is used in an embankment.

The line/soda-ash sludge can also be used as an impervious core for an earth-fill embankment. In this application, the sludge would be compacted during placement; therefore its impermeability would be improved. Experience has shown that for maximum reduction in the permeability of clayey silts(38), the material should be compacted just slightly on the wet side of the optimum moisture. A schematic illustration of this is given in Figure 25. By such a change in moisture, the permeability can be reduced by one order of magnitude.



FROM LAMBE AND WHITMAN (38)

Figure 25. Typical Water Content of Compacted Sludge vs Dry Density and Permeability.

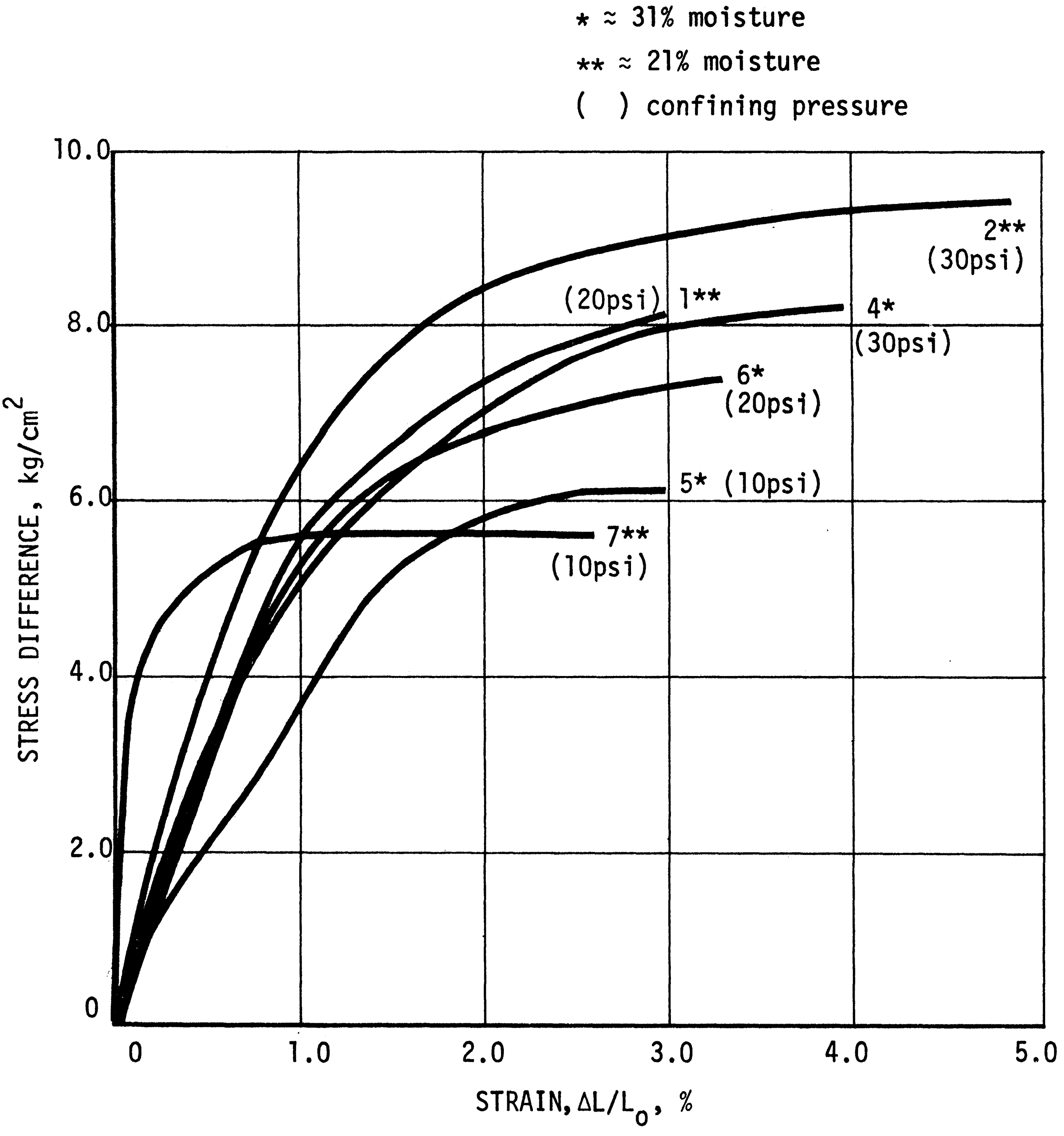
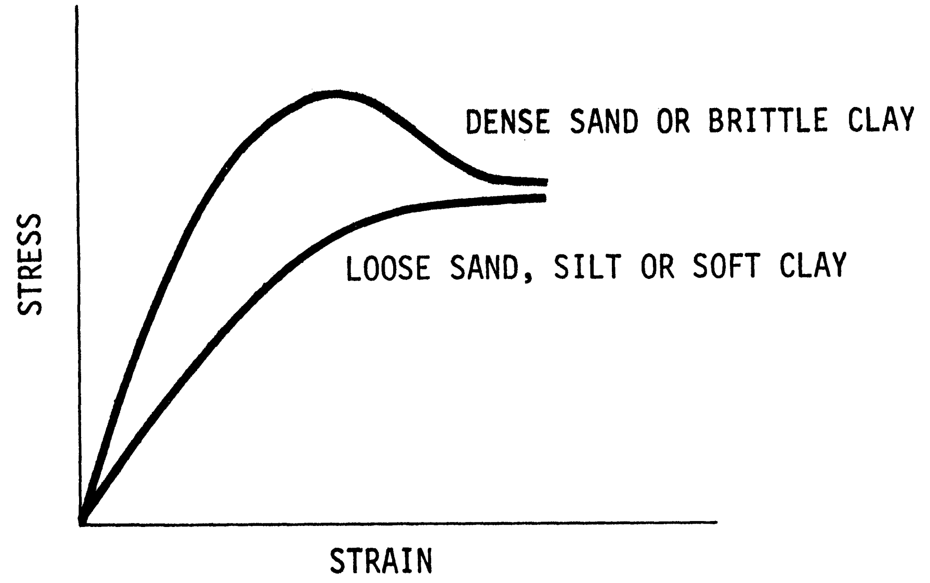


Figure 26. Stress Difference vs Strain.

In order to support earth-moving equipment, the moisture content of the sludge must not be high enough to prohibit compaction. The optimum content to produce maximum density is about 32 percent moisture on a dry-weight basis or 24.2 percent on a wet-weight basis. It has been shown elsewhere in this study (Table 19) that sludge with a moisture content on a wet-weight basis of 35-40 percent can be handled and worked with earth-moving equipment. Therefore one can reasonably expect to accomplish an improvement in permeability when the lime sludge is used as a core material in an embankment.

The curves in Figure 26 showing stress difference vs strain are characteristic of curves for silt and soft clay rather than curves for dense sand and brittle clay. This is shown schematically in Figure 27.



FROM LAMBE & WHITMAN (38)

Figure 27. Typical Stress-Strain Relationship for Certain Materials.

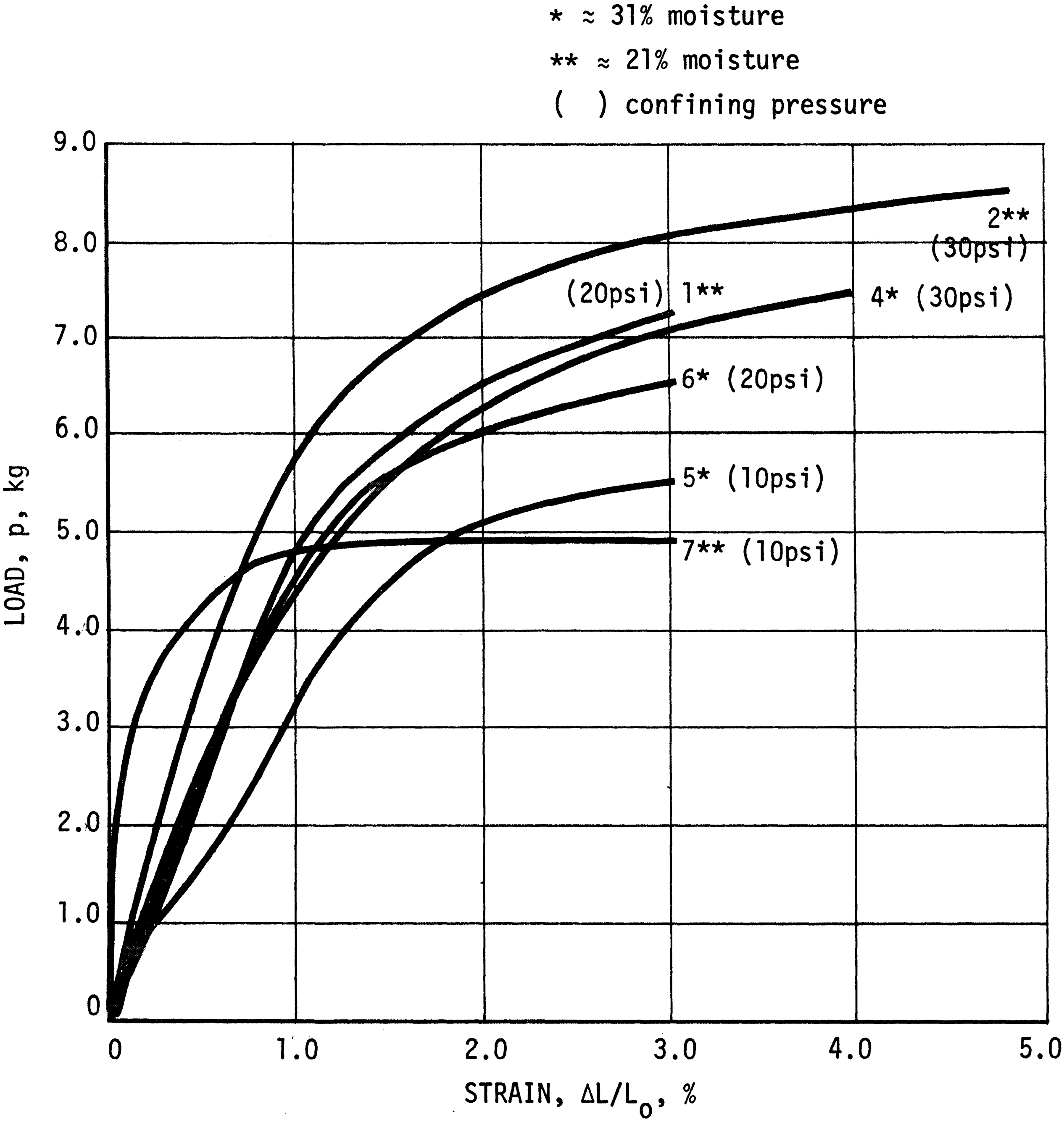


Figure 28. Load vs Strain.

As shown in Figure 26, the maximum stress is mobilized at a strain of ≈2 percent, and failure occurs in a range of from 3 to 5 percent. Since the failure is a fracture-type failure and a definite fracture plane develops in each case, the lime sludge is shown to be much less plastic than a normally consolidated clay.

As might be expected, the load vs strain relationship is improved by increasing the confining pressure. This is shown in Figure 28.

Wu(69) shows that the failure angle in the triaxial test (α) is $\alpha = 45° + \frac{\Phi}{2}$. Measurement of the failure plane of samples from the triaxial test in the present study shows $\alpha \approx 60°$, as shown in Figure 29.

This suggests that the Φ of these samples should be in the order of 30°; they are 24° and 28°.

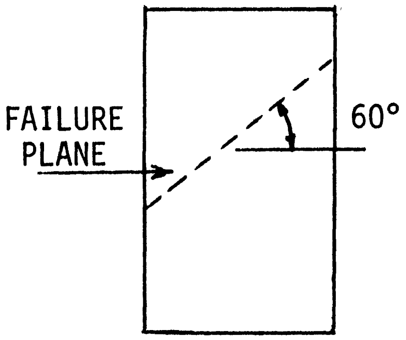


Figure 29. Typical Failure Plane of Triaxial Test Specimen.

The bulk density of the wet sludge was determined on samples as taken from the lagoon by the tubular sampler: the results are given in Table 17.

TABLE 17

BULK DENSITY OF LIME SLUDGE

Sample	Bulk Density (pcf)
1	90.4
2	98.0
3	95.0
4	96.5

The mean value is 95.0 pcf. On this basis the specific gravity of the wet sludge is 1.52. As mentioned elsewhere in the present study, the moisture content ranges from 44 percent to 54 percent on a wet-weight basis.

Samples of the wet sludge as taken by the tubular sampler were analyzed for their volatile content as a measure of the amount of carbon and organics present. The results are given in Table 18.

These findings identify the sludge as a relatively light-weight material, and one which contains very little in the way of organic material.

TABLE 18

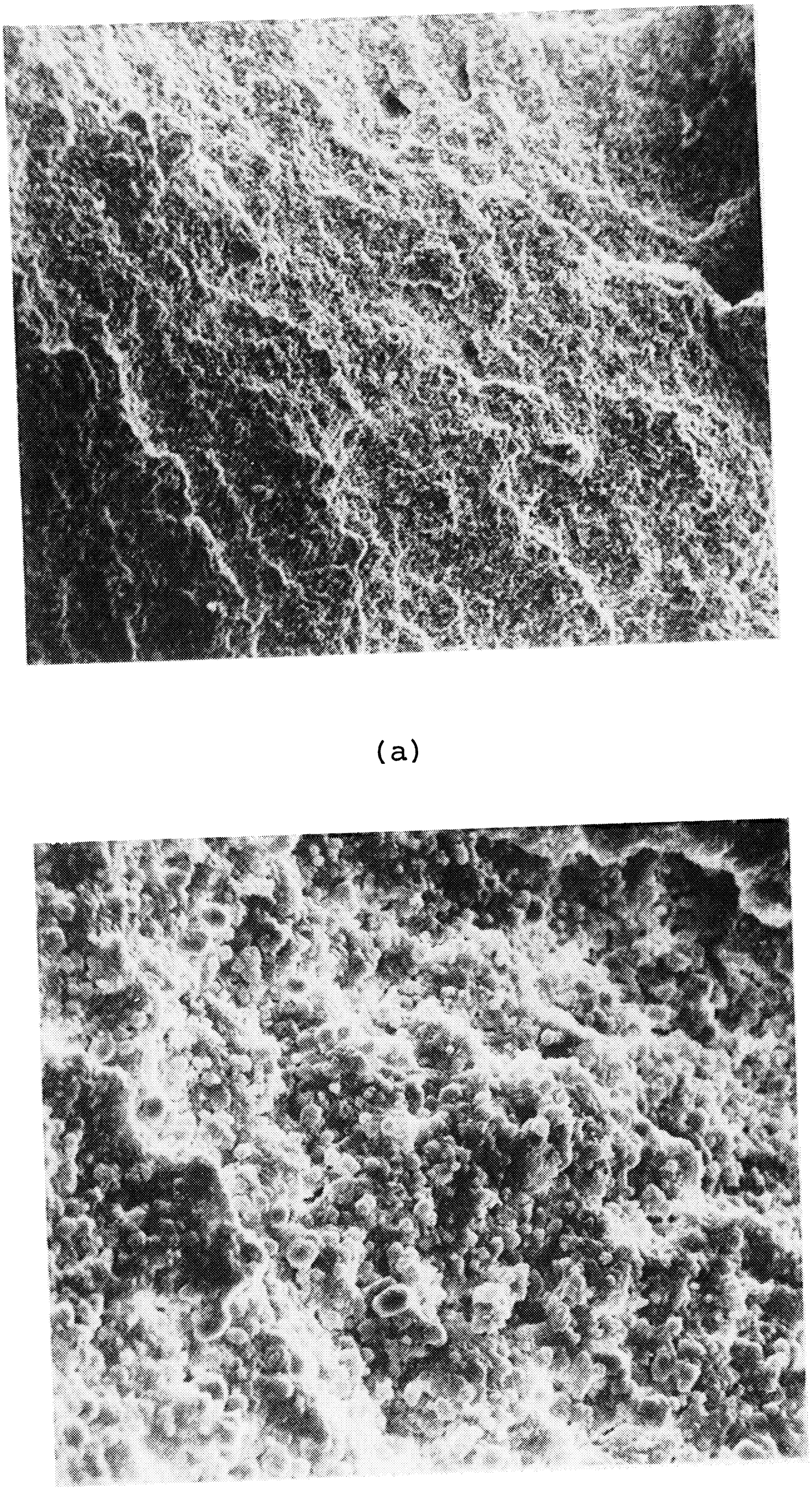
VOLATILE CONTENT OF LIME SLUDGE

Sample No.	Wt. of Wet Sludge (gm)	Wt. of Dry Sludge (gm)	Loss of Wt. at 600.C (gm)	% Volatile Dry Wt. Basis	
1	129.58	78.40	4.58	5.85	
3	124.07	73.47	4.55	6.20	
4	116.52	65.99	4.46	6.75	
9	126.05	75.67	5.01	6.60	Avg.6.35%

X. ANALYSIS OF THE SLUDGE FABRIC

In studying the physical characteristics of the lime/soda-ash sludge, it was deemed desirable to observe the shape and size of the particles comprising the sludge fabric. Since all indications were that most of the particles were less than .01 mm (10µ) in size, an electron microscope had to be used.

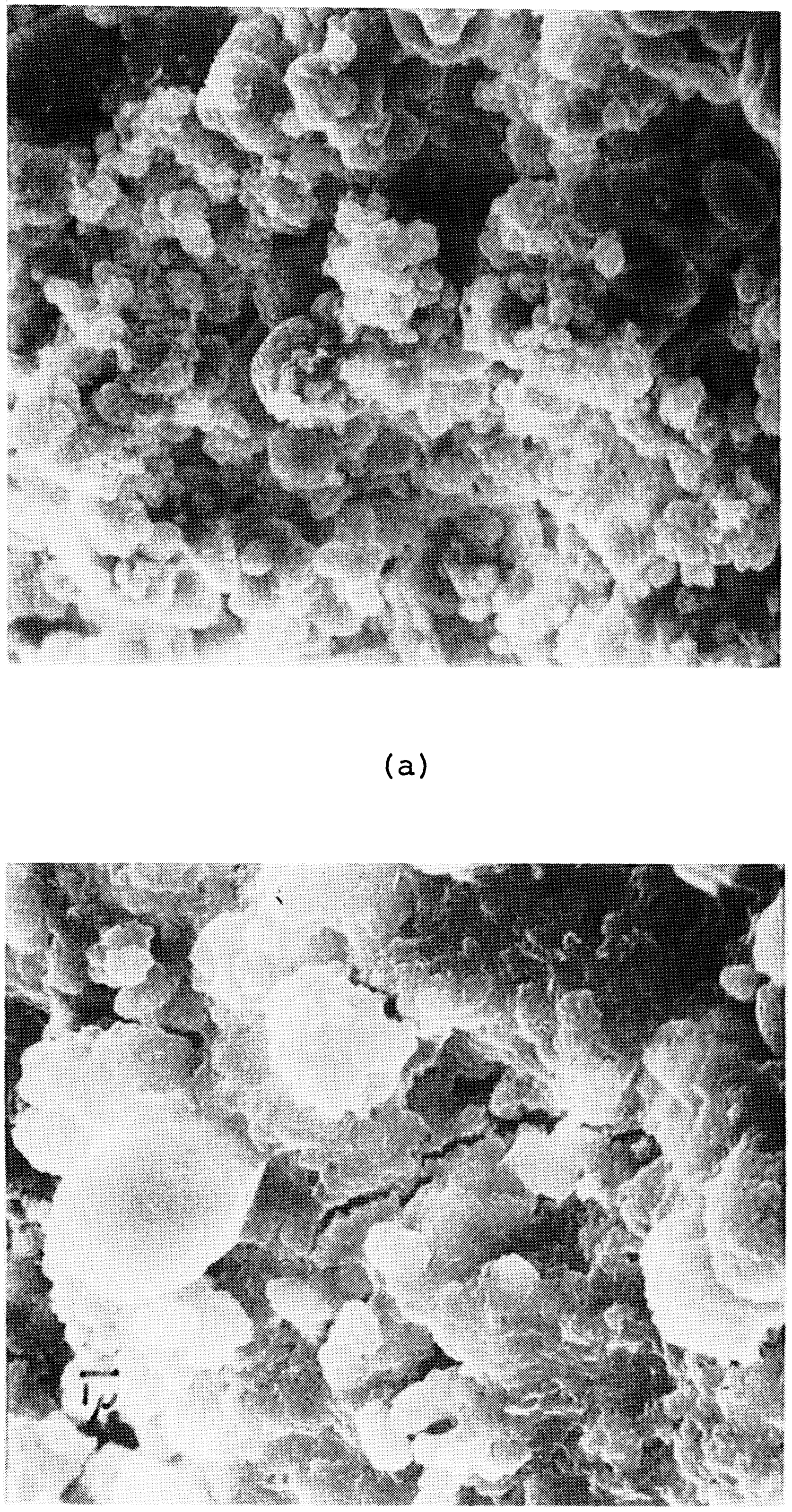
A JSM-U3 (Japan Electron Optic Laboratory, Inc.) scanning electron microscope was made available. The samples to be studied were mounted on a suitable support and coated in a vacuum with vapor-deposited chromium. During the scanning, an accelerating voltage of from 10-25 kv was used. Electron micrographs were made of the specimens at magnifications of 100X, 200X, 500X, 1000X, 2000X, 5000X, and 10,000X. Several stereoscopic pairs were used in studying the crystal structure in two dimensions. Typical examples of the electron micrographs are shown in Figures 30, 31, and 32.



(a)

(b)

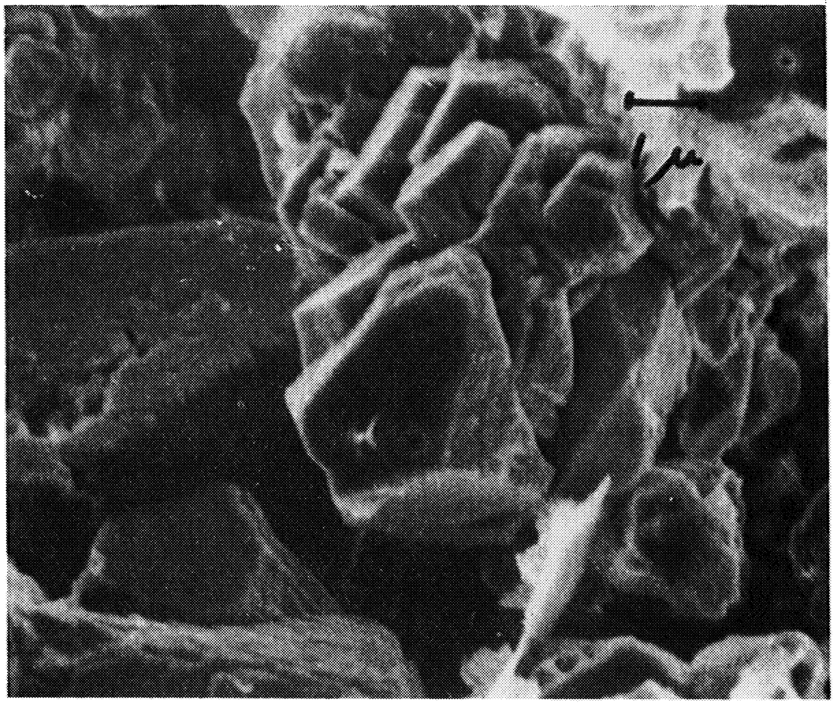
Figure 30: Electron Micrographs of Lime-Soda Ash Sludge (a) 100x Magnification (b) 500x Magnification



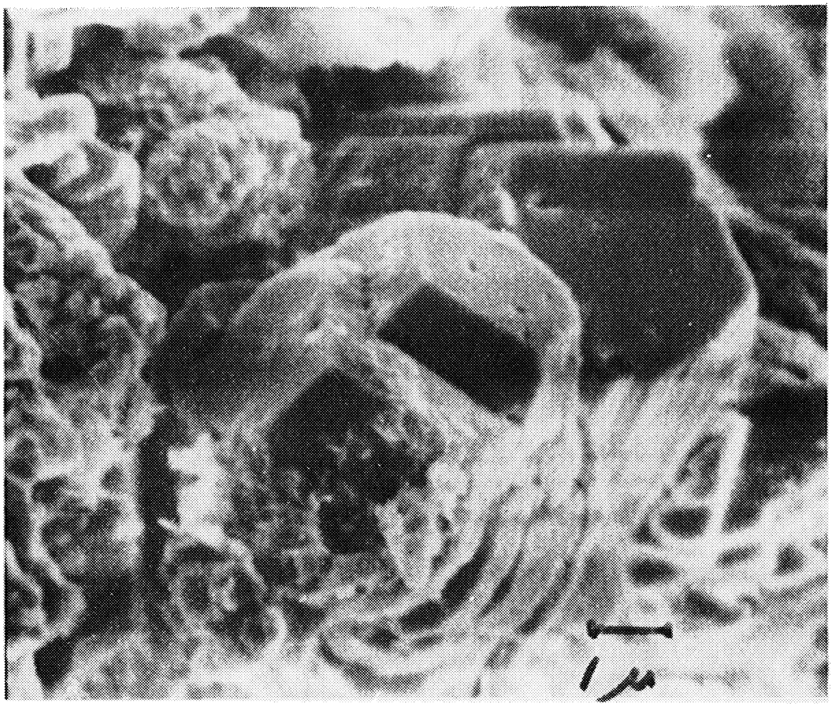
(a)

(b)

Figure 31: Electron Micrographs of Lime-Soda Ash Sludge
(a) 2,000x Magnification
(b) 5,000x Magnification (1μ shown to scale)



(a)



(b)

Figure 32: Electron Micrographs of Lime-Soda Ash Sludge
(a) 10,000x Magnification (1μ shown to scale)
(b) 10,000x Magnification (1μ shown to scale)

Several observations can be made regarding these micrographs. The sludge particles are small, in the order of 2 to 3 microns, as shown on Figure 31 upon which a 1μ scale has been drawn. The elemental analysis has conclusively shown that the sludge consists almost entirely (90+ percent) of $CaCO_3$ (calcite), the crystalline shape of which is rhombohedral. In the micrographs that are of great enough magnification to show the structure of individual crystals, it is interesting to note that a distinct rhombohedral shape is in evidence throughout the mass of crystals. Some of the crystals have become rather rounded, having had their edges broken off. This is probably due at least partially to the manner in which they are handled during the water-softening process, being transported by sludge pumps through pipe lines at relatively high velocities. Moreover, these samples were derived from a sludge lagoon that was subjected to freezing and thawing, and that would also tend to round off some of the edges of the original crystals.

It is also important to note that the crystals tend to be spherical rather than flat-plate in shape. This helps to explain the fact that the lime sludge behaves more like a silt than a clay, since silt particles tend to be spherical whereas clay particles tend to be shaped like flat plates.

XI. CONCLUSION

As a result of this evaluation of the physical parameters of the line/soda-ash sludge, the following conclusions can be drawn. The material is made up of very small particles in the order of 2-5μ that are generally spherical in shape. It is classified as low to very low in permeability, has a high void ratio, and is highly compressible. The addition of sand does not seem to influence permeability to any significant extent. The natural water content varies between 80 and 120 percent on a dry-weight basis, and between 44.5 and 54.5 percent on wet-weight basis. When dried, the sludge exhibits the property of not reacquiring its initial water content, probably due to physical property changes during oven drying.

Because of the fine particle size, capillary action holds considerable water in the air-dried samples obtained under natural conditions. This means that considerable moisture will be present if the sludge is exposed at the surface of a landfill to reduce its dust potential. If the sludge is subjected to traffic, however, the structure of the material will be broken down and the fine particles will become quite dusty. Therefore, sludge should not be used as road surface material; it will become very dusty in dry weather and slippery in wet weather. But it will give no trouble if it is left at the surface in an area that is not subject to traffic.

The moisture content of the sludge must be at a reasonably low level if it is to be useful as a cover material on a landfill or if it is to be moved around the disposal site without trouble to the earth-moving equipment. Samples of sludge which were judged to be suitable for moving and working by the landfill operator were collected and analyzed for moisture content. The results are shown in Table 19.

TABLE 19

MOISTURE CONTENT OF WORKABLE LIME SLUDGE

Sample No.	Moisture Content % of Wet Weight
1	.3875
2	.3904
3	.3574
4	.3887
5	.3993
6	.3845

From the findings reported in the literature and in this study, one concludes that if the moisture content of lime sludge can be reduced to 35-40 percent (on a wet-weight basis) by air drying or some other means, it can be (1) readily handled as cover material or (2) incorporated into the landfill without causing any trouble to the earth-moving equipment or undesirable conditions for other vehicles (trucks, etc.) that might pass over it. In this dry condition, the sludge does not demonstrate any thixotropic properties, is not excessively slippery or slimy, and is not dusty, odorous, or in any way objectionable. If it should become wetter, it will again revert to a thixotropic material and become very sticky and slippery; this could cause trouble to trucks and tracked vehicles on the surface of the landfill.

CHAPTER 4

SOME PRACTICAL APPLICATIONS FOR THE SLUDGE AND METHODS OF HANDLING IT AT A LANDFILL

As a result of this study, several practical suggestions can be made relative to the use and disposal of the lime/soda-ash sludge formed in the sludge lagoons of water treatment plants that use the lime-softening process.

As shown in the work on high-iron-bearing solution in the present study, the sludge can be used beneficially by exploiting its acid-neutralizing potential. For example, the sludge might possibly be used to help improve the soil conditions of acidic coal-mine spoil. One study in which fly ash was used has already been conducted.(1) Lime sludge might well prove to be better than fly ash because metals which are toxic to plants (i.e., boron and manganese) are almost completely absent. No attempt has been made in the present study to determine the amount of lime sludge actually needed for improving acidic coal-mine spoil. However, on the basis of the available calcium present as calcium carbonate in lime/soda-ash sludge (as compared with the calcium present as calcium oxide in fly ash), the sludge would appear to possess much more neutralizing capacity.

Fly ash is reported (1) to contain approximately 4% calcium oxide, whereas lime/soda-ash sludge contains at least 95% calcium carbonate. In order to provide neutralization to encourage the growth of grass, it was determined that about 600 tons of fly ash per acre would have to be applied (plowed and harrowed with farm equipment, fertilized and seeded). As a control, pulverized limestone was applied to a plot at the rate of 8 tons per acre. Pulverized limestone can be assumed to contain approximately the same content of calcium carbonate as lime/soda-sludge; but since the sludge has a much smaller particle size, it would affect the soil more efficiently. The ratio of 8 to 600 tons per acre is roughly comparable to the calcium content of the two materials, indicating that the sludge would be much more efficient for this purpose. The rate of application of the sludge would be about 8 tons (dry solids) per acre.

The impermeability and acid-neutralizing potential of the lime sludge might also make it useful as an impermeable lining for landfill sites that would otherwise be unsuitable due to porous soil conditions. Many state regulatory agencies are requiring that prospective landfill sites be modified so that the amount of leachate leaving the landfill is limited or eliminated completely. The use of clay or some other impermeable material is suggested for this purpose, and properly compacted lime sludge with the proper moisture content would be suitable. It is adequately impervious and also has the ability to remove iron and to neutralize any acid leachate that comes in contact with it.

Because of its light weight ($\simeq$100 lbs./cu.ft.), the sludge is also suitable for use as a light-weight backfill. When it is properly compacted under controlled moisture conditions, its settlement is not excessive and it has adequate supporting strength for many applications. The sludge is doubly satisfactory when used as backfill for concrete pipe in an aggressive soil, since it aids in protecting the concrete pipe against acid attack from the soil.

When there is a possibility that acid leachate from a landfill will come into contact with a concrete structure, the sludge backfilled around the structure will protect the concrete against acid attack.

As a part of this study field investigations were carried out on a refuse landfill in Rawsonville, Michigan, along with discussions with the operator.(23) Various methods of handling lime sludge were tried by the operator at this site to determine their feasibility. Excavation of the sludge was observed at two lagoons in the area as a basis for the time and motion studies conducted. When the Rawsonville landfill first began receiving the wet sludge, the trucks dumped it immediately in front of the slope of the active face of the fill. Because of its natural slump, the sludge was on the order of 2 to 3 feet deep. A bulldozer was used to push refuse over the sludge. This method proved unsatisfactory because the wet sludge was unable to support the weight of the refuse and bulldozer; under these pressures, it revealed its thixotropic properties and became very fluid. The sludge came up through the refuse and turned the whole mixture into a sticky, slimy, wholly unsuitable quagmire.

Among the suitable methods for handling the wet sludge, one is to deposit the sludge in layers of from 6 to 12 inches, tailgating it from the truck. A bulldozer is then used to cover it over with a 2-foot layer of refuse. A refuse layer of this thickness has the capacity to absorb the fluidity of the sludge and prevents both the boiling through and the liquid conditions that are found with thicker layers of sludge.

The beneficial characteristics of the sludge are best exploited by allowing it to air-dry to a moisture content of about 40% before using it in the landfill. This can be accomplished by spreading it out over a reasonably large area in rather shallow depths (2 feet or so); an even better method is to place it on a slope which will allow the moisture to drain out as well as evaporate. Under average summer weather and temperature conditions, about two weeks will suffice to reduce the moisture to the 40% figure that allows the sludge to be worked with conventional earth-moving equipment. At this moisture content, it has lost all its sticky and slimy characteristics.

When dried to a moisture content of 40% or less, the sludge can be used as temporary (daily) cover in the landfill, which is stockpiled and used as needed. It contains no putrescrible material, has no odor or other nuisance-causing constituents, is fire-proof, and is impermeable enough to serve as a very adequate cover material. The sludge's small particle size may cause it to erode somewhat more readily than a more granular material, and it will not be suitable for final cover because it does not have the ability to support vegetation. The sludge will become dusty if used on areas where traffic is concentrated, but not if it is used on areas where traffic is light.

As excavated by dragline from the lagoon, the sludge contains at least 50% moisture. Sometimes large quantities must be disposed of in this condition, as when the lagoon is completely emptied in one operation and stockpiling for drying and later usage is impractical. In such case, the following method is suggested. As narrow a trench as possible (depending on the equipment available) should be dug in the original bottom of the landfill in an area to be covered with refuse. This trench should also be as deep as possible, without involving ground water, etc. Into such a trench, the sludge can be discharged directly from the open trucks and filled to the top. Then it is covered with refuse, which will have a kind of bridging effect over the trench. It is to encourage this bridging action that the trench should be kept as narrow as possible.

The latter method is disadvantageous in that the beneficial attributes of the sludge are lost, and the cost of excavating the trench adds to the disposal cost of the sludge. Also, it may be difficult to find space for a trench large enough to accept all the sludge to be disposed.

The possibility of introducing the sludge to the landfill as a slurry has been considered. This method has been used to distribute the sludge onto the soil as a soil conditioner in correcting the pH of an acid soil.(13) For several reasons, however, this approach was not deemed feasible for applying the sludge to a refuse landfill. If the sludge is to be handled as a slurry, it must be fluidized and pumped out of the lagoon, and transported in a tank truck. Fluidization requires that it be mixed with water, an operation that usually requires the use of additional water. Because the sludge particles are more or less spherical in shape, their separation from the liquid tends to be comparatively rapid. This means that the sludge will tend to settle in the tank truck while in transit, adding to the difficulty of removing it from the truck. The transport of the additional water required to fluidize the sludge would add to the cost. Moreover, the additional moisture would not be desirable at the landfill because it would add to the leachate potential. Although the acid-neutralizing capability of the sludge would remain effective with this method, most of its potential advantages as a cover material would go unrealized.

This study considered the possibility of adding lime sludge as a soil conditioner to the kind of final clay cover material being used in the Rawsonville landfill. If successful, this would not only have helped in the disposal problem but would have produced a more favorable pH condition in the clay, thereby improving its growth potential. Clay can be either acidic or basic; if lime is to be used to advantage, it must obviously be acidic. An analysis of the clay being used for cover at the Rawsonville landfill showed it to have a pH of 9.5, indicating that additional lime would hinder rather than promote the growth of vegetation. For any cover material that does have an acid condition, however, the lime sludge should be a valuable additive if it is spread and disked into the soil along with fertilizer and seed.

CONCLUSIONS

Based on the information gathered in this study the best method for handling the sludge in a refuse landfill is to first allow it to dry in a shallow pile (2 or 3 feet deep). When the moisture content has been reduced to approximately 40% it can be moved and spread in a layer 6 inches to 1 foot deep as daily cover or mixed with soil being used as cover material.

CHAPTER 5

COST ANALYSIS

This chapter deals with a cost analysis of the various phases of removing lime/soda-ash sludge from a storage lagoon and incorporating it into a landfill for permanent disposal.

The costs analyzed consist of:

(1) Excavation from the lagoon by dragline.

(2) Transport of the sludge by open dump truck.

(3) Incorporation into the landfill by selected means.

Cost data is very difficult to obtain relative to these operations. At best, they are generalizations which must be used with caution, due to variations in wage scales, weather conditions, traffic conditions, etc. The data presented here are derived from field observations where possible, and also from reference to the literature and from discussions with experienced persons.

A time and motion study was carried out on a 2-cu.yd. dragline while it was engaged in excavating lime sludge from a lagoon. In general, the dragline swung 180° to empty its bucket, which was emptied in a shallow pile on a slope. A time breakdown for the operations (giving values as the averages of all the times gathered) is as follows:

Time to fill dragline bucket	- 12 seconds
Time to swing 180° with a full bucket	- 15 seconds

Time to empty bucket	- 3 seconds
Time to swing 180° with empty bucket and position for next fill	- 18 seconds
A total time for each bucket	= 48 seconds

The results of the study are given in Table 20.

This particular dragline was hired at $45/hr., including operator and all other costs. On each filling, the bucket was observed to be about 3/4 full. If 90 percent availability is assumed for the dragline, then the cost for excavation under the outlined conditions is $.44/cu.yd.

An estimate for dragline excavation was obtained from another excavation contractor(23), who estimated that the cost would range between $.45 and $.50 per cu.yd. using a 2-cu.yd. dragline. This compares very well with the calculated figure.

A second time-motion study was conducted involving a 2-cu.yd. dragline which was engaged in excavating lime sludge from a lagoon and filling 20-cu.yd. open dump trucks for transport to a landfill disposal site. In general, the trucks were positioned so that they were parallel to the bucket, and the dragline swung 90° to empty its bucket into them. A time breakdown for the operations (giving values as the averages of all the times gathered) is as follows:

Time to fill bucket	11.5 seconds
Time to swing 90° with a full bucket to truck	15.5 seconds
Time to empty bucket into truck	4.3 seconds

Table 20

Time Study of 2 cu. yd. Dragline

(180° degree swing to empty, discharge onto ground onto sha shallow pile on a slope) All times in hundredths of a minute.

D = portion of time to fill bucket
S_1 = portion of time to swing to point of emptying
E = portion of time to empty
S_2 = portion of time to swing back and position to begin to dig.

D	20	20	22	10	18	17	20	20	14	25	22	30
S_1	40	42	45	35	40	40	40	40	35	45	45	55
E	50	53	55	45	55	45	50	45	40	55	50	60
S_2	80	74	80	70	80	75	80	73	70	100	100	90
D	20	20	25	15	20	28	25	20	20	20	25	20
S_1	40	40	45	45	45	50	45	45	45	45	50	43
E	45	45	50	55	50	55	50	50	50	50	60	50
S_2	80	80	80	80	75	90	80	80	75	80	85	75
D	20	22	25	20	20	15	23	14	10	15	23	20
S_1	48	50	48	40	40	35	45	35	30	38	45	50
E	55	60	55	45	45	40	48	40	35	42	55	55
S_2	80	93	80	70	70	65	75	65	65	70	84	85
D	23	25	20	30	25	15	15	25	30	30	25	
S_1	50	50	45	58	55	40	45	45	50	50	45	
E	55	58	50	62	65	50	50	50	53	55	50	
S_2	80	80	75	90	100	75	80	90	85	85	80	

Summation of Time = 37.54 minutes to produce 47 buckets, therefore it takes an average of .80 min. (48 sec) per bucket. Observations indicated that in this material the bucket was 3/4 full on the average which means that 114.18 cu.yd. of material can be excavated per hour. Assuming 90% availability, then, 102.76 cu.yd. per hour can be expected to be produced. At the rental rate of $45.00/hr. for machine and operator, excavation of the sludge costs $.44/cu.yd.

Time to swing empty bucket 90° and position for next fill 9.4 seconds

Total time for complete cycle 40.7 seconds

The results of the study are given in Table 21.

Transport times were measured over the 3-mile haul to the landfill and averaged 10 minutes. Positioning the truck at the landfill required one minute on the average; so did emptying the wet sludge out of the truck. The return trip to the sludge lagoon took 10 minutes at an average of about 20 miles per hour. If a 50-minute hour is assumed to allow for various nonproductive times, three loads are delivered every two hours.

3 loads @ 20 cu.yds./load = 60 cu.yds.

Truck rental @ $20.68/hr. $41.36 for 60 cu.yds.

Delivered 3 miles is $.69/cu.yd. or $.23/cu.yd./mile

Analysis of the dragline costs in this case are not representative; since only three trucks were used and the time spent to load each truck averaged only 10 minutes, the dragline was unused about 50 percent of the time. If the cost of the dragline is included at the rate of $35.00/hr., the total cost of excavating and of transporting the sludge three miles is $1.85/cu.yd. This could be reduced markedly if five trucks were used instead of three.

A cost estimate from a construction contractor(23) for trucking this type of material was $.50 - $.70/cu.yd./mile. Still another study(13) quotes trucking costs as averaging $.80/ton/mile, a figure that seems unrealistically high.

TABLE 21

TIME STUDY OF 2 - CU.YD. DRAGLINE LOADING TRUCKS

(All values, minutes x 10^{-2})

																		Avg.	Avg. Seconds
Dig	18	25	18	20	18	30	15	15	16	20	18	25	20	18	15	17	18	19.2	11.5
Swing Full Bucket to Truck	27	25	22	25	27	25	20	25	29	25	22	30	30	30	25	23	22	25.4	15.5
Empty 2 Cu. Yd. into Truck	5	10	5	5	5	10	5	5	5	10	7	10	5	7	10	8	10	7.2	4.3
Swing Empty Bucket & Position	10	15	15	15	10	15	15	20	15	13	20	15	20	15	10	22	20	15.6	9.4
Total Cycle Time	60	75	60	65	60	80	55	65	65	68	73	80	75	70	60	70	70	67.7	40.7

Average 10 buckets per load, excess not desired due to danger of spilling.

Approximately 10 minutes to load a 20 cu. yd. truck, truck rental @$20.68/hr. including driver

10 minutes to drive 3 miles to landfill site

1 minute to position

1 minute to empty

10 minutes to drive to lagoon

Approximately 32 minutes per round trip

Assuming a 50 minute hour - 3 loads in two hours

Costs for placing the sludge on the landfill are based on discussions with the landfill operator(23), and reflect his experience in working with the lime sludge.

Using a bulldozer to spread the air-dried sludge (40 percent moisture) on the surface of the landfill in a thin layer costs approximately $.10/cu.yd.

Dumping from open trucks over a bank in the landfill will cost approximately $.25/cu.yd. because upon drying, the sludge has to be moved to another location on the landfill where it is spread and compacted.

Once the sludge has been spread on the surface of the landfill, disking is required to mix it with the other cover materials. That adds another $.02 to $.05/cu.yd. to the cost.

Covering the wet sludge with separate earth cover is both unnecessary and expensive. Nothing about the sludge requires such cover; but if the operation is being contemplated anyway, it will cost from $.50 to $.60/cu.yd. This high cost is only for placing the earth cover; since earth-moving equipment cannot be operated over wet sludge at any depth, a dragline must be used to reach out over it. Instead of this approach, it is much more advisable to allow the sludge to drain and air-dry in a temporary location, and then use it for cover material.

To develop costs for disposal of the lime sludge by different methods a general method of cost analysis was devised. It is outlined below.

The costs of excavation by dragline can be established by dividing the rental rate of the dragline (dollars/hr) by its production rate in terms of cubic yards per hour. Its production rate can be determined by time study or by reference to standard production tables.(48,29)

Trucking costs can be analyzed by first selecting the truck capacity that is commensurate with the size of the dragline. Then the rental rate can be established by reference to a standard rental rate.(4,41) If the distance to be traveled and the average rate of travel are known, the time required to go to and from the loading and disposal points can be calculated. If the capacity of the dragline bucket is known, the time required to fill the truck and the time required to empty it can also be established either by time study or from standard tables.(48) This calculation will make it possible to determine the number of trucks needed to keep the dragline busy. Once the time and the size of the truck have been established, the cost of transporting the sludge to the disposal site can be determined by reference to standard rental rates. (4,41)

When sludge has been allowed to dry out (in low piles or on a slope) to a moisture content of approximately 40 percent, its handling at the disposal site can be analyzed as follows. A bulldozer is selected according to size, or the one in use at the site is made the basis for figuring the costs of handling. The production rate in this case is the amount of material (in cu.yd.) that the bulldozer can spread from a pile in an hour. Average production rates can be obtained (29) by taking into account the fact that air-dried sludge is lighter in weight than ordinary soil. Rental rates are available for the particular machine being considered.(4,41) If the rate of production and the rental rate are known, it is possible to determine the cost/cu.yd. to spread the material on the landfill. It should be taken into account that the machine is already at the landfill site, and no provision need be made for bringing it to and from the site.

There is always a possibility of removing the sludge from the lagoon by pumping and transporting it to a disposal site by tank truck. But problems arise due to the low moisture content of the sludge in the lagoon, which means that the sludge must somehow be fluidized in order to be pumped. Such a disposal procedure is not considered desirable on a landfill because of the excess moisture that is thereby introduced. Possibly this procedure might prove more suitable for disposal onto other sites such as farm land, yet attempts to implement it have not proven to be continuously successful.(17,55)

An outline of the cost-analysis procedure for removal by pumping is provided, just in case this method is contemplated. A centrifugal pump of non-clog design capable of pumping against the existing head condition is selected and its rental cost determined.(4,41) This method requires some means of fluidizing the sludge, such as reversing the direction of flow from the pump so that water is added to the sludge before it is pumped out of the lagoon. The pump selected should be such that it could be mounted with the tank, an arrangement that allows the same pump to be used both in loading the slurry and pumping it out onto the land-disposal site.

The capacity of the tank should be selected bearing in mind its weight when full (a 15 percent slurry will weigh 2026 lb./cu.yd. or 10 lb./gal). The capacity of the pump and the size of the tank will determine how long it will take to fill the tank and empty it at its destination. Rental rates for some types of tanks can be obtained.(4)

Following are two typical cost analyses - for removing sludge from a storage lagoon by dragline and open truck, and for removing it by pumping and tank truck.

Cost Analysis of Removal by Dragline and Open Truck

Assumptions:

Sludge contains 50 percent solids
Dragline capacity, 2 cu.yd.
Truck capacity, 12 cu.yd.
Time to fill 6 min. (1 bucket/min)
Time to disposal point 15 min.
(5 miles @ 20 mph)
Time to empty and return 14 min.
Bulldozer at landfill is a D-6

Rental rates(4,41)

Dragline $45/hr. including operator
Trucks $12.50/hr.
Bulldozer $22.50/hr.

Production rates(48,29)

Dragline load 2 cu.yd./min
Trucks 35 min/round trip
6 min to fill
Dozer level 190 cu.yd/hr

Production and Cost Analysis:

Dragline will produce 120 cu.yd./hr

$$\frac{50 \text{ min/hr}}{35 \text{ min/trip}} = 1.43 \text{ trips/hr} \times 7 \text{ trucks} \times 12 \text{ cu.yd. truck} = 120 \text{ cu.yd./hr}$$

$$\text{Dragline } \frac{\$45}{120} = \$.375\text{/cu.yd.}$$

$$\text{Trucks } \frac{7\text{x}12.50}{120} = .730\text{/cu.yd. trucked 5 miles}$$

$$\text{Dozer } \frac{22.50}{190} = \underline{\$\ .118}\text{/cu.yd.}$$

$1.223/cu.yd. trucked 5 miles

Cost Analysis of Removal by Pumping and Transport in a Tank Truck

Assumptions:

Sludge contains 15 percent solids
Pump 450 gpm (130 cu.yd./hr.)
Tank 4000 gal (20 cu.yd.)
10 min to fill tank
15 min to reach disposal site
10 min to empty tank
14 min to return to lagoon
Total approx. 50 min for each trip
Assume a 50-min hour: 1 trip per hour

Rental Rates:(4,41,8)

Pump $21.00/day
Tank Truck $25.00/day

Cost Analysis:

Pump $\frac{\$21}{8}$ = \$2.63/hr per 20 cu.yd.

= \$.135/cu.yd.

Truck $\frac{\$25}{8}$ = \$3.12/hr per 20 cu.yd.

= \$.156/cu.yd.

\$.291/cu.yd.

(trucked 5 miles)

In comparing these two calculations, it must be recognized that the slurry being pumped is assumed to contain only 15 percent solids, whereas the sludge being trucked is assumed to contain 50 percent solids. That makes it necessary to increase the amount of sludge pumped by $\frac{50}{15}$ or 3.33 times, which increases the cost accordingly:

3.33 x .291 = \$.97/cu.yd. (transported 5 miles)

The assumption in these figures is that no charge will be made for disposal of the sludge at the disposal site. Obviously, pumping sludge and handling it as a slurry is the most economical method. But for reasons stated earlier in this study, a slurry is not nearly as feasible for use on a landfill.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The results of the various analyses of the chemical characteristics of the lime/soda-ash sludge indicates that it consists of calcium carbonate (calcite) in excess of 90%. Very little other material is present; it consists of magnesium hydroxide, some silica, carbon and sulfur. In general, the sludge could be compared to a finely divided limestone.

Several tests were conducted in which various solutions were put in contact with this sludge. The results showed that depending on the characteristic of the solution and the time of contact either equilibrium or steady state conditions can be expected to occur. With solutions of demineralized water equilibrium conditions will occur within 2 to 3 hours as indicated by the change in pH which leveled off at a value between 9 and 10. For leachate solutions of low mineral content, the pH at equilibrium will be 8 or above. Steady-state conditions develop with shorter time of contact and with higher mineral content in the leaching solution. This was indicated by the high-iron solution in contact with the sludge in the soxhlet apparatus. The pH of the effluent solution stabilized at 6+ from an original value of 4.6. Hardness and alkalinity will increase somewhat due to exposure to the lime sludge. If the leachate contains very low hardness to begin with an equilibrium appears to be established with the hardness increasing in the order of 50 - 80 mg/ℓ (as $CaCO_3$). When the sludge is in contact with a leaching solution containing a high concentration of iron, the results indicate that the sludge contributes to a large reduction in the amount of iron in the leachate. As stated in the text, this is due to multiple causes; they may be summarized as precipitation, oxidation, ionic attraction, and surface adsorption. An empirical expression for the removal of iron in an anaerobic environment by the finely divided lime sludge was developed: $y = -4.1 + .0214\, x$, where y is the grams of finely divided dry sludge and x is the milligrams of iron as Fe^{++} removed. In connection with the removal of iron, the polarity and magnitude of the charge on the sludge particles were determined. The sludge has a positive charge, which helps to explain some of its effects in removing iron from solution.

The rate of solution of the sludge in distilled water with a pH adjusted to a low pH (5.0) indicates that the sludge will go into solution very slowly and will remain in a landfill for a rather long time.

The results of the analysis relative to the physical characteristics of the sludge show that the sludge consists of small (2μ to 5μ) spherical particles of rather high uniformity ($\approx$ 100% passing a 200 mesh sieve); thus it would be classified as a silt-like material. It is rather light in weight with respect to most soils (specific gravity of 2.35) and is quite alkaline, being composed largely of calcite (calcium carbonate) and having a pH of 10.1.

The permeability of the sludge is in the range of 1×10^{-5} to 1×10^{-7} cm/sec, which places it in the general soil classification of "very low" permeability. It was observed that the permeability increases as the void ratio increases. A relationship of the type of the Kozeny-Carmen equation was formulated. This equation relates the permeability (k) and the void ratio (e), and is in the form $k = C\ e^{M}$. Value of C was found to be 7.65×10^{-8} and the value of M, 3.70.

The results of the consolidation test show the sludge to be highly compressible. This comes about due to the small particle size, the high initial void ratio, the high natural water content, and the large change in void ratio which occurs with loading. This will cause a considerable settlement in the sludge used as fill. However, the settlement will occur in a relatively short time after the sludge is put into place and loading is applied. If proper moisture and compaction are provided, very little settlement will occur. The optimum moisture corresponding to the maximum density of the sludge was determined to be 32% (on a dry-weight basis). This resulted in a density of 81 lb/cu.ft.

The triaxial test on compacted material was used to evaluate the shear strength of the sludge. This evaluation showed that the sludge has an angle of internal friction

(Φ) of 28.6° on the dry side of optimum moisture (21 percent), with a cohesion of 1.595 kg/cm^2. At approximately optimum moisture (31 percent) and with cohesion of 1.645 kg/cm^2, the sludge has a (Φ) of 24.3°. These values should be reduced somewhat when applied to field conditions, since optimum moisture and density cannot then be achieved. But even so, the sludge shows favorable characteristics as a fill and embankment material. When used for embankment, the sludge must meet the stated moisture and density conditions (90 percent of maximum dry density). The fracture type of failure showed that the sludge is much less plastic than normally consolidated clay.

There are several practical ways in which the sludge as excavated from a lagoon can be handled at a landfill. It can be spread in thin layers and covered with refuse immediately, or (preferably) it can be stored in a manner that will allow it to dry to a moisture content of 35 to 40 percent, after which it can be used as cover material or as an impervious barrier at the landfill site. Use of the dried sludge as cover material spread to a depth of 6 inches to 1 foot over the refuse and compacted with earth-moving equipment is recommended. If no further use is to be made of the lime sludge, it can be disposed of in a narrow trench.

The lime sludge has potential for use as a means to neutralize acid soil conditions or acid leachates.

The costs of excavating and disposing of sludge at a landfill site were considered in this study. A reasonable estimate of costs for sludge removal by a dragline, transportation in open trucks, and bulldozer placement at the landfill is as follows:

Excavation by 2 cu.yd. dragline	\$.45/cu.yd.
Trucking in open truck	\$.25/cu.yd.mi.
If trucks are emptied over a bank to allow sludge to dry, and sludge is to be rehandled	\$.25/cu.yd.
If sludge is emptied in small piles to dry and needs only to be leveled and spread	\$.12/cu.yd.

The total amounts to \$.82 to \$.95/cu.yd., transported 1 mile. (It should be emphasized that these costs apply only to a specific area and time (Michigan, 1972) and must be adjusted for other areas and times.)

CONCLUSION

On the basis of the research conducted and summarized in this chapter, the hypothesis outlined in Section I.B can be discussed and conclusions drawn.

The characteristics of the lime/soda-ash sludge have been shown to be such that the sludge is highly impermeable and quite insoluble with respect to the normal flow of liquids over its surface. The effect of contact between the sludge and low-mineral-containing leachate with low pH is a moderate increase in the total hardness of the leachate (up to the solubility of $CaCO_3 \approx 55$ mg/ℓ), and an increase in the pH to approximately 9-10. In general, these changes would not be considered to constitute pollution of either ground or surface waters.

Contact between the sludge and high-iron-bearing solution with low pH has been shown to result in a neutralization of the acid condition in the solution accompanied by the precipitation of a considerable amount of the iron. Therefore the presence of the sludge might prove to be beneficial in a refuse landfill in which an iron-bearing leachate might occur; it would reduce the amount of iron in solution and would overcome any acid condition that prevailed. The same results are considered possible in other situations where a low pH, high-iron condition is likely to occur.

Since the sludge is impermeable and can be landfilled when its moisture content has been reduced to approximately 40 percent, it can be used for lining landfill sites in which leachate might otherwise seep away through granular or porous material.

The lime/soda-ash sludge contains no objectional substances which give rise to odors or attract flies or other vectors in any way. Both compactable and fire-resistant, it could serve as daily cover on a refuse landfill as long as its moisture content were low enough (40 percent) to allow it to be spread and compacted over the refuse. Since the sludge will become dusty if it is allowed to dry out and its structure is broken down, it should not be used in areas of continuous traffic.

The results of the consolidation tests and the drained triaxial tests show that the sludge can be used as a backfill material or in an embankment provided that the moisture conditions are controlled and good compaction is provided. Due to its light weight (81 lbs/cu.ft. at optimum moisture), it would serve well as a light-weight backfill and, if compacted thoroughly, would possess very satisfactory shear strength. (Compacted samples of sludge exhibit an average angle of internal friction of 26° and a cohesion intercept of 1.6 kg/cm^2 (1.6 tons/sq.ft.)) This is equivalent to an unconfined compressive strength of approximately 2.5 kg/cm^2 (2.5 tons/sq.ft.). Stiff clay has an unconfined compressive strength of 1.00 - 2.00 $tons/ft^2$, and very stiff clay an unconfined compressive strength of 2.00 - 4.00 $tons/ft^2$.(38)

When use of the sludge in an embankment was considered in the present study, the maximum height was developed using a safety factor of one (which is impending failure). Under actual conditions it is advisable to increase the safety factor because of uncertainty in the long-term cohesion of the sludge. Accordingly, the slope height should be reduced by requiring a safety factor of at least two. On this basis, the maximum permissible height of embankment which should be constructed using compacted sludge is about 115 ft. The side slopes should be limited to 26° (1 ft. vertical to 2 ft. horizontal), which is approximately equal to the angle of internal friction. This includes an additional safety factor of two, allowing for uncertainties due to the internal friction angle and seepage. In the absence of cohesion, seepage parallel to the slope will limit the allowable slope angle to approximately one-half the material's internal angle of friction.

It has been shown that the sludge can be removed from storage lagoons by use of a dragline, and can be trucked in dump trucks to the disposal site without difficulty if the trucks have leakproof tail gates. The sludge can be spread to dry either in shallow piles or on a slope. When its moisture content has been reduced to 40 percent on a wet-weight basis, it can be moved and spread with a bulldozer over the surface of the landfill. It should be noted that prior to drying, the sludge as excavated from the lagoon is a very slippery, thixotropic material which is easily fluidized. Therefore it will not support any appreciable weight unless confined, and will cause trouble when tracked or other vehicles try to spread it or run over or through it.

The cost of ultimate disposal of the sludge must be calculated in three phases: (1) excavation from the storage lagoon, (2) transportation to the disposal site and (3) final placement at the disposal site. A cost analysis of each phase indicates that it costs about \$.40 to \$.50/cu.yd. to excavate the sludge by dragline from the lagoon, and about \$.10 to \$.25/cu.yd. to handle and spread the sludge at the disposal site. The major portion of the cost is in transporting the sludge to the disposal site. Trucking costs range from approximately \$.25/cu.yd./mile based on observed data to \$.50/cu.yd./mile based on responses from truckers. If the sludge is to be placed in a landfill, it is economic to transport the least possible amount of water. Based on the data gathered for this study, the overall cost for excavation and bulldozer placement in a landfill ranges from \$.60 to \$.75/cu.yd. With the addition of transportation costs, the total becomes \$.85 to \$1.00/cu.yd. transported one mile.

Since these costs allow the volume in the sludge-lagoon to be used over again, the economical feasibility of the operation becomes obvious. The alternative is to obtain a new sludge storage facility, which, since it will generally be more remote, will require not only a land investment but additional piping, etc.

In conclusion, it can be said that the sludge removed from the lagoons used by the lime/soda-ash water-softening-treatment plants can be disposed of in landfills economically and without causing environmental problems according to this study.

It should be noted that the solutions used in this research did not contain any organic constituents so that the effect of lime on the organic compounds which are associated with landfill leachate is unknown. This aspect of the disposal of lime sludge into a refuse landfill as well as the effect of the lime on the biological activity within the landfill should be the basis for further research.

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APPENDICES

APPENDIX A

ELEMENTAL ANALYSIS

APPENDIX A (CONT'D)

ELEMENTAL ANALYSIS

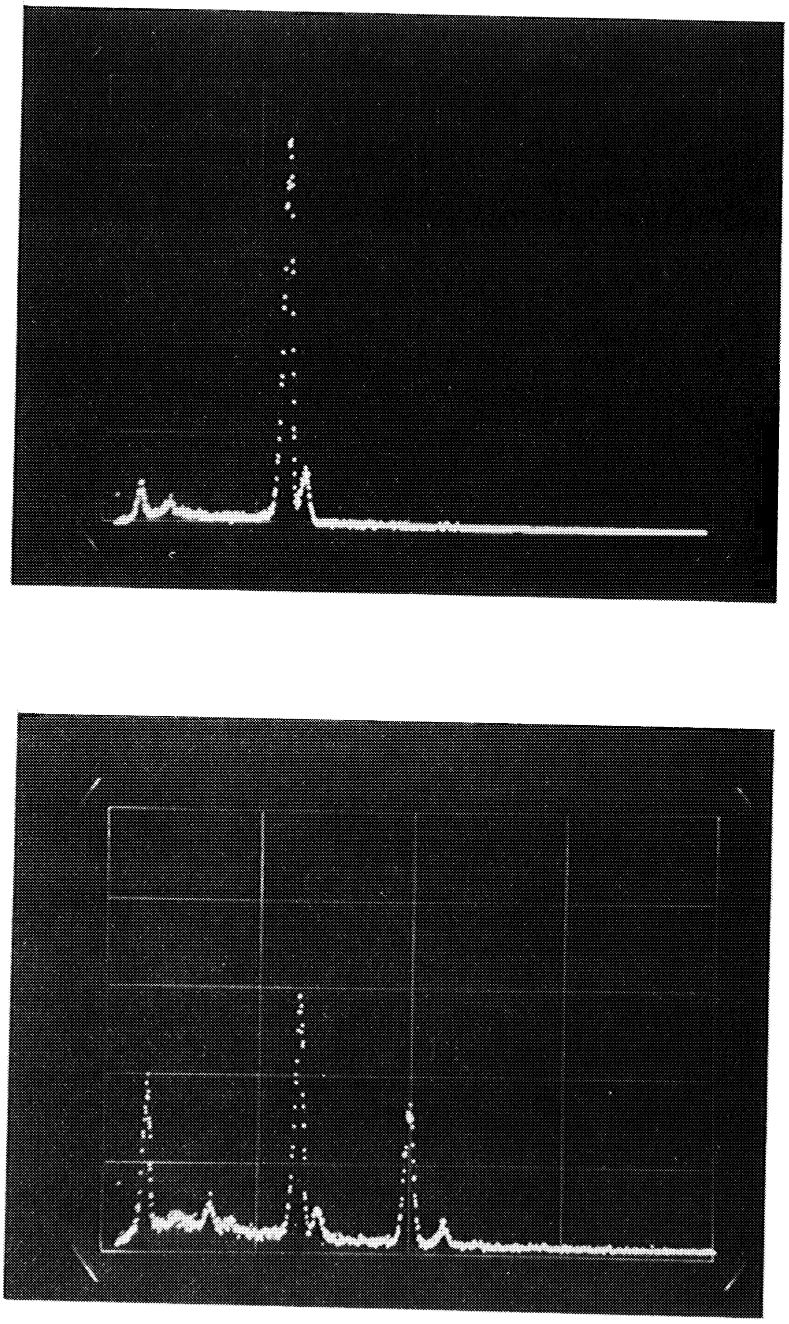


Figure 33. Two Typical Traces of Captured Photons from Electron Microprobe During Elemental Analysis of Sludge Samples.

APPENDIX A (CONT'D)

ELEMENTAL ANALYSIS

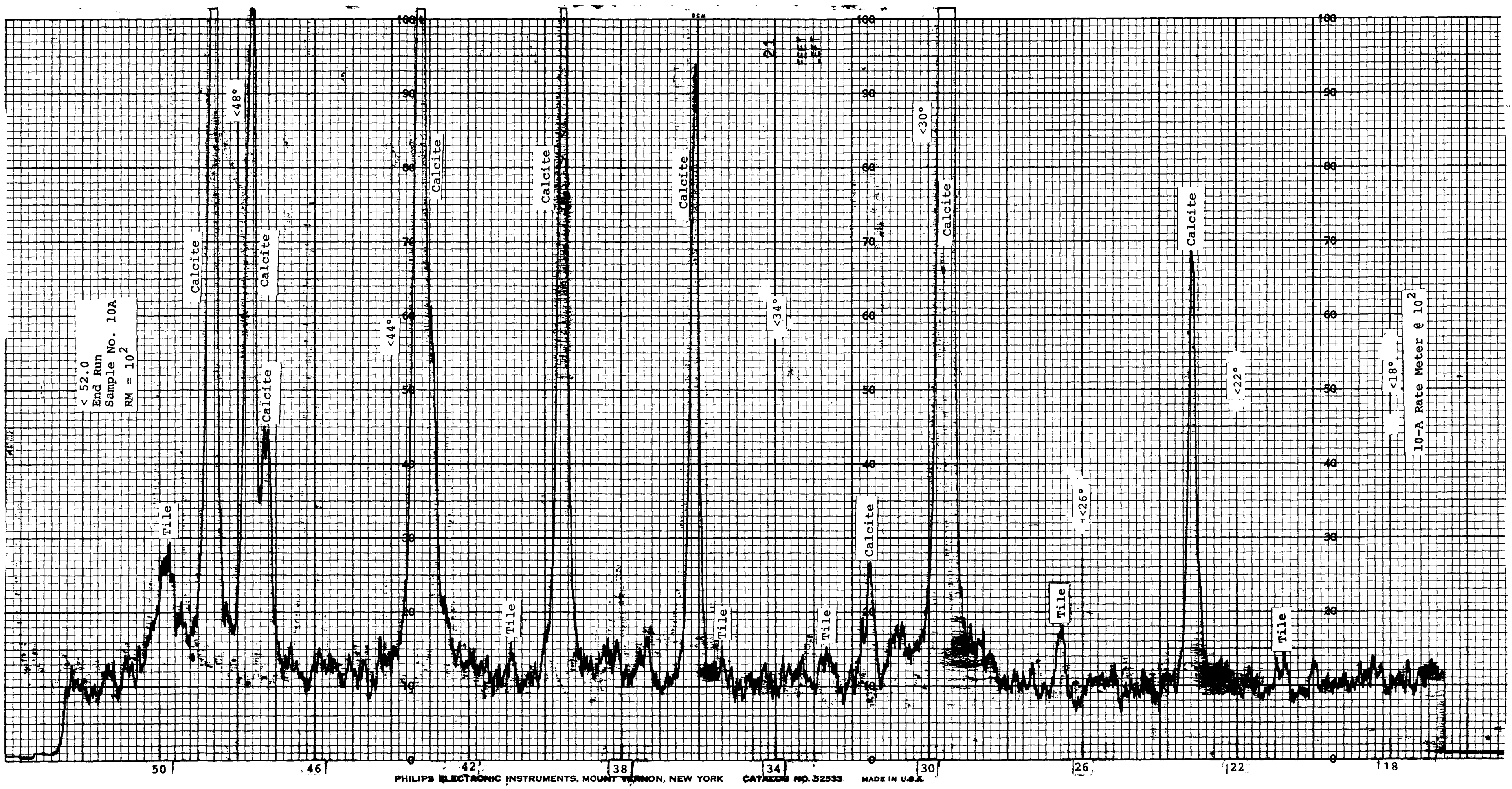


Figure 34. Typical Diffraction Pattern of Sludge Sample by X-Ray Diffraction.

APPENDIX B

APPARATUS USED FOR EVALUATION OF CHEMICAL EFFECT

APPENDIX B (CONT'D)

APPARATUS USED FOR EVALUATION OF CHEMICAL EFFECTS

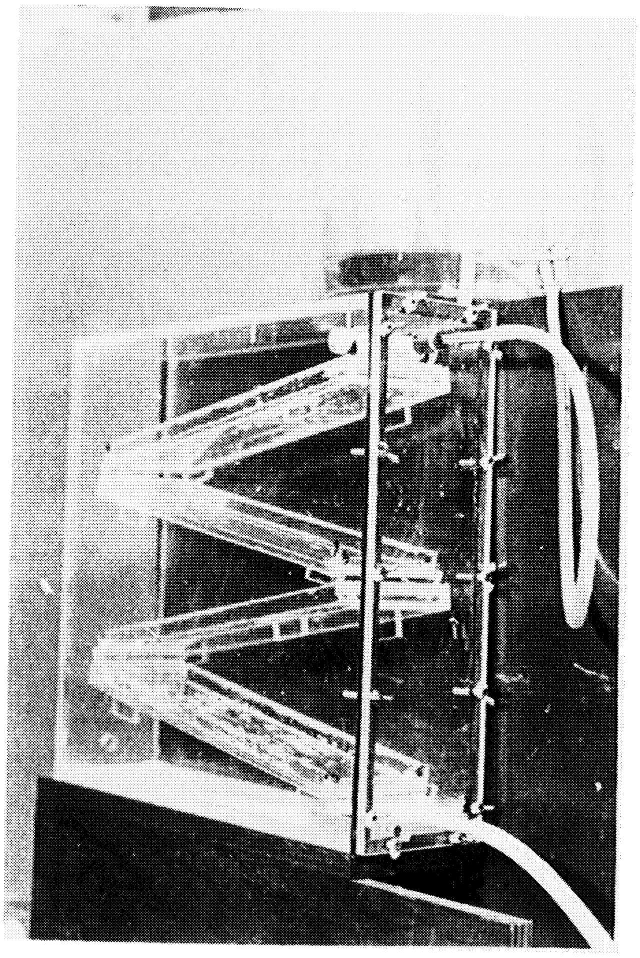


Figure 35. Apparatus Used for Evaluating the Effect of Leachate Flowing Over the Surface of Sludge.

APPENDIX B (CONT'D)

APPARATUS USED FOR EVALUATION OF CHEMICAL EFFECTS

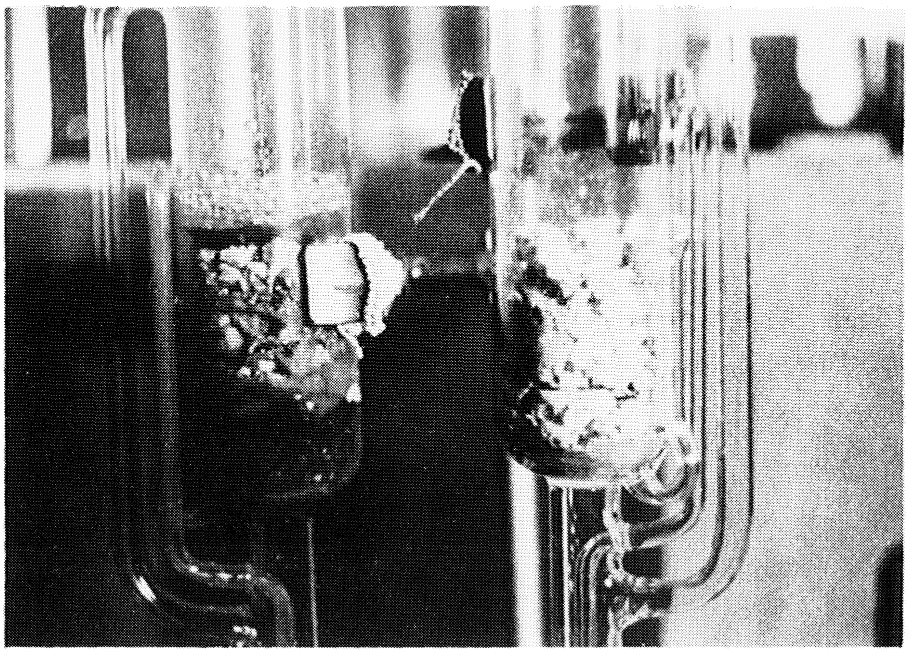


Figure 36. Soxhlet Apparatus for Surface Contact of High Iron Containing Solution Showing One Unit Before Application of Solution and One After Several Liters Have Been Passed Over Sludge.

APPENDIX C

PHYSICAL TESTING APPARATUS

APPENDIX C (CONT'D)

PHYSICAL TESTING APPARATUS

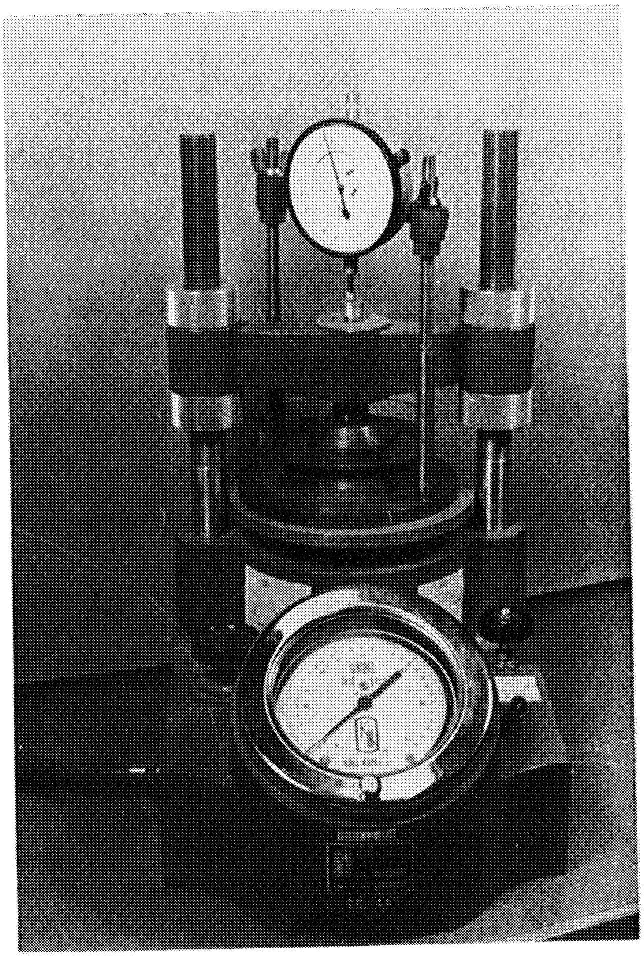


Figure 37. Karol-Warner Constant Stress Consolidation Apparatus with Sludge Specimen in Place.

APPENDIX C (CONT'D)

PHYSICAL TESTING APPARATUS

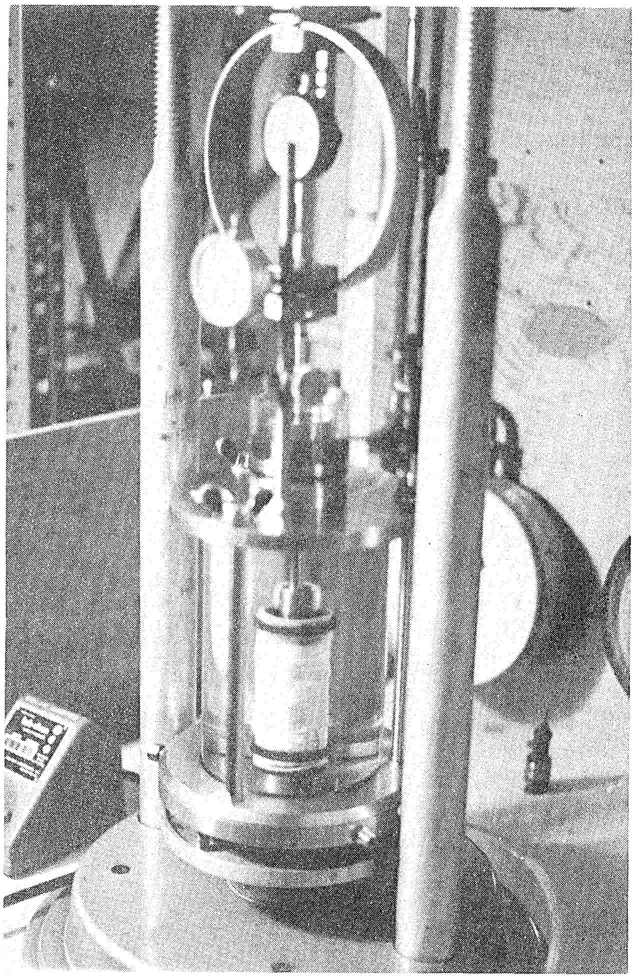


Figure 38. Geonor-AS Triaxial Test Apparatus with Specimen in Place.

APPENDIX C (CONT'D)

PHYSICAL TESTING APPARATUS

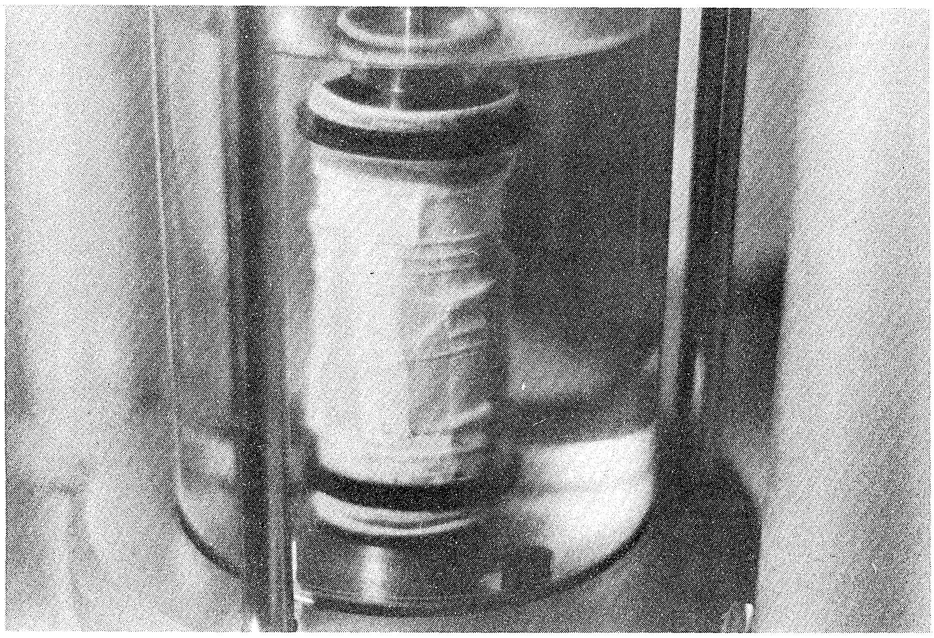


Figure 39. Triaxial Test Specimen at Failure Showing Method of Preparation and Type of Failure.

APPENDIX C (CONT'D)

PHYSICAL TESTING APPARATUS

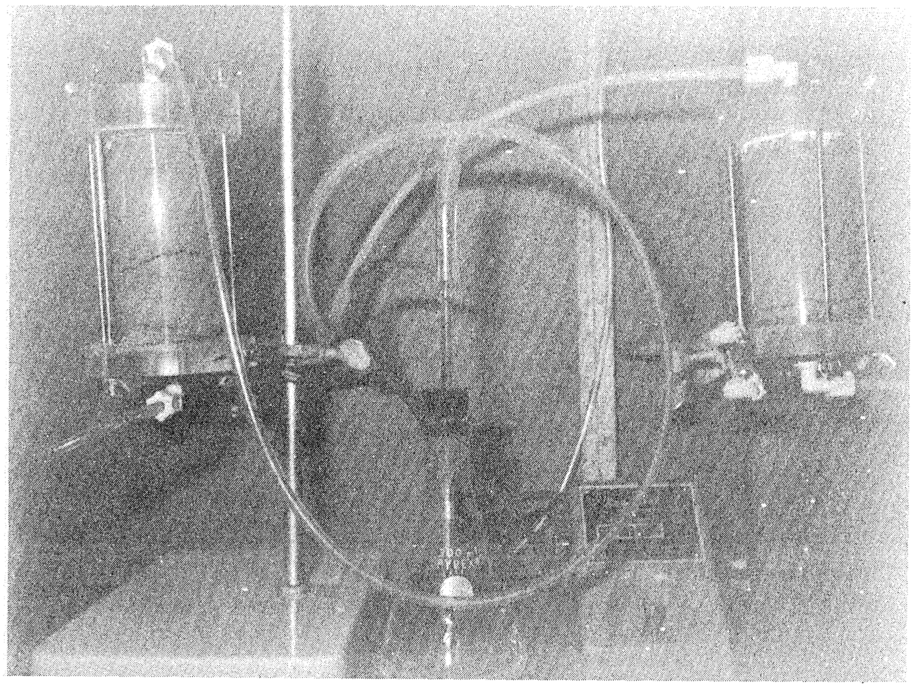


Figure 40. Permeameters Used for Measuring Coefficient of Permeability (k).

APPENDIX C (CONT'D)

PHYSICAL TESTING APPARATUS

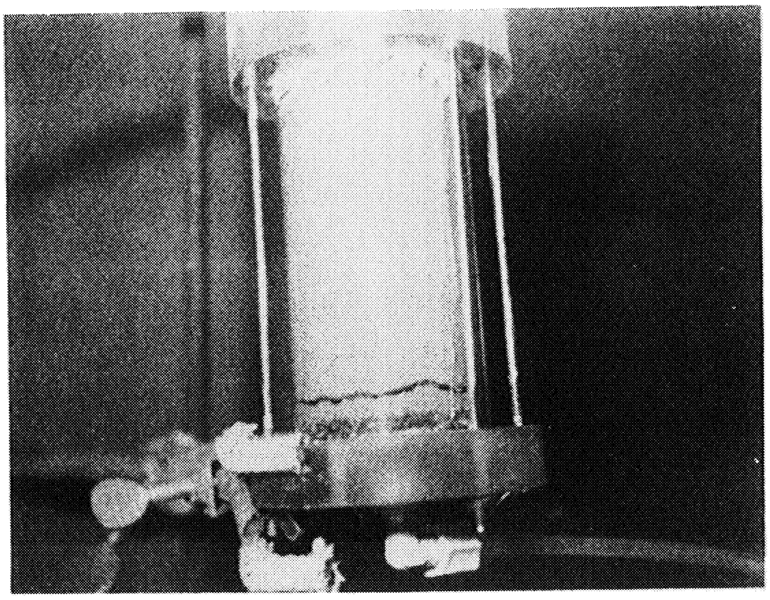


Figure 41. Permeameter with Sludge Sample Following Permeability Test. Note Consolidation Crack Near Base of Up-Flow Cylinder.

APPENDIX C (CONT'D)

PHYSICAL TESTING APPARATUS

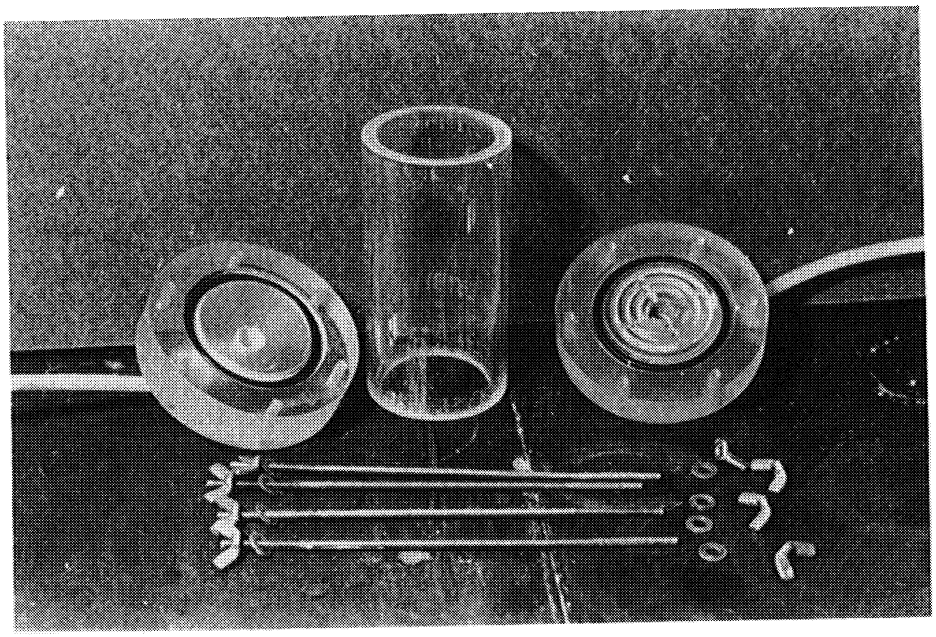


Figure 42. Permeameter Disassembled (Porous Stones Used Top and Bottom Not Shown).

APPENDIX D

ATTERBERG LIMITS DATA

APPENDIX D (CONT'D)

ATTERBERG LIMITS DATA

JOB NAME: | BY: | DATE: | SHEET:
JOB LOCATION: | SUBJECT: LIQUID & PLASTIC LIMITS
CLIENT: | BORING NO. S-11

LIQUID LIMIT

DETERMINATION NO.	1	2	3	4	5
NO. OF BLOWS	37	25	19		
CONTAINER NO.	8	20	6		
WT. WET SOIL + CONT. (g)	23.72	27.95	21.96		
WT. DRY SOIL + CONT. (g)	18.32	20.79	16.84		
WT. WATER (g)	5.40	7.16	5.12		
WT. CONTAINER (g)	8.45	8.50	8.33		
WT. DRY SOIL (g)	9.87	12.29	8.51		
WATER CONTENT (%)	54.5	58.3	60.3		

PLASTIC LIMIT

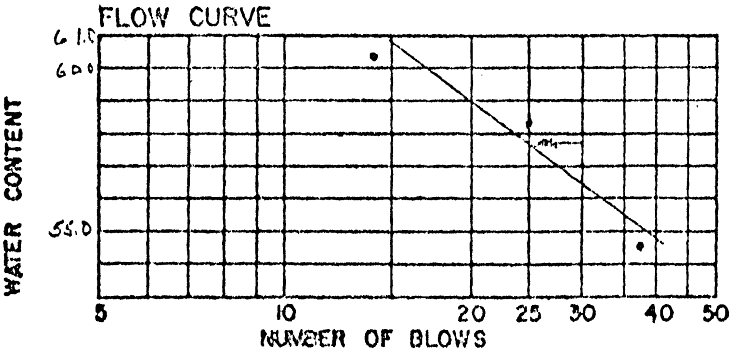
DETERMINATION NO.	1	2	3
CONTAINER NO.	1	12	
WT. WET SOIL + CONT. (g)	9.62	9.59	
WT. DRY SOIL + CONT. (g)	9.29	9.25	
WT WATER (g)	.33	.34	
WT. CONTAINER (g)	8.44	8.37	
WT. DRY SOIL (g)	.85	.88	
WATER CONTENT (%)	38.9	38.7	

Visual Soil Description

light gray silt

(Air-dried)

FLOW CURVE



RESULT SUMMARY

NATURAL WATER CONTENT	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX	LIQUIDITY INDEX	UNIFIED CLASSIFICATION
	57.7	38.8	18.9		

APPENDIX E

DATA FOR DRY DENSITY VS. MOISTURE RELATIONSHIP

APPENDIX E

DATA FOR DRY DENSITY VS. MOISTURE RELATIONSHIP

JOB NAME:
JOB LOCATION:
CLIENT:

BY: CLB DATE: 12-15 SHEET:
SUBJECT: Glysson's Research

COMPACTION METHOD

MATERIAL Gray SILT (sludge)

NO. OF LAYERS 3

BLOWS/LAYER 25

SPECIFIC GRAVITY 2.35

VOLUME OF MOLD 61.0 cc

DENSITY DETERMINATION

Test No.	1	2	3	4		
Mold and Wet Soil (gm)	497.62	503.98	513.37	509.29		
Mold (gm)	407.72	407.72	407.72	407.72		
Wet Soil (gm)	89.90	96.26	105.65	101.57		
Wet Density (gm/cm^3)	1.44	1.56	1.73	1.67		
Dry Density (gm/cm^3)	1.25	1.26	1.29	1.17		
Dry Density (pcf)	78.0	78.8	80.5	73.2		

WATER CONTENT DETERMINATION

Can No.	155	106	151	105		
Wet Soil and Can (gm)	52.61	64.06	70.78	78.46		
Dry Soil and Can (gm)	48.49	55.66	58.35	61.55		
Wt. of Water (gm)	4.12	8.40	12.43	16.91		
Wt. of Can (gm)	21.87	21.24	21.68	21.72		
Wt. of Dry Soil (gm)	26.62	34.42	36.67	39.83		
Water Content (%)	15.4	24.4	34.0	42.5		

REMARKS:

APPENDIX F

TYPICAL CONSOLIDATION TEST DATA

APPENDIX F (CONT'D)

TYPICAL CONSOLIDATION TEST DATA

ANALYSIS TIME: 7:40

TEST SERIES 10A

FIELD DATA

BORING NO. 10A

SAMPLE NO. 3

DEPTH ______

ELEVATION ______

DESCRIPTION Grey

LABORATORY DESC.

disturbed sample

REMARKS ______

APPARATUS MEASUREMENTS

RING HEIGHT Z_1 = .76 IN

RING DIAMETER = IN

RING AREA A = 4.9 SQ IN

DRY DENSITY $\frac{W_s}{AZ_1}$ =

SOLIDS HEIGHT (G_s = 2.35)

$2H_o = \frac{W_s}{G_s \gamma_w A}$ =

WATER CONTENT

SPECIMAN LOCATION	TOP	BOTTOM		START	END	
CONTAINER NO.				RING		
WT. CONT + WET SOIL (g)				223.8	198.1	
WT. CONT + DRY SOIL (g)				184.5	184.5	
WT. WATER, W_W (g)				39.3	13.6	
WT. CONTAINER (g)				146.8	146.8	
WT. DRY SOIL, W_S (g)				37.7	37.7	
WATER CONTENT $w = \frac{W_W}{W_S}$	%	%	%	104.2%	36.1 %	%

DEGREE OF SATURATION

START ____ %

END ____ %

APPLIED PRES (KG/SQ CM)	INITIAL DIAL READING (IN)	* FINAL DIAL READING (IN)	DIAL CHANGE ΔZ (INCH)	SPECIMAN HEIGHT $2H = Z_1 - \Sigma \Delta Z$ (IN)	VOID HEIGHT $2H - 2H_o$ (IN)	VOID RATIO $e = \frac{2H - 2H_o}{2H_o}$	FITTING TIME $\sqrt{}$ METHOD t_{90} (SEC)	FITTING TIME LOG METHOD t_{50} (SEC)	COEF. OF CONSOL. C_v (SQ CM/SEC) $\frac{.848H^2}{t_{90}}$	COEF. OF CONSOL. C_v (SQ CM/SEC) $\frac{.197H^2}{t_{50}}$
0	0	0	0				0	.0		
2	.0012	.1041	.1029				1.69	.50		
4	.1041	.1315	.0274				4.00	.90		
8	.1315	.1628	.0313				3.24	.55		
16	.1628	.2025	.0397				1.69	.45		
32	.2025	.2550	.0525				2.25	.39		
64	.2550	.3048	.0498				1.46	.30		

10184 * FINAL DIAL READING MAY BE INFERRED DEPENDING ON ANALYSIS TIME

APPENDIX F (CONT'D)

TYPICAL CONSOLIDATION TEST DATA

CONBEL GAGE SETTING 2.6

TEST SERIES 10A

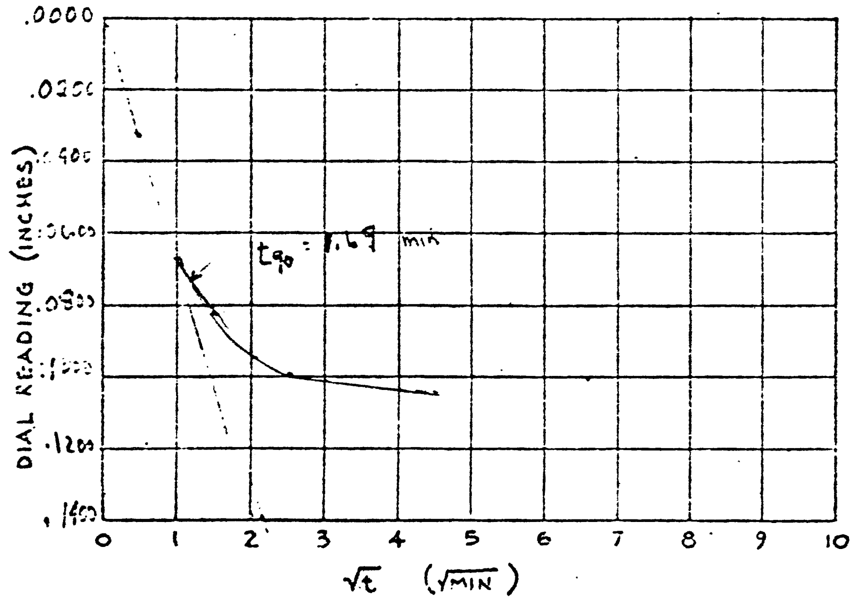
PRESSURE INCREMENT APPLIED 2 psi ~~KG/SQ.CM~~

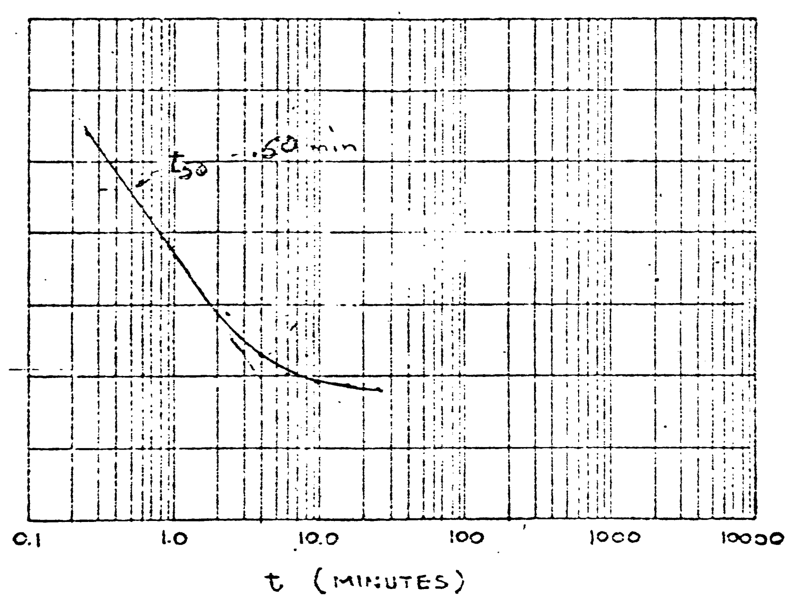
FROM PRESSURE OF 0 ~~KG/SQ.CM~~ psi

REMARKS:

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)
		0	0	.0012
		0.25	0.5	.0330
		1.00	1.0	.0630
		2.25	1.5	.0820
		4.00	2.0	.0952
		6.25	2.5	.0998
		9.00	3.0	.1015
		12.25	3.5	.1025
		16.00	4.0	.1035
		20.25	4.5	.1041
		25.00	5.0	

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)





APPENDIX F (CONT'D)

TYPICAL CONSOLIDATION TEST DATA

CONSOL GAGE SETTING 3.4

TEST SERIES 10A

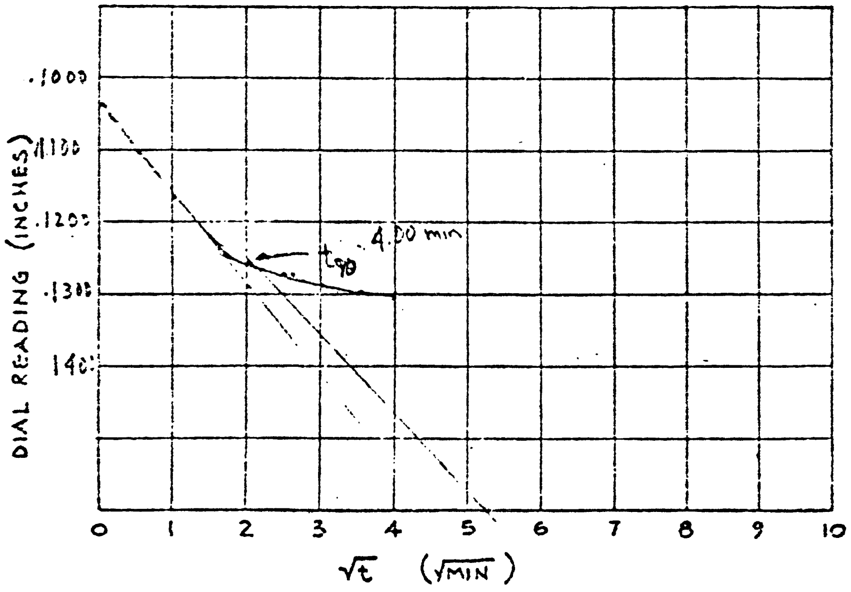
PRESSURE INCREMENT APPLIED 4 psi ~~KG/SQCM~~

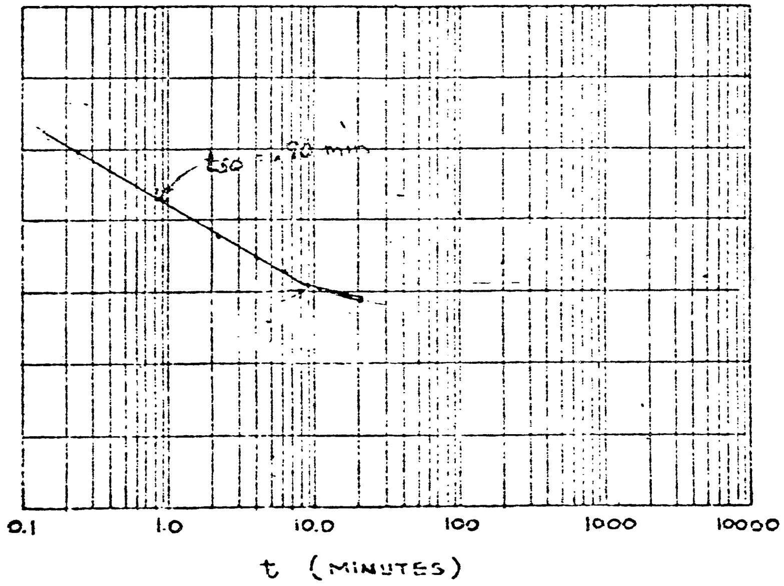
FROM PRESSURE OF 2 KG/SQCM psi

REMARKS: ______

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)
		0	0	.1041
		0.25	0.5	.1104
		1.00	1.0	.1173
		2.25	1.5	.1224
		4.00	2.0	.1256
		6.25	2.5	.1276
		9.00	3.0	.1291
		12.25	3.5	.1301
		16.00	4.0	.1307
		20.25	4.5	1315
		25.00	5.0	

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)





APPENDIX F (CONT'D)

TYPICAL CONSOLIDATION TEST DATA

CONBEL GAGE SETTING 4.8

TEST SERIES 10 A

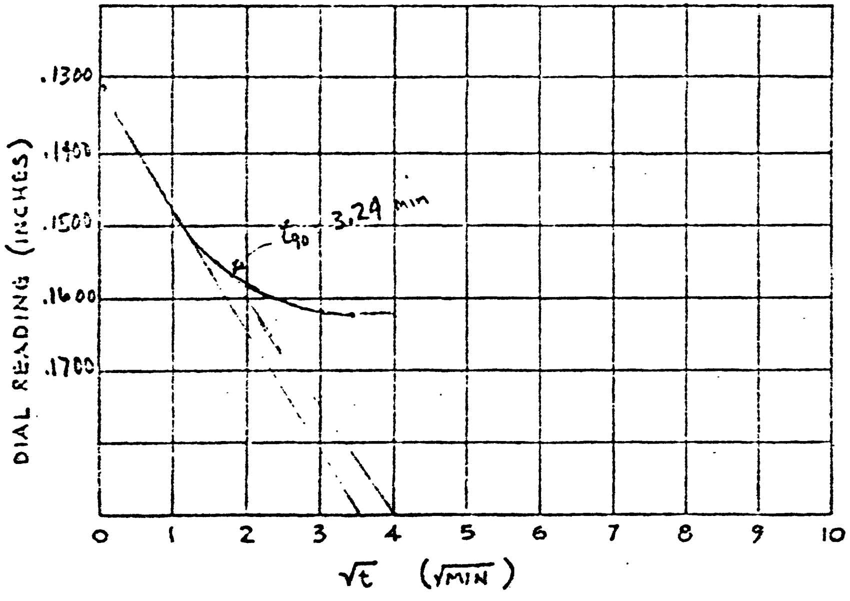
PRESSURE INCREMENT APPLIED 8 ~~KG/SQ CM~~ PSC

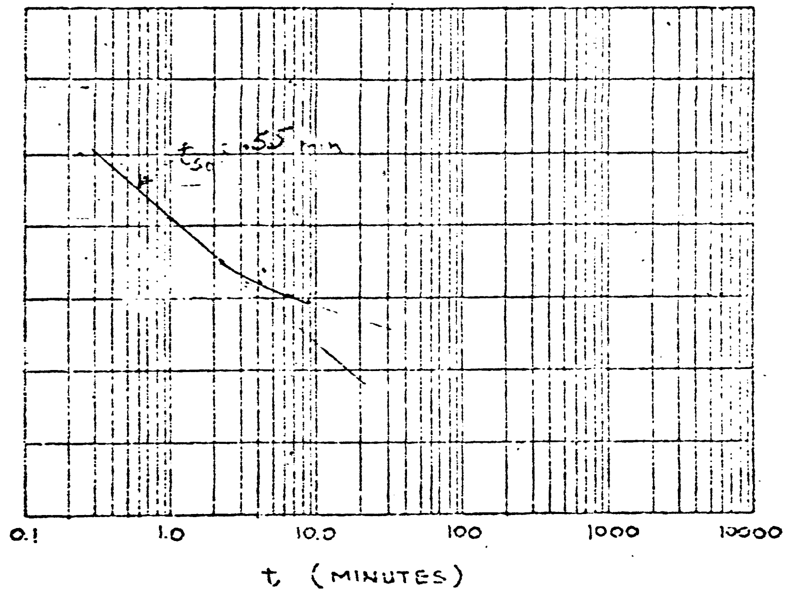
FROM PRESSURE OF 4 ~~KG/SQCM~~ PSC

REMARKS:

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)
		0	0	.1315
		0.25	0.5	.1400
		1.00	1.0	.1492
		2.25	1.5	.1554
		4.00	2.0	.1586
		6.25	2.5	.1604
		9.00	3.0	.1615
		12.25	3.5	.1623
		16.00	4.0	.1628
		20.25	4.5	
		25.00	5.0	

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)





APPENDIX F (CONT'D)

TYPICAL CONSOLIDATION TEST DATA

CONSEL GAGE SETTING 7.4

TEST SERIES 10 A

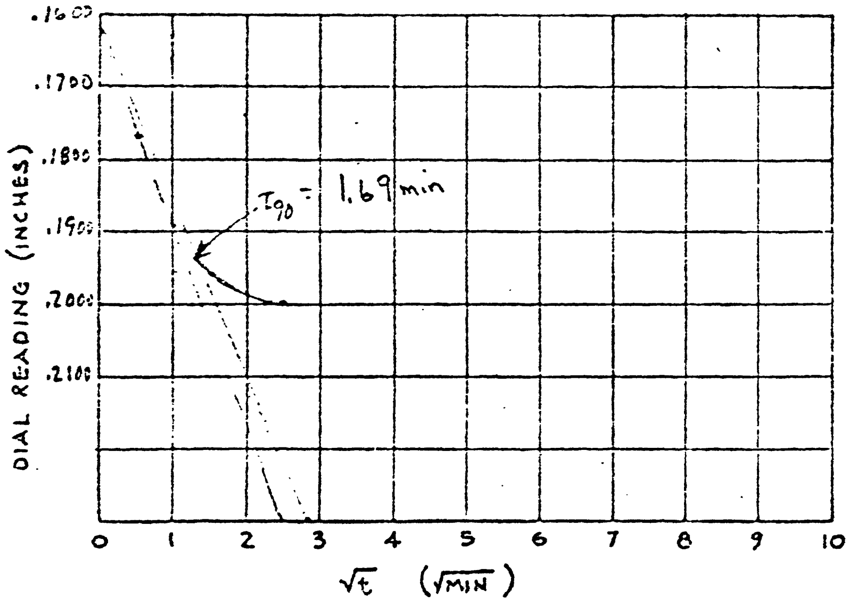
PRESSURE INCREMENT APPLIED 16 psi ~~KG/SQCM~~

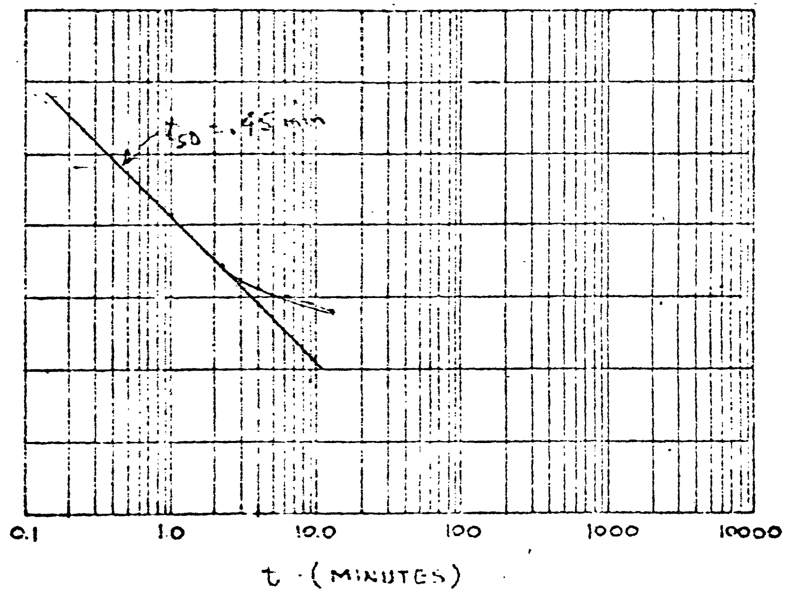
FROM PRESSURE OF 5 ~~KG/SQCM~~ psi

REMARKS:

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)
		0	0	.1628
		0.25	0.5	.1770
		1.00	1.0	.1894
		2.25	1.5	.1960
		4.00	2.0	.1970
		6.25	2.5	.2004
		9.00	3.0	.2013
		12.25	3.5	.2020
		16.00	4.0	.2026
		20.25	4.5	
		25.00	5.0	

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)





APPENDIX F (CONT'D)

TYPICAL CONSOLIDATION TEST DATA

CONBEL GAGE SETTING 13.5

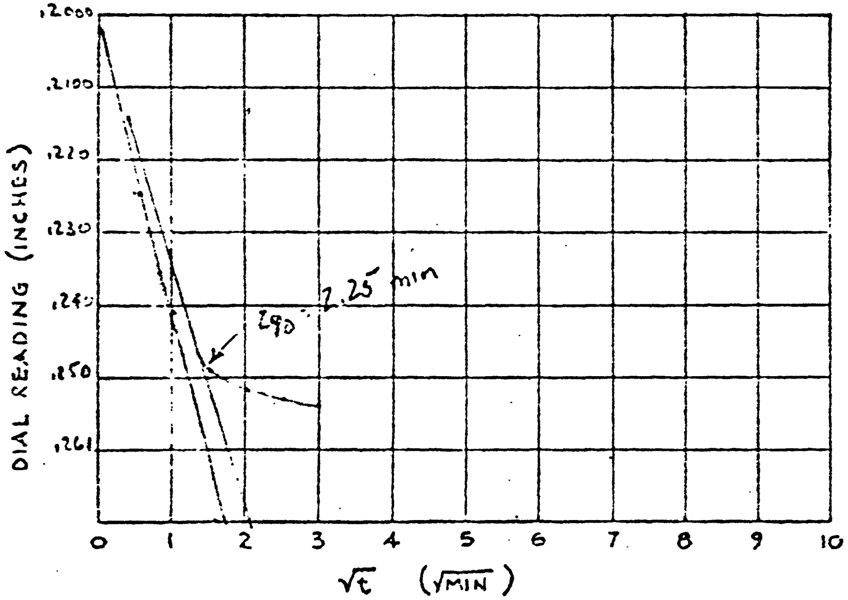
TEST SERIES 10 A

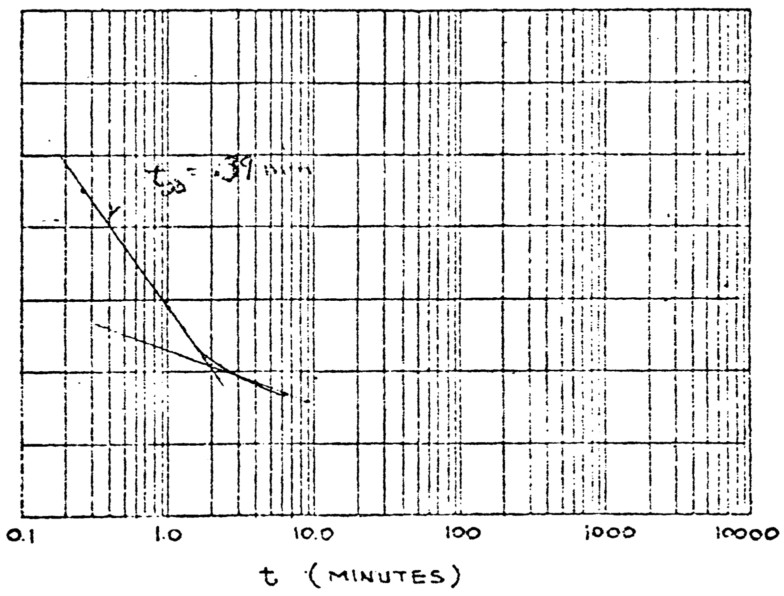
PRESSURE INCREMENT APPLIED 32 KG/SQ CM
FROM PRESSURE OF 16 KG/SQ CM

REMARKS:

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)
		0	0	.2025
		0.25	0.5	.2250
		1.00	1.0	.2418
		2.25	1.5	.2472
		4.00	2.0	.2520
		6.25	2.5	.2530
		9.00	3.0	.2540
		12.25	3.5	.2545
		16.00	4.0	.2550
		20.25	4.5	
		25.00	5.0	

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)





APPENDIX F (CONT'D)

TYPICAL CONSOLIDATION TEST DATA

CONBEL GAGE SETTING 26.5

TEST SERIES 10 A

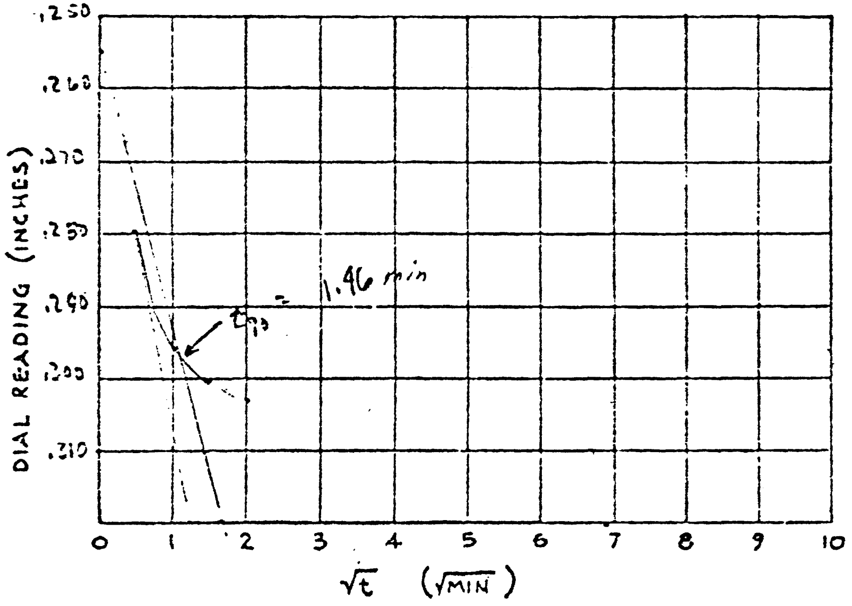
PRESSURE INCREMENT APPLIED 64 KG/SQ CM psi

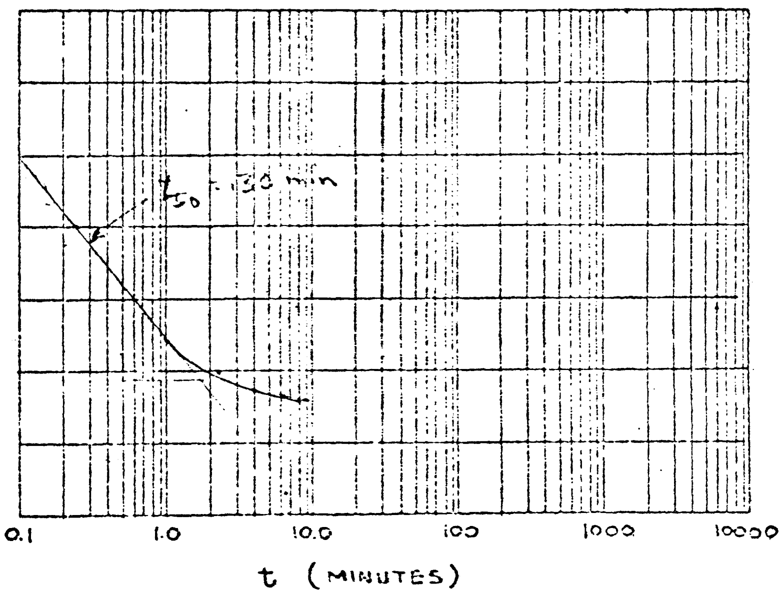
FROM PRESSURE OF 32 KG/SQCM psi

REMARKS:

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)
		0	0	.2550
		0.25	0.5	.2800
		1.00	1.0	.2960
		2.25	1.5	.3009
		4.00	2.0	.3032
		6.25	2.5	.3036
		9.00	3.0	.3043
		12.25	3.5	.3098
		16.00	4.0	
		20.25	4.5	
		25.00	5.0	

DATE	TIME	ELAPSED TIME t (MIN)	$\sqrt{t}$ ($\sqrt{MIN}$)	COMPRESSION DIAL READING (INCHES)





APPENDIX G

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
RUN
LIME     0940

SAMPLE?9A
WEIGHTS: DRY SAMPLE, WATER?
                                   39.0,50.0
NUMBER OF LOADINGS?
                         7
PRESSURE, DELTA Z, T90, T50
?
 2,.0850,1.96,.50
?
 4,.0256,2.89,.80
?
 8,.0400,1.44,.75
?
 16,.0478,1.00,.55
?
 32,.0599,1.00,.45
?
 64,.0567,1.44,.50

TEST NUMBER  9A

     INITIAL CONDITIONS: MOISTURE CONTENT 128.2 %OF DRY WEIGHT
                         SATURATION       112.6 %
                         DRY DENSITY        .639 GRAMS/CUCM

APPLIED                 COEF OF CONSOLIDATION        PERMEABILITY COEF
PRESSURE    VOID             (SQCM/SEC)                  (CM/SEC)
(KG/SQCM)   RATIO       METHOD 1    METHOD 2        METHOD 1    METHOD 2
---------   -----       ---------   ---------       ---------   ---------

   .000     2.68
   .141     2.26        6.0E-03     5.5E-03         5.0E-06     4.6E-06
   .281     2.14        3.5E-03     2.9E-03         9.5E-07     8.0E-07
   .562     1.95        6.3E-03     2.8E-03         1.4E-06     6.3E-07
  1.125     1.72        7.8E-03     3.3E-03         1.1E-06     4.8E-07
  2.250     1.43        6.4E-03     3.3E-03         6.5E-07     3.3E-07
  4.500     1.15        3.5E-03     2.4E-03         1.9E-07     1.3E-07
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS
OF CONSOLIDATION TEST DATA

```
SAMPLE?
      10A
WEIGHTS: DRY SAMPLE, WATER?
                               37.7,39.3
NUMBER OF LOADINGS?
                       7
PRESSURE, DELTA Z, T90, T50
?
 2,.1029,1.69,.50
?
 4,.0274,4.00,.90
?
 8,.0313,3.24,.55
?
 16,.0397,1.69,.45
?
 32,.0525,2.25,.39
?
 64,.0498,1.46,.30

TEST NUMBER  10A

     INITIAL CONDITIONS: MOISTURE CONTENT 104.2 %OF DRY WEIGHT
                         SATURATION        87.4 %
                         DRY DENSITY        .618 GRAMS/CUCM

APPLIED                   COEF OF CONSOLIDATION      PERMEABILITY COEF
PRESSURE    VOID              (SQCM/SEC)                 (CM/SEC)
(KG/SQCM)   RATIO         METHOD 1    METHOD 2     METHOD 1    METHOD 2
---------   -----         ---------   ---------    ---------   ---------

   .000     2.80
   .141     2.29          6.8E-03     5.3E-03      7.0E-06     5.5E-06
   .281     2.15          2.4E-03     2.4E-03      7.1E-07     7.4E-07
   .562     1.99          2.7E-03     3.6E-03      4.8E-07     6.6E-07
  1.125     1.80          4.5E-03     3.9E-03      5.5E-07     4.8E-07
  2.250     1.53          2.9E-03     3.8E-03      2.5E-07     3.4E-07
  4.500     1.28          3.6E-03     4.1E-03      1.7E-07     1.9E-07
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
      11A
WEIGHTS: DRY SAMPLE, WATER?
                                   56.1,39.8
NUMBER OF LOADINGS?
                           9
PRESSURE, DELTA Z, T90, T50
?
 2,.0477,.49,0
?
 4,.0080,.49,0
?
 8,.0509,.30,0
?
 16,.0156,.20,.15
?
 32,.0862,←←←←←0259,.16,.13
?
 64,.0340,.16,0
?
 16,-.0026,0,0
?2,-.0040,0,0

TEST NUMBER  11A

     INITIAL CONDITIONS: MOISTURE CONTENT   70.9 %OF DRY WEIGHT
                         SATURATION        107.2 %
                         DRY DENSITY          .920 GRAMS/CUCM

APPLIED                   COEF OF CONSOLIDATION        PERMEABILITY COEF
PRESSURE     VOID              (SQCM/SEC)                   (CM/SEC)
(KG/SQCM)    RATIO       METHOD 1    METHOD 2        METHOD 1    METHOD 2
---------    -----       ---------   ---------       ---------   ---------

   .000      1.56
   .141      1.39        2.5E-02
   .281      1.37        2.3E-02                     1.2E-05
   .562      1.20        3.5E-02                     1.9E-06
  1.125      1.14        4.8E-02                     9.3E-06
  2.250      1.06        5.6E-02     1.5E-02         2.0E-06     6.3E-07
  4.500       .94        5.0E-02     1.6E-02         2.0E-06     5.9E-07
  1.125       .95                                    1.3E-06
   .141       .97
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?12A
WEIGHTS: DRY SAMPLE, WATER?
                                    36.7,45.1
NUMBER OF LOADINGS?
                   9
PRESSURE, DELTA Z, T90, T50
?
 2,.0807,.16,0
?
 4,.0193,2.25,.41
?
 8,.0249,1.96,.36
?
 16,.0337,1.44,.32
?
 32,.0472,.81,.23
?
 64,.0477,.49,.19
?
 16,-.0040,0,0
?
 2,-.0058,0,0

TEST NUMBER  12A

      INITIAL CONDITIONS: MOISTURE CONTENT 122.9 %OF DRY WEIGHT
                          SATURATION        99.4 %
                          DRY DENSITY        .602 GRAMS/CUCM

APPLIED                COEF OF CONSOLIDATION       PERMEABILITY COEF
PRESSURE    VOID           (SQCM/SEC)                  (CM/SEC)
(KG/SQCM)   RATIO     METHOD 1     METHOD 2       METHOD 1     METHOD 2
---------   -----     ---------    ---------      ---------    ---------

   .000     2.91
   .141     2.49      7.4E-02                     5.9E-05
   .281     2.39      4.5E-03      5.8E-03        9.3E-07      1.2E-06
   .562     2.26      4.9E-03      6.2E-03        6.7E-07      8.4E-07
  1.125     2.09      6.1E-03      6.3E-03        5.9E-07      6.1E-07
  2.250     1.85      9.4E-03      7.7E-03        6.8E-07      5.6E-07
  4.500     1.60      1.3E-02      7.8E-03        5.2E-07      3.1E-07
  1.125     1.62
   .141     1.65
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
      13A
WEIGHTS: DRY SAMPLE, WATER?
                                34.2,48.0
NUMBER OF LOADINGS?
                         9
PRESSURE, DELTA Z, T90, T50
?
 2,.0767,1.00,.30
?
 4,.0151,1.00,.30
?
 8,.0259,.49,.39
?
 16,.0457,1.69,.20
?
 32,.0606,1.21,.24
?
 64,.0561,.64,.17
?
 16,-.0033,0,0
?
 2,.0048,0,0

TEST NUMBER  13A

    INITIAL CONDITIONS: MOISTURE CONTENT 140.4 %OF DRY WEIGHT
                        SATURATION       103.3 %
                        DRY DENSITY        .561 GRAMS/CUCM
APPLIED
PRESSURE    VOID     COEF OF CONSOLIDATION     PERMEABILITY COEF
(KG/SQCM)   RATIO          (SQCM/SEC)              (CM/SEC)
---------   -----    METHOD 1   METHOD 2      METHOD 1   METHOD 2
                     ---------  ---------     ---------  ---------

  .000      3.19
  .141      2.77     1.2E-02    9.2E-03       9.0E-06    6.9E-06
  .281      2.69     1.0E-02    8.1E-03       1.7E-06    1.3E-06
  .562      2.54     2.0E-02    5.8E-03       2.8E-06    8.2E-07
 1.125      2.29     5.2E-03    1.0E-02       6.8E-07    1.3E-06
 2.250      1.96     6.0E-03    7.1E-03       5.7E-07    6.7E-07
 4.500      1.65     9.2E-03    8.0E-03       4.5E-07    3.9E-07
 1.125      1.66
  .141      1.64
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
      9A, 20% SAND
WEIGHTS: DRY SAMPLE, WATER?
                        66.4,36.3
NUMBER OF LOADINGS?
                 9
PRESSURE, DELTA Z, T90, T50
?
 2,.0095,.10,0
?
 4,.0022,.16,0
?
 8,.0057,1.69,.25
?
 16,.0151,.64,.30
?
 32,.0145,.16,.10
?
 64,.0151,1.69,.15
?
 16,-.0031,0,0
?
 2,-.0045,0,0

TEST NUMBER  9A, 20% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT  54.7 %OF DRY WEIGHT
                         SATURATION       110.9 %
                         DRY DENSITY        1.089 GRAMS/CUCM

APPLIED              COEF OF CONSOLIDATION     PERMEABILITY COEF
PRESSURE   VOID          (SQCM/SEC)                (CM/SEC)
(KG/SQCM)  RATIO     METHOD 1   METHOD 2   METHOD 1   METHOD 2
---------  -----     ---------  ---------  ---------  ---------

   .000    1.16
   .141    1.13      1.3E-01               1.2E-05
   .281    1.13      8.0E-02               1.7E-06
   .562    1.11      7.5E-03    1.2E-02    2.0E-07    3.2E-07
  1.125    1.07      1.9E-02    9.5E-03    7.0E-07    3.5E-07
  2.250    1.03      7.4E-02    2.7E-02    1.3E-06    4.9E-07
  4.500     .98      6.7E-03    1.8E-02    6.4E-08    1.7E-07
  1.125     .99
   .141    1.00
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
 SAMPLE?
          10A, 20% SAND
 WEIGHTS: DRY SAMPLE, WATER?
 NUMBER OF LOADINGS?           54.0,39.7
                               8
 PRESSURE, DELTA Z, T90, T50
 ?
  2,.0363,.64,.18
 ?
  4,.0393,1.0,.30
 ?
  8,.0216M-,1.44,.19
 ?
  16,.0286,2.56,.27
 ?
  32,.0368,.64,.16
 ?
  8,.0038,0,0
 ?
  2,.0018,0,0

TEST NUMBER  10A, 20% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT   73.5 %OF DRY WEIGHT
                         SATURATION        104.4 %
                         DRY DENSITY         .885 GRAMS/CUCM
APPLIED
PRESSURE    VOID       COEF OF CONSOLIDATION       PERMEABILITY COEF
(KG/SQCM)   RATIO          (SQCM/SEC)                  (CM/SEC)
---------   -----      METHOD 1    METHOD 2       METHOD 1    METHOD 2
                       ---------   ---------      ---------   ---------
  .000      1.65
  .141      1.53       2.0E-02     1.6E-02        6.8E-06     5.6E-06
  .281      1.39       1.1E-02     8.8E-03        4.5E-06     3.5E-06
  .562      1.32       7.2E-03     1.3E-02        8.2E-07     1.4E-06
 1.125      1.22       3.7E-03     8.2E-03        2.9E-07     6.5E-07
 2.250      1.09       1.4E-02     1.3E-02        7.2E-07     6.7E-07
  .562      1.07
  .141      1.07
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
        11A, 20% SAND
WEIGHTS: DRY SAMPLE, WATER?
                              56.6,39.6
NUMBER OF LOADINGS?
                     8
PRESSURE, DELTA Z, T90, T50
?
 2,.0504,.64,.15
?
 4,.0106,.36,0
?
 8,.0149,.49,0
?
 16,.0225,.25,0
?
 32,.0281,.25,0
?
 8,.0030,0,0
?
 2,.0029,0,0

TEST NUMBER  11A, 20% SAND

      INITIAL CONDITIONS: MOISTURE CONTENT  70.0 %OF DRY WEIGHT
                          SATURATION       107.3 %
                          DRY DENSITY        .928 GRAMS/CUCM

APPLIED               COEF OF CONSOLIDATION     PERMEABILITY COEF
PRESSURE    VOID          (SQCM/SEC)                (CM/SEC)
(KG/SQCM)   RATIO     METHOD 1    METHOD 2     METHOD 1    METHOD 2
---------   -----     ---------   ---------    ---------   ---------

   .000     1.53
   .141     1.36      1.9E-02     1.9E-02      9.4E-06     9.3E-06
   .281     1.33      3.1E-02                  3.4E-06
   .562     1.28      2.2E-02                  1.7E-06
  1.125     1.20      4.1E-02                  2.5E-06
  2.250     1.11      3.8E-02                  1.5E-06
   .562     1.10
   .141     1.09
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
       12A, 20% SAND
WEIGHTS: DRY SAMPLE, WATER?
                            58.1,37.4
NUMBER OF LOADINGS?
                    8
PRESSURE, DELTA Z, T90, T50
?
 2,.0331,.25,0
?
 4,.0062,.36,0
?
 8,.0111,.16,0
?
 16,.0154,.16,0
?
 32,.0205,.16,0
?
 8,-.0024,0,0
?2,-.0018,0,0

TEST NUMBER  12A, 20% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT  64.4 %OF DRY WEIGHT
                         SATURATION       103.1 %
                         DRY DENSITY         .952 GRAMS/CUCM

APPLIED                 COEF OF CONSOLIDATION     PERMEABILITY COEF
PRESSURE    VOID             (SQCM/SEC)                (CM/SEC)
(KG/SQCM)   RATIO       METHOD 1    METHOD 2     METHOD 1   METHOD 2
---------   -----       ---------   ---------    ---------  ---------

   .000     1.47
   .141     1.36        5.0E-02                  1.6E-05
   .281     1.34        3.3E-02                  2.0E-06
   .562     1.30        7.3E-02                  4.0E-06
 1.125      1.25        7.0E-02                  2.7E-06
  2.250     1.19        6.7E-02                  1.8E-06
   .562     1.19
   .141     1.20
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?13A, 20% SAND
WEIGHTS: DRY SAMPLE, WATER?
                           53.6,38.4
NUMBER OF LOADINGS?
                   9
PRESSURE, DELTA Z, T90, T50
?
 2,.0048,.36,0
?
 4,.0035,.25,.20
?
 8,.0058,.16,0
?
 16,.0103,.16,0
?
 32,.0204,.25,0
?
 64,.0292,.16,0
?
 16,.0030,0,0
?
 2,.0036,0,0

TEST NUMBER  13A, 20% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT  71.6 %OF DRY WEIGHT
                         SATURATION       100.5 %
                         DRY DENSITY         .879 GRAMS/CUCM

APPLIED               COEF OF CONSOLIDATION     PERMEABILITY COEF
PRESSURE    VOID           (SQCM/SEC)             (CM/SEC)
(KG/SQCM)   RATIO     METHOD 1    METHOD 2    METHOD 1   METHOD 2
---------   -----     ---------   ---------   ---------  ---------

   .000     1.67
   .141     1.66      3.6E-02                 1.6E-06
   .281     1.65      5.2E-02     1.5E-02     1.7E-06    5.0E-07
   .562     1.62      8.0E-02                 2.2E-06
  1.125     1.59      7.8E-02                 1.9E-06
  2.250     1.52      4.8E-02                 1.2E-06
  4.500     1.41      7.0E-02                 1.3E-06
  1.125     1.40
   .141     1.39
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
       9A, 20% SAND←←←←←←←←40% SAND
WEIGHTS: DRY SAMPLE, WATER?67.2,33.0
NUMBER OF LOADINGS?
                  9
PRESSURE, DELTA Z, T90, T50
?
 2,.0175,.16,0
?
 4,.0059,.12,0
?
 8,.0066,.12,0
?
 16,.0102,.16,0
?
 32,.0170,.16,0
?
 64,.0240,.10,0
?
 16,.0029,0,0
?
 2,.0122,0,0

TEST NUMBER  9A, 240% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT  49.1 %OF DRY WEIGHT
                         SATURATION       101.8 %
                         DRY DENSITY        1.102 GRAMS/CUCM

APPLIED                COEF OF CONSOLIDATION      PERMEABILITY COEF
PRESSURE     VOID          (SQCM/SEC)                 (CM/SEC)
(KG/SQCM)    RATIO     METHOD 1    METHOD 2     METHOD 1    METHOD 2
---------    -----     ---------   ---------    ---------   ---------

   .000      1.13
   .141      1.08      8.0E-02                  1.3E-05
   .281      1.07      1.0E-01                  5.9E-06
   .562      1.05      1.0E-01                  3.3E-06
  1.125      1.02      7.5E-02                  1.9E-06
  2.250       .97      7.2E-02                  1.5E-06
  4.500       .91      1.1E-01                  1.7E-06
  1.125       .90
   .141       .86
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
       10A, 40% SAND
WEIGHTS: DRY SAMPLE, WATER?
                                    54.9,38.7
NUMBER OF LOADINGS?
                         8
PRESSURE, DELTA Z, T90, T50
?
 2,.0722,2.25,.45
?
 4,.0164,1.21,.35
?
 8,.0212,1.69,.30
?
 16,.0288,.81,.25
?
 32,.0300,.81,.18
?
 8,-.0026,0,0
?
 2,-.0033,0,0

TEST NUMBER  10A, 40% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT  70.5 %OF DRY WEIGHT
                         SATURATION       102.8 %
                         DRY DENSITY        .900 GRAMS/CUCM

APPLIED                  COEF OF CONSOLIDATION     PERMEABILITY COEF
PRESSURE    VOID              (SQCM/SEC)               (CM/SEC)
(KG/SQCM)   RATIO        METHOD 1   METHOD 2     METHOD 1   METHOD 2
---------   -----        ---------  ---------    ---------  ---------

   .000     1.61
   .141     1.36         5.3E-03    6.2E-03      3.8E-06    4.4E-06
   .281     1.31         8.7E-03    7.0E-03      1.5E-06    1.2E-06
   .562     1.23         5.9E-03    7.7E-03      6.7E-07    8.8E-07
  1.125     1.13         1.1E-02    8.6E-03      9.2E-07    6.9E-07
  2.250     1.03         1.0E-02    1.1E-02      4.6E-07    4.8E-07
   .562     1.04
   .141     1.05
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
       11A, 40% SAND
WEIGHTS: DRY SAMPLE, WATER?
                            59•1,37•7
NUMBER OF LOADINGS?
                   8
PRESSURE, DELTA Z, T90, T50
?
 2,•0622,•81,0
?
 4,•0106,•64,0
?
 8,•0163,•64,0
?
 16,•0218,•49,0
?
 32,•0300,•49,0
?
 8,•0026,0,0
?
 2,•0026,0,0

TEST NUMBER  11A, 40% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT  63•8 %OF DRY WEIGHT
                         SATURATION       105•2 %
                         DRY DENSITY         •969 GRAMS/CUCM

APPLIED                 COEF OF CONSOLIDATION      PERMEABILITY COEF
PRESSURE    VOID              (SQCM/SEC)                (CM/SEC)
(KG/SQCM)   RATIO       METHOD 1    METHOD 2     METHOD 1    METHOD 2
---------   -----       ---------   ---------    ---------   ---------

   •000     1•43
   •141     1•23        1•5E-02                  9•1E-06
   •281     1•19        1•7E-02                  1•9E-06
   •562     1•14        1•6E-02                  1•4E-06
  1•125     1•07        2•0E-02                  1•2E-06
  2•250      •98        1•9E-02                  7•9E-07
   •562      •97
   •141      •96
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
       12A, 40% SAND
WEIGHTS: DRY SAMPLE, WATER?
                               61.5,35.6
NUMBER OF LOADINGS?
                     8
PRESSURE, DELTA Z, T90, T50
?
 2,.0586,1.69,.30
?
 4,.0089,2.25,.50
?
 8,.0157,.81,.18
?
 16,.0187,.49,0
?
 32,.0222,.25,0
?
 8,-.0024,0,0
?
 2,-.0026,0,0

TEST NUMBER  12A, 40% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT  57.9 %OF DRY WEIGHT
                         SATURATION       102.2 %
                         DRY DENSITY        1.008 GRAMS/CUCM

APPLIED                  COEF OF CONSOLIDATION     PERMEABILITY COEF
PRESSURE     VOID             (SQCM/SEC)                (CM/SEC)
(KG/SQCM)    RATIO       METHOD 1     METHOD 2     METHOD 1    METHOD 2
---------    -----       ---------    ---------    ---------   ---------

   .000      1.33
   .141      1.15        7.2E-03      9.4E-03      4.1E-06     5.4E-06
   .281      1.12        4.9E-03      5.1E-03      4.5E-07     4.7E-07
   .562      1.08        1.3E-02      1.4E-02      1.1E-06     1.1E-06
  1.125      1.02        2.1E-02                   1.0E-06
  2.250       .95        3.8E-02                   1.2E-06
   .562       .96
   .141       .97
```

APPENDIX G (CONT'D)

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
SAMPLE?
       13A, 40% SAND
WEIGHTS: DRY SAMPLE, WATER?
                                    40.5,44.1
NUMBER OF LOADINGS?
                              8
PRESSURE, DELTA Z, T90, T50
?
 2,.0345,1.69,.25
?
 4,.0275,1.00,.35
?
 8,.0192,.81,.25
?
 16,.0543,4.0,0
?
 32,.0654,1.0,.40
?
 8,.0026,0,0
?
 2,.0030,0,0

TEST NUMBER- 13A, 40% SAND

     INITIAL CONDITIONS: MOISTURE CONTENT 108.9 %OF DRY WEIGHT
                         SATURATION       100.8 %
                         DRY DENSITY         .664 GRAMS/CUCM

APPLIED                 COEF OF CONSOLIDATION      PERMEABILITY COEF
PRESSURE    VOID            (SQCM/SEC)                 (CM/SEC)
(KG/SQCM)   RATIO       METHOD 1    METHOD 2     METHOD 1    METHOD 2
---------   -----       ---------   ---------    ---------   ---------

   .000     2.54
   .141     2.38        7.4E-03     1.2E-02      2.5E-06     3.9E-06
   .281     2.25        1.2E-02     7.7E-03      3.2E-06     2.1E-06
   .562     2.16        1.3E-02     1.0E-02      1.3E-06     1.0E-06
  1.125     1.91        2.4E-03                  3.6E-07
  2.250     1.60        8.0E-03     4.6E-03      7.8E-07     4.6E-07
   .562     1.59
   .141     1.58
```

APPENDIX G

COMPUTER PRINTOUT OF ANALYSIS OF CONSOLIDATION TEST DATA

```
90  DIM A$[20]
100  PRINT "SAMPLE";
110  INPUT A$
120  PRINT "WEIGHTS: DRY SAMPLE, WATER";
130  INPUT G1,G2
135  PRINT "NUMBER OF LOADINGS";
136  INPUT N
140  PRINT "PRESSURE, DELTA Z, T90, T50"
150  FOR J=2 TO N
160  INPUT P[J],D[J],T[J],U[J]
170  NEXT J
300  LET P[1]=Z=0
310  LET V1=31.6*.76*2.54001
320  LET V2=G1/2.35
330  LET E[1]=(V1-V2)/V2
340  LET S=G2/(V1-V2)*100
350  LET G3=G1/V1
360  PRINT
365  PRINT USING 600,A$
366  PRINT
370  PRINT USING 610,G2/G1*100
371  PRINT USING 611,S
372  PRINT USING 612,G3
373  PRINT
380  PRINT USING 640
381  PRINT USING 650
382  PRINT USING 660
383  PRINT USING 670
384  PRINT
400  FOR J=2 TO N
405  LET P[J]=P[J]*.4536/2.54001/2.54001
410  LET Z=Z+D[J]
420  LET V3=31.6*Z*2.54001
430  LET E[J]=(V1-V2-V3)/V2
440  LET H=(.76-Z+D[J]/2)*2.54001
445  IF T[J]<.05 THEN 455
450  LET B[J]=.848*H↑2/4/T[J]/60
455  IF U[J]<.05 THEN 470
460  LET C[J]=.197*H↑2/4/U[J]/60
470  LET K[J]=(E[J-1]-E[J])/(P[J]-P[J-1])
472  LET K[J]=K[J]/(1+E[J-1]/2+E[J]/2)
473  IF U[J]<.05 THEN 475
474  LET L[J]=K[J]*C[J]*.001
475  IF T[J]<.05 THEN 490
480  LET K[J]=K[J]*B[J]*.001
490  NEXT J
500  PRINT USING 700,P[1],E[1]
510  FOR J=2 TO N
511  IF T[J]<.05 AND U[J]<.05 THEN 517
512  IF T[J]<.05 THEN 519
513  IF U[J]<.01 THEN 521
514  GOTO 523
517  PRINT USING 700,P[J],E[J]
518  GOTO 530
519  PRINT USING 720,P[J],E[J],C[J],L[J]
520  GOTO 530
521  PRINT USING 730,P[J],E[J],B[J],K[J]
522  GOTO 530
523  PRINT USING 710,P[J],E[J],B[J],C[J],K[J],L[J]
530  NEXT J
535  PRINT
536  PRINT
537  PRINT
540  GOTO 100
600  :TEST NUMBER  ################
610  :      INITIAL CONDITIONS: MOISTURE CONTENT ###.# %OF DRY WEIGHT
611  :                          SATURATION       ###.# %
612  :                          DRY DENSITY        #.### GRAMS/CUCM
640  :APPLIED                 COEF OF CONSOLIDATION      PERMEABILITY COEF
650  :PRESSURE     VOID           (SQCM/SEC)                  (CM/SEC)
660  :(KG/SQCM)    RATIO      METHOD 1     METHOD 2     METHOD 1    METHOD 2
670  :---------    -----      ---------    ---------    ---------   ---------
700  :  #.###      #.###
710  :  #.###      #.###      #.###1111    #.###1111    #.###1111   #.###1111
720  :  #.###      #.###                   #.###1111                #.###1111
730  :  #.###      #.###      #.###1111                 #.###1111
800  END
```

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

The theory and assumptions used in this method are stated in the text. Application of the method is to be shown here.

Each layer is 12 inches of sludge

H = 1/2 total thickness of sludge

$C_v = 1.93 \times 10^{-2}$ ft^2/hr

γ_b = bouyant weight of sludge = **24 pcf**

t = 24 hours

$$C_v \times t_{24} = .019 \times 24 = .456$$

$$T_v = \frac{C_v \cdot t_{24}}{H^2} = n\Delta T_v \qquad n = \frac{.456}{H^2 \Delta T_v}$$

$$\Delta T_v = A \cdot (\Delta\zeta)^2 \qquad A = 1/2$$

$$\zeta = \frac{Z}{H}$$

Z = depth to point in question

H = thickness of one drainage layer

$\Delta\zeta$	ΔT_v
1/2	.125
1/4	.03125
1/3	.0555
1/5	.02
1/6	.0139

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

Layer	H (ft)	n/1 day $\Delta\zeta=1/4$	$\Delta\zeta=1/2$	$\Delta\zeta=1/6$	$\Delta\zeta=1/3$	$\Delta\zeta=1/5$
I	.5	59	14.7			
II	1.0	14.7	3.65			
III	1.5				3.65	
IV	2.0	3.65				
V	2.5					3.65
VI	3.0			3.65	.9	
Surcharge	3.0			3.65	.9	

PORE PRESSURE COMPUTATIONS (PSF) FOR LAYER NO. 1 (See Figure 43)

$\Delta T_v = .03125$ $\Delta T_v = .125$

H = .5	n = 0	1	2		20 5	6	7.4	14.7
	0	0	0	....	0	0	0	0
	3	3	3	....	1.13			
	6	6	6	....	1.93	1.36	.85	.05
	9	9	9	....	2.73			
I	12	12	12	....	2.73	1.93	1.20	.08
	15	15	15	....	2.73			
	18	18	12	....	1.93	1.36	.85	.05
	21	9	9	....	1.13			
	0	0	0	....	0	0	0	0

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

PORE PRESSURE COMPUTATIONS (PSF) FOR LAYERS NO. I and II (See Figure 43)

	ΔT_v = .03125			ΔT_v = .125		
n =	0	1	8	3	3.7	4
H = 1.0	0	0	0	0	0	0
	6	6	4.7			
	12	12	8.8	6.55	5.2	4.6
	18	18	11.8			
II	24	21.02	13.1	9.20	7.3	6.55
	24.05	24.04	12.5			
I	24.08	24.05	9.6	6.55	5.2	4.6
	24.05	12.04	5.3			
	0	0	0	0	0	0

PORE PRESSURE COMPUTATIONS (PSF) FOR LAYERS NO. I, II and III (See Figure 43)

	ΔT_v = .0555			
n =	0	1	3	3.7
H = 1.5	0	0	0	0
III	12	12	9.9	9.1
	24	20.6	17.6	16.0
II	29.2	27.6	20.7	19.2
	31.3	29.2	19.7	17.6
I	29.2	15.6	10.8	10.1
	0	0	0	0

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

PORE PRESSURE COMPUTATIONS (PSF)
FOR LAYERS I, II, III and IV (See Figure 44)

$T_v = .03125$

		n = 0	1		3.7
H = 2.0	IV	0		. . . .	0
		12	12	. . . .	10.5
		24	22.5	. . . .	20.3
	III	33.1	32.0	. . . .	28.0
		40.0	38.2	. . . .	32.5
	II	43.2	40.8	. . . .	32.1
		41.6	38.6	. . . .	25.8
	I	34.1	20.8	. . . .	14.7
		0	0	. . . .	0

PORE PRESSURE COMPUTATIONS (PSF)
FOR LAYERS I, II, III, IV and V (See Figure 45)

$T_v = .02$

		n = 0		1.8		3.7
H = 2.5	V	0	. .	0	. .	0
		12	. .	11.7	. .	11.2
		24	. .	23.0	. .	22.0
	IV	34.5	. .	33.3	. .	31.5
		44.3	. .	42.4	. .	39.7
	III	52.0	. .	49.0	. .	45.2
		56.5	. .	52.2	. .	46.1
	II	56.1	. .	51.2	. .	43.4
		49.8	. .	40.7	. .	32.4
	I	38.7	. .	23.9	. .	18.6
		0	. .	0	. .	0

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

PORE PRESSURE COMPUTATIONS (PSF)

FOR LAYERS I, II, III, IV, V AND VI (See Figure 46)

$\Delta T_v = .0139$

		n = 0	1.8	3.7
H = 3.0		0	0	0
	VI	12	11.8	11.6
		24	22.8	23.0
	V	35.2	34.4	33.7
		46.1	45.0	43.7
	IV	55.8	54.0	52.2
		64.0	61.6	59.1
	III	69.7	66.1	62.3
		71.2	66.6	61.1
	II	68.0	62.6	55.0
		57.8	48.4	41.3
	I	42.9	27.9	22.7
		0	0	0

PORE PRESSURE COMPUTATIONS (PSF)

FOR LAYERS I, II, III, IV, V and VI PLUS 100 psf SURCHARGE
(See Figure 47)

		$\Delta T_v = .0139$		$\Delta T_v = .0555$		
		n = 0	6	2.5	19	28
H = 3.0		0	0	0	0	0
	VI	111.6	42.0			
		123.0	76.0	63	6	1.6
	V	133.7	109.0			
		143.7	126.0	110.5	10.4	2.8
	IV	152.2	142.0			
		159.1	145.0	129.5	12.1	3.2
	III	162.3	146.5			
		161.1	132.0	113.5	10.4	2.8
	II	155.0	117.5			
		141.3	82.0	66.0	6.0	1.6
	I	122.7	46.5			
		0	0	0	0	0

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

TABLE 22

CONSOLIDATION BY LAYERS*

$$\Delta = \frac{e}{1+e_o} \times 2H; \quad e_o = 2.80; \quad H = 0.5'$$

Layer	Avg. Pore Pressure psf	σ_{avg} Kg/cm^{-2}	e (Figure 20)	Δe	Δ (inches)
VI	109	.055	2.43	.37	1.17
V	127.8	.064	2.41	.39	1.23
IV	148.8	.074	2.39	.41	1.29
III	172.8	.086	2.37	.43	1.30
II	199.8	.100	2.34	.46	1.45
I	229.0	.115	2.31	.49	1.55

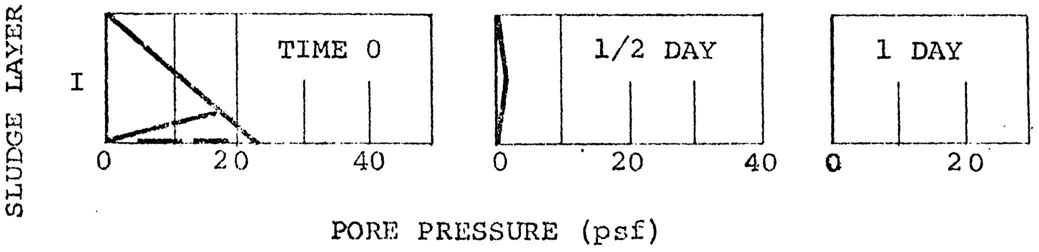
$\xi = 8.05''$

NOTE: This consolidation takes place at the end of the sixth day assuming that the placing of the surcharge at the end of the sixth day takes zero time.

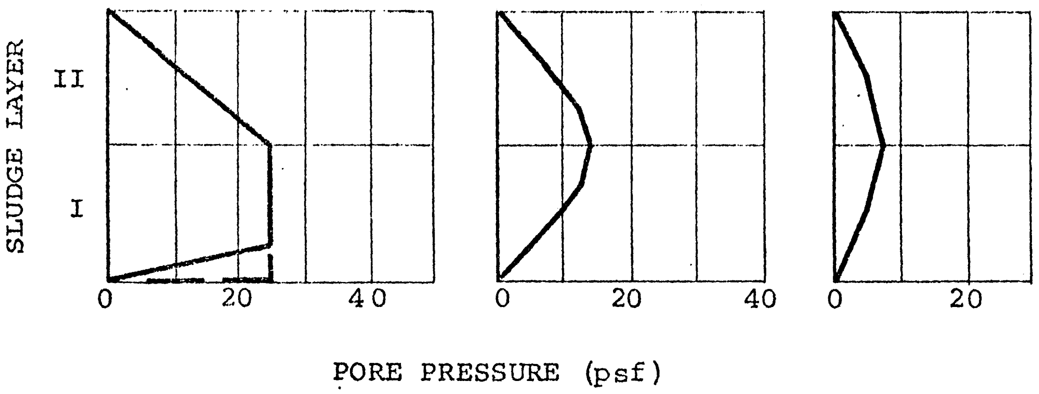
* All six layers plus 100 psf surcharge.

APPENDIX H

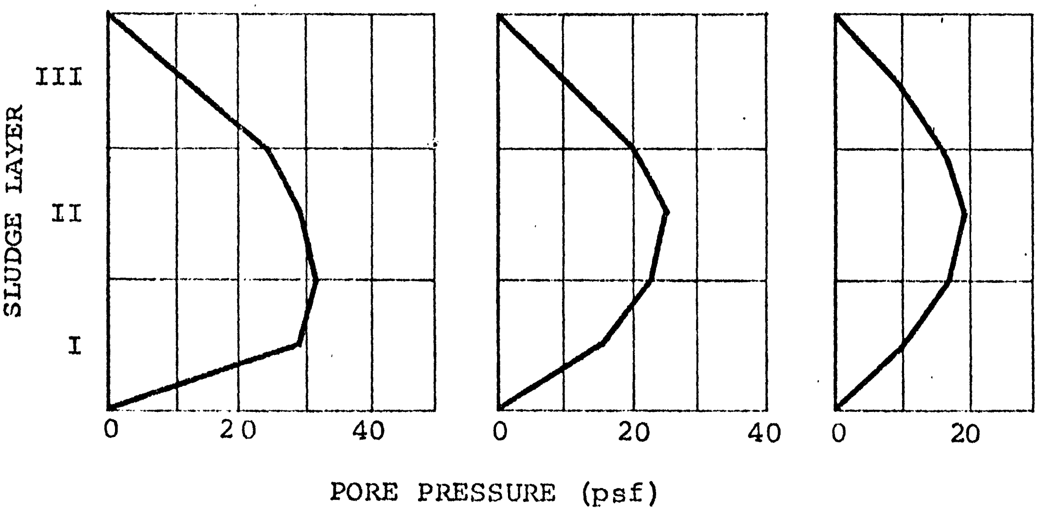
CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD



FIRST - 1 FOOT LAYER - SETTLED ONE DAY



SECOND - 1 FOOT LAYER ADDED AT END OF ONE DAY
- SETTLED ONE DAY

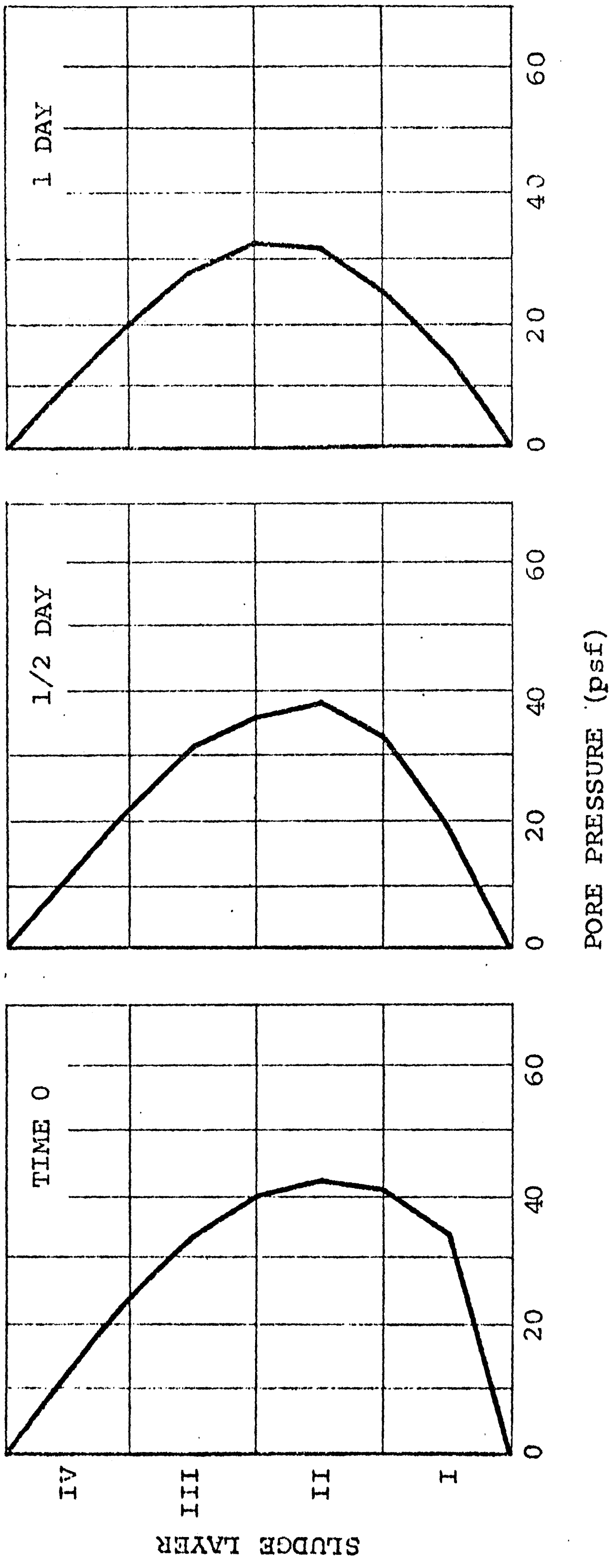


THIRD - 1 FOOT LAYER ADDED AT END OF SECOND DAY
- SETTLED ONE DAY

Figure 43. Pore Pressure Profiles
(1, 2, 3 - 1 Foot Layers of Sludge)

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

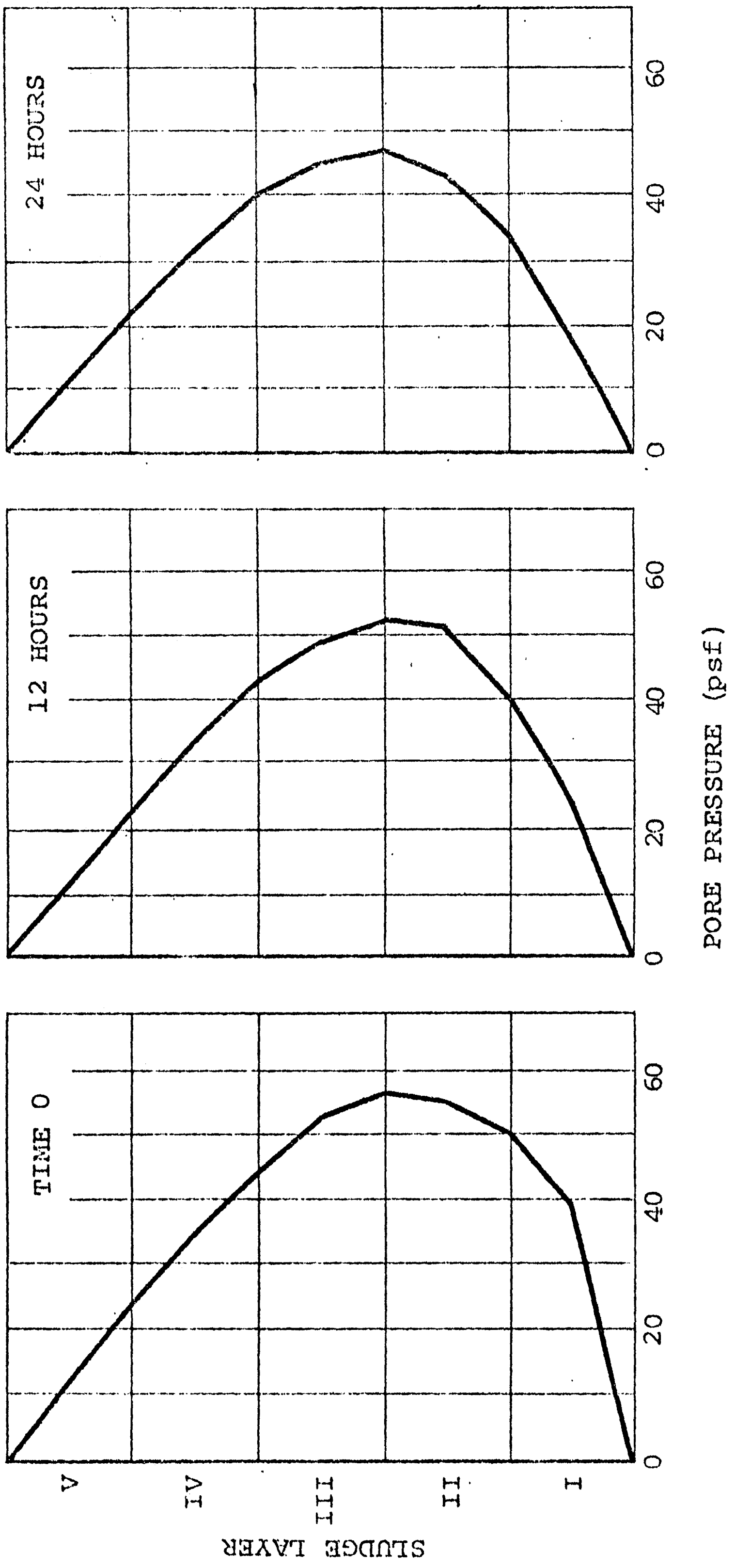


FOURTH - 1 FOOT LAYER ADDED AT END OF THIRD DAY
- SETTLED ONE DAY

Figure 44. Pore Pressure Profile
(4 - 1 Foot Layers of Sludge)

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

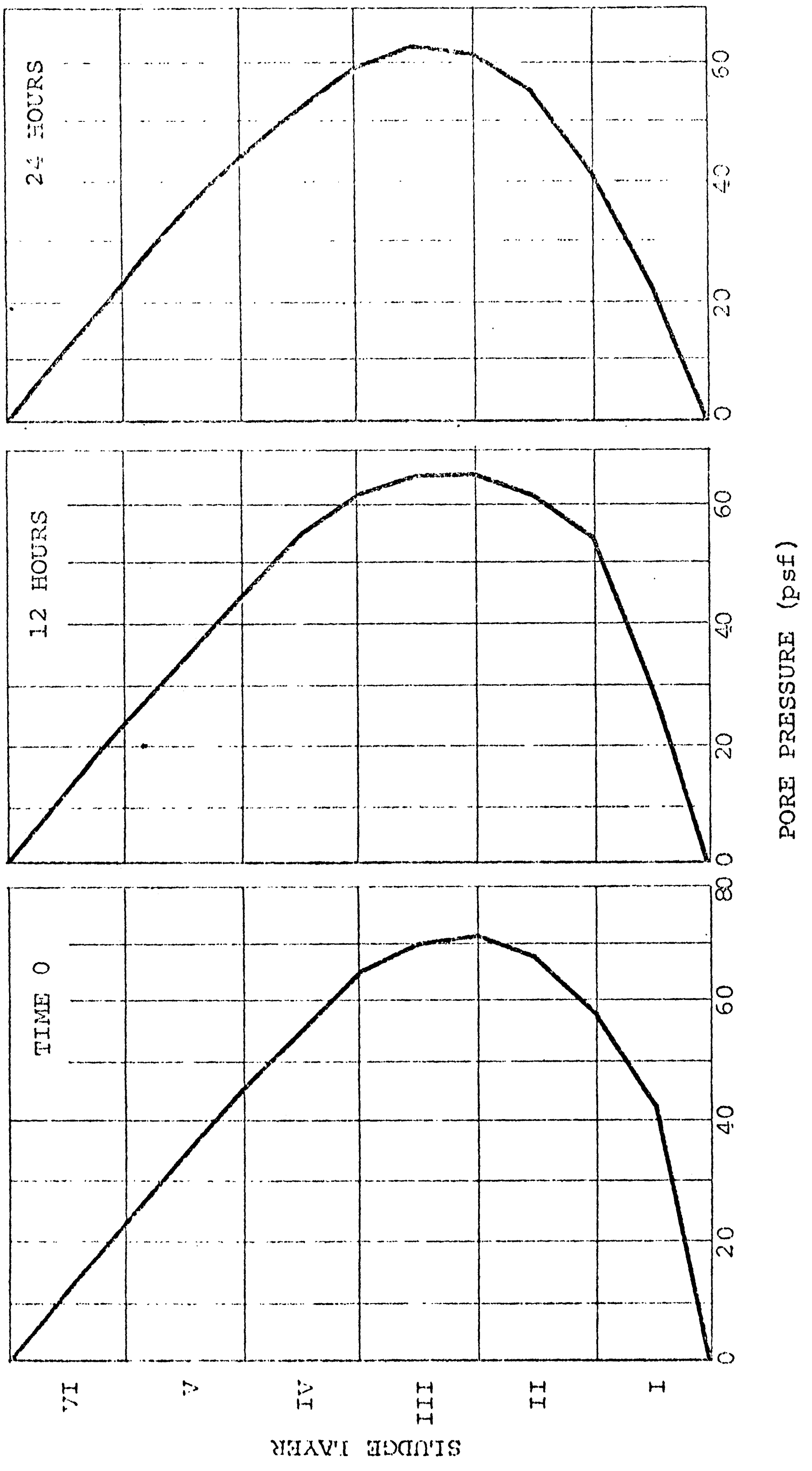


FIFTH - 1 FOOT LAYER ADDED AT THE END OF FOURTH DAY
- SETTLED ONE DAY

Figure 45. Pore Pressure Profile
(5 - 1 Foot Layers of Sludge)

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD

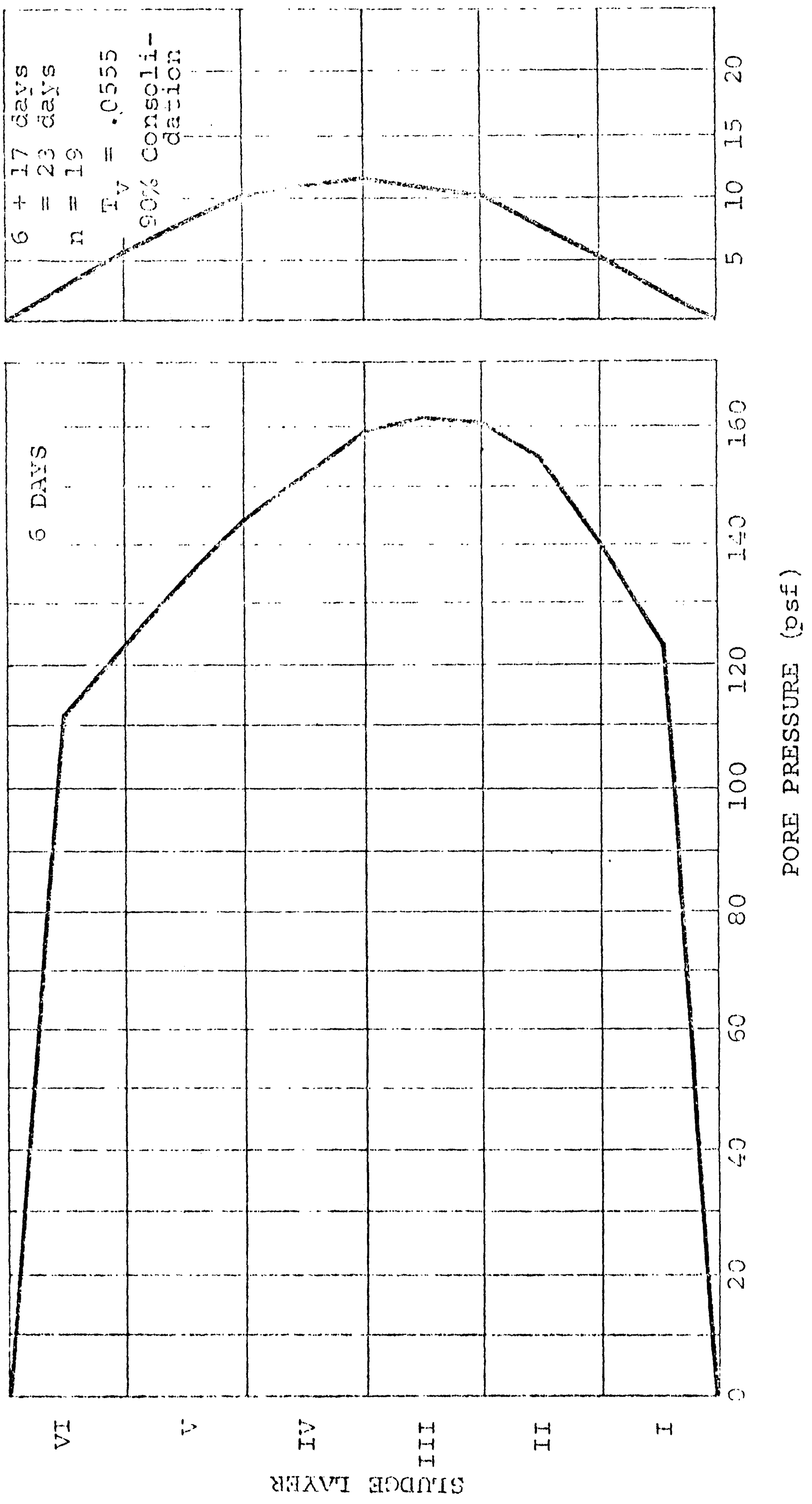


SIXTH - 1 FOOT LAYER ADDED AT END OF FIFTH DAY
- SETTLED ONE DAY

Figure 46. Pore Pressure Profile
(6 - 1 Foot Layers of Sludge)

APPENDIX H

CALCULATIONS FOR CONSOLIDATION OF LAYERED SYSTEMS BY NUMERICAL METHOD



100 PSF SURCHARGE - ADDED AT END OF SIXTH DAY

Figure 47. Pore Pressure Profile (100 psf Surcharge)

APPENDIX I

SAMPLE DATA AND COMPUTATIONS FROM TRIAXIAL TEST

APPENDIX I (CONT'D)

SAMPLE DATA AND COMPUTATIONS FROM TRIAXIAL TEST

Sample #4 Diam = 3.32 cm, Length = 8.30 cm, Area = 8.65 cm^2

31% Moisture, 30 psi Confining Pressure

Diff. Dial L	$\Delta L/L_o$ (Strain)	$A/(1 - \Delta L/L_o)$ (Strain)	Load Dial	(p) Load (kg)	$\Delta\sigma_1 = P/A$ (Stress)
.02	.024	8.659	60	3.120	.360
.05	.06	8.662	115	5.98	.69
.10	.12	8.667	195	10.14	1.17
.15	.181	8.673	250	13.00	1.499
.20	.241	8.678	320	16.64	1.918
.25	.30	8.683	370	19.240	2.216
.30	.36	8.688	415	21.580	2.484
.35	.422	8.694	467	24.284	2.793
.40	.482	8.699	515	26.780	3.079
.45	.542	8.704	560	29.120	3.346
.50	.602	8.709	600	31.200	3.582
.55	.663	8.715	640	33.28	3.82
.60	.72	8.72	680	35.36	4.055
.65	.78	8.725	715	37.18	4.26
.70	.84	8.73	750	39.00	4.47
.75	.90	8.74	790	41.08	4.70
.80	.96	8.74	820	42.64	4.88
.85	1.02	8.75	852	44.30	5.06
.90	1.08	8.75	882	45.86	5.24
.95	1.145	8.76	910	47.32	5.40
1.00	1.21	8.76	937	48.72	5.56
1.05	1.27	8.77	962	50.02	5.71
1.10	1.32	8.77	988	51.38	5.86
1.15	1.40	8.78	1017	52.88	6.02
1.20	1.45	8.78	1035	53.82	6.13
1.25	1.51	8.79	1060	55.12	6.27
1.30	1.57	8.795	1084	56.37	6.41

APPENDIX I (CONT'D)

SAMPLE DATA AND COMPUTATIONS FROM TRIAXIAL TEST

Sample #4 Diam = 3.32 cm, Length = 8.30 cm, Area = 8.65 cm^2

31% Moisture, 30 psi Confining Pressure

Diff. Dial L	$\Delta L/L_o$ (Strain)	$A/(1 - \Delta L/L_o)$ (Strain)	Load Dial	(p) Load (kg)	$\Delta\sigma_1 = P/A$ (Stress)
1.40	1.69	8.81	1122	58.34	6.63
1.45	1.75	8.81	1140	59.28	6.73
1.55	1.87	8.82	1160	60.32	6.84
1.60	1.93	8.83	1175	61.10	6.92
1.65	1.99	8.83	1200	62.40	7.07
1.70	2.05	8.84	1213	62.56	7.08
1.75	2.11	8.84	1225	63.70	7.20
1.80	2.17	8.85	1238	64.38	7.28
1.85	2.23	8.85	1253	65.16	7.36
1.90	2.29	8.86	1265	65.78	7.42
1.95	2.35	8.86	1280	66.56	7.51
2.00	2.41	8.87	1290	67.08	7.56
2.05	2.47	8.88	1302	67.70	7.63
2.10	2.53	8.88	1310	68.12	7.67
2.15	2.59	8.89	1320	68.64	7.72
2.20	2.65	8.89	1328	69.06	7.76
2.25	2.71	8.90	1335	69.42	7.80
2.30	2.77	8.90	1344	69.89	7.85
2.35	2.83	8.91	1350	70.20	7.88
2.40	2.89	8.92	1360	70.72	7.93
2.45	2.95	8.92	1368	71.14	7.98
2.50	3.01	8.93	1375	71.50	8.01
2.55	3.07	8.93	1382	71.86	8.05
2.60	3.13	8.94	1388	72.18	8.08
2.65	3.19	8.94	1397	72.64	8.12
2.70	3.25	8.95	1404	73.01	8.16

APPENDIX I (CONT'D)

SAMPLE DATA AND COMPUTATIONS FROM TRIAXIAL TEST

SAMPLE #4 Diam = 3.32 cm, Length = 8.30 cm, Area = 8.65 cm^2

31% Moisture, 30 psi Confining Pressure

Diff. Dial L	$\Delta L/L_o$ (Strain)	$A/(1 - \Delta L/L_o)$ (Strain)	Load Dial	(p) Load (kg)	$\Delta\sigma_1 = P/A$ (Stress)
2.75	3.31	8.95	1410	73.32	8.19
2.80	3.37	8.96	1415	73.58	8.21
2.90	3.49	8.97	1425	74.10	8.26
2.95	3.55	8.98	1432	74.46	8.30
3.00	3.61	8.98	1437	74.72	8.32
3.05	3.68	8.99	1443	75.04	8.35
3.10	3.74	8.99	1446	75.19	8.36
3.15	3.795	9.00	1448	75.30	8.37
3.20	3.86	9.00	1450	75.40	8.37
3.25	3.92	9.01	1450	75.40	8.37
3.30	3.97	9.02	1450	75.40	8.36

VITA

VITA

Eugene Andrus Glysson was born on August 16, 1926, in Montpelier, Vermont. He was graduated from Lamoille Central Academy in Hyde Park, Vermont, June, 1944. In September, 1944 he entered the University of Vermont in the Civil Engineering curriculum. He was called into the United States Navy in December, 1944, and served in the U. S. Navy until August, 1946. In September, 1946, he returned to the University of Vermont and completed his undergraduate work in June, 1949, with a Bachelor of Science in Civil Engineering. After graduation he was employed as a civil engineer in the Vermont State Highway Department and served as Assistant to the District Highway Commissioner, in District 5 of that department. In January, 1950, he entered the University of Michigan in the Horace H. Rackham School of Graduate Studies in the Sanitary Engineering graduate program; and in February, 1951, received the Master of Science in Sanitary Engineering. In February, 1951, he was appointed Instructor in the Civil Engineering Department of the University of Michigan; was promoted to Assistant Professor in July, 1955; and Associate Professor in July 1962.

During his tenure at the University of Michigan, he has been involved with teaching and research in the field of water supply, waste water treatment, and solid waste engineering. He has held the position of Director of the Rocky Mountain Field Station, during the years 1959-63, and was Director of the Solid Waste Engineering Training Program in the Civil Engineering Department, 1966-71.

In September, 1968 he requested and was granted a sabbatical leave to attend Drexel University for a calendar year during which time he fulfilled the residence requirement for the Ph.D. in the Environmental Engineering and Science Program.

Mr. Glysson is a Registered Professional Engineer and has served as consultant to various public and private agencies. He is currently Project Manager of the Solid Waste Management Study for Washtenaw County, Michigan and has served as a consultant to the U. S. Bureau of Solid Waste Management Operations of the Environmental Protection Agency, and the World Health Organization.

Also, Mr. Glysson is the author of several papers in environmental engineering and solid waste technology, and holds membership in Sigma Xi, Chi Epsilon, Phi Kappa Phi, honoary societies.