DRAINAGE CHARACTERISTICS OF AEROBICALLY DIGESTED PRIMARY SLUDGE ON SAND BEDS

By

YOUSIF ANTONE BADRA

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

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SAND BEDS

Thesis Approved:

Quintin B. Graves
Thesis Adviser

R. L. Janes

H. F. Gaudy Jr.

D. Durham
Dean of the Graduate College

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CHAPTER I

INTRODUCTION

Sludge treatment and disposal are two unit processes where a considerable interest is being shown in their importance at many sewage treatment plants throughout the world. Dr. P. McCarty, Professor at Stanford University, had this to say regarding the problem of sludge disposal:

> The rapid population and industrial expansion as well as the need for cleaner rivers and streams to satisfy the aesthetic demands of the people have led to more intensive and efficient waste treatment. This trend has resulted in the amplification of an already difficult problem, that of sludge treatment and disposal. (8)

Recently, research on aerobic digestion of sludge has been directed toward finding new and more efficient methods of treating sludge and hopefully to change their condition so that they will dewater faster, more easily, and at less cost.

A. Dewatering Processes

Sludge dewatering is a part of the problem of sludge disposal, while sludge disposal is a major part of the complex problem of waste treatment and disposal.

The process of sludge dewatering can be generally classified into two catagories: mechanical dewatering and dewatering on sand beds.

Mechanical dewatering processes which include common vacuum filtration or centrifugation processes, are mainly utilized in large cities where land space is scarce and expensive. However, for relatively small sewage plants the first costs and the maintenance costs for the equipment are high and uneconomical.

Dewatering of sludge on sand beds on the other hand, requires relatively large land areas and the uncertain effects of weather remain major problems.

However, because of the ease and flexibility of operation, low cost of power and chemicals, and the fact that highly skilled operators are not required and maintenance costs are low, the drying of waste sludge on sand beds becomes economical. Therefore, sand beds will continue to be utilized in the waste treatment process serving small communities throughout the world.

B. Purpose of the Study

The specific objectives of this study are summerized as follows:

(1) To compare the drainage and drying characteristics of aerobically digested sludge having various detention times.

(2) To compare the drainage characteristics of aerobically digested sludge with the drainage characteristics of anaerobically digested sludge.

(3) To correlate the filterability to the drainability of sludge on sand beds.

(4) To compare the biological and chemical characteristics of the sludge filtrate (through Whatman #40 filter paper) to the sand beds filtrate (no filter paper).

CHAPTER II

LITERATURE REVIEW

A careful study of past literature reveals that very limited research work has been done on the drainage behavior of primary digested sludge. However, most of the research done in the dewatering phase in the early years had focused on determining and establishing the optimum sludge filling depth on sand beds, while important factors and parameters such as characteristics of sludge, amount of rainfall, amount of sunshine, ambient temperature, relative humidity, etc. were neglected, which in turn made this kind of results limited in value and consequently of little significance to the true process of dewatering. Therefore, recent studies have been conducted as laboratory-scale tests under controlled environments, where drainage, drying and evaporation characteristics were studied separately (2), (5), (6), (7), (9), (10), (13), and (16).

A. Drainability

Of the two major processes of sludge dewatering, i.e. drainage and drying, the drainage process seems to be more difficult to evaluate than any other parameter involved, mainly because of the uncertain characteristics and the behavior of the sludge on the surface of the sand beds.

Lawton and Norman (7) in their studies of aerobic sludge digestion concluded that the drainability of the sludge digested for short periods (five days) was poorer than non-digested samples, but for digestion periods greater than ten days the drainability of the sludge was improved.

Quon, et al (10) using secondary digested sludge in his studies observed that the drainage rate increased and the sludge surface had dropped substantially after approximately three days of application. This phenomenon was explained by Quon et al (10) as follows: the air entrapped in the voids of the sand layer is not free to move, hence it delays the initial flow of water through the drainage media. However, after a period of three days, this air is eventually absorbed, thus increasing the porosity of the sand and therefore, increasing the flow.

Randall et al (12) using aerobically digested waste activated sludge from contact stabilization plants, showed that a high proportion of the water will drain within eight hours on sand beds with underdrains, but the amount of water remaining to be lost by evaporation is the significant factor in determining the overall drying period. It was considered that an eight-inch depth of well-digested sludge with a high solids concentration would give the most efficient use of sand beds.

Randall et al (11) examining activated sludge in his studies claims that solids concentration is the most important factor which affects drainability and concluded that drainability decreases rapidly with increasing solids up to concentrations in excess of 2.5 per cent.

Recent work on the use of sand beds for dewatering raw and digested sewage sludge by Swanwick et al (15) showed that drainage of sludge was obstructed due to the formation of a thin, almost impervious layer of sludge solids about ¼ inch thick on top of the sand surface. This occured as a result of fermentation with the formation of a subnatant layer of water up to four inches deep in sludge twelve inches deep. Tests showed that this sealing of the drainage medium could be prevented by flooding the beds with tap water so that the water surface was just above the top of the sand surface. The sludge was then applied and left for three to five days for floatation to occur before allowing drainage to take place. It was found that the six-inch layers of sludge then drained much more rapidly.

Jeffrey (6) investigated the dewatering rates of digested sludge, utilizing a standard laboratory sand bed known as a Drainometer. He concluded that the rate of initial discharge can be described by a first-order equation: the quantity of water initially available for discharge is inversely proportional to the initial solids concentration and that maximum drying by drainage alone produces a sludge having a moisture content of 70 to 80 per cent.

Tang et al (16) using in their investigation, sterilized sludge to eliminate the biological activity in the sludge during the experiment and to release the dissolved gases from the sludge, found that the time required to complete the drainage of the sludge is a function of the initial sludge depth. They observed a drainage period of three to five days for an initial sludge depth of 15 cm. They concluded that the evaporation rate and depth of the sand have little effect on the drainage process. Also, the drainage process accounts for about two-thirds of the total volume of the water removed from the sludge.

B. Filterability

It was necessary to find a method comparing the filtration capacities of sludge to the drainability capacities of sludge on sand beds. The Buchner funnel technique was not used. Instead, an automatic filterability apparatus based on "capillary suction time" for the measurement of sludge filterability was used (1).

Trubnick and Mueller (17) in their studies of sludge filtration noted that in general, fresh sludge is more filterable after chemical conditioning than digested sludge;

and primary sludge is more filterable than secondary sludge.

Reyes (13), in his studies on aerobic digestion of nightsoil, concluded that the filtration characteristics of digested nightsoil varied with the total solids content. He observed poorer filterability results when the total solids of sludge were increased.

Hatfield (4), using the automatic instrument for measuring sludge filterability (1) indicated the following:

(1) Filterability improves sharply as the pH is lowered until a point is reached where no further decrease of Capillary Suction Time (CST) occurs.

(2) Filterability of sludge decreases as the total solids content increases.

C. Settleability

Joworski et al (5) using blends of primary and waste activated sludge with total solids concentration of up to three per cent in his investigation of aerobic sludge digestion noted that settling characteristics of aerobically digested sludge (30 days or less) were generally poorer than those of undigested sludge.

Reyes (13), on aerobic digestion of nightsoil concluded the following:

(1) After digestion at temperatures above 27^{o} C, the aerobically digested nightsoil is readily settle-

able.

(2) It was noted during the digestion that there is apparent "clumping" of solids after about 20 days of digestion at the higher temperatures (27° C and above). This improved the settling characteristics of the digested nightsoil.

(3) The settleability of aerobically digested nightsoil was poorer as the total solids increased.

CHAPTER III

MATERIALS AND METHODS

A. Apparatus

The drainage beds used for this study are illustrated schematically in Fig. 1. They are the portable, model-size type, made of ¼ inch thick plexiglass with the following dimensions:

Length . . . . 1 foot

Width . . . . 1 foot

Depth . . . . 3 feet

Cross-sectional Area . . . . 1 square foot

Six of the above mentioned containers were used in this study. Each contained a three-inch depth of gravel sieved through a ¼ inch sieve and retained on a 1/8 inch sieve; and a 12-inch depth of sand sieved through sieve No. 20 and retained on sieve No. 40.

Both the gravel and the sand were supported by a strong polyethelene mesh fitted to the base of each bed. A galvanized wire mesh was inserted between the gravel and the sand layer to keep the sand particles from penetrating through the gravel to the underdrain base.

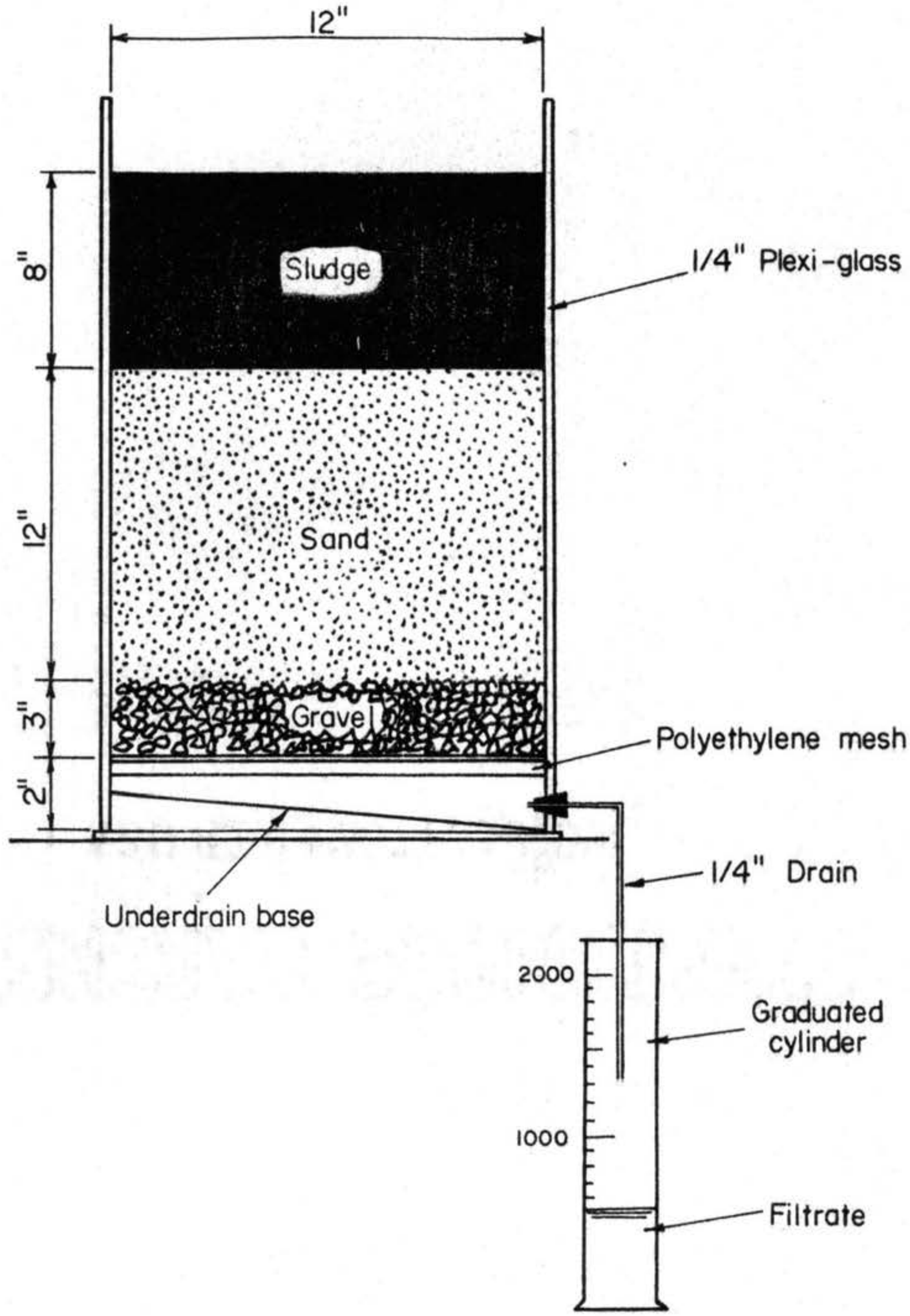

Figure 1. Schematic Diagram of Sand Bed Container

A sloping base to each bed permitted the drained filtrate to be removed through a ½ inch drain for collection in a graduated cylinder.

Filterability was used for comparing the drainability of the sludge. This was determined by using a simple automatic instrument for determining the filterability of sludge (1). Six of these instruments were imported from England and were used throughout this study. The instrument is illustrated schematically in Fig. 2. It consists of two separate components: the filtration segment and the automatic time recorder.

The filtration segment consists of two 7 cm. by 9 cm. pieces of plexiglass where a Whatman rectangular filter paper was placed between the two blocks. The upper block had a 1.9 cm. circular hole, where a stainless steel collar which served as a sludge reservoir, was tightly placed through the hole resting on the filter paper uniformly.

On the underside of the upper plexiglass block are two engraved circles with diameters of 3.2 cm. and 4.5 cm. concentric with the reservoir. This plexiglass block stands clear of the filter paper by resting on five stainless steel supports (1, 2, 3, 4, and 5 in Fig. 2).

Electrical connections are made to probes 1, 2, and 3 which lead to the other component, the automatic time recorder. Terminals 4 and 5 are provided to hold the upper

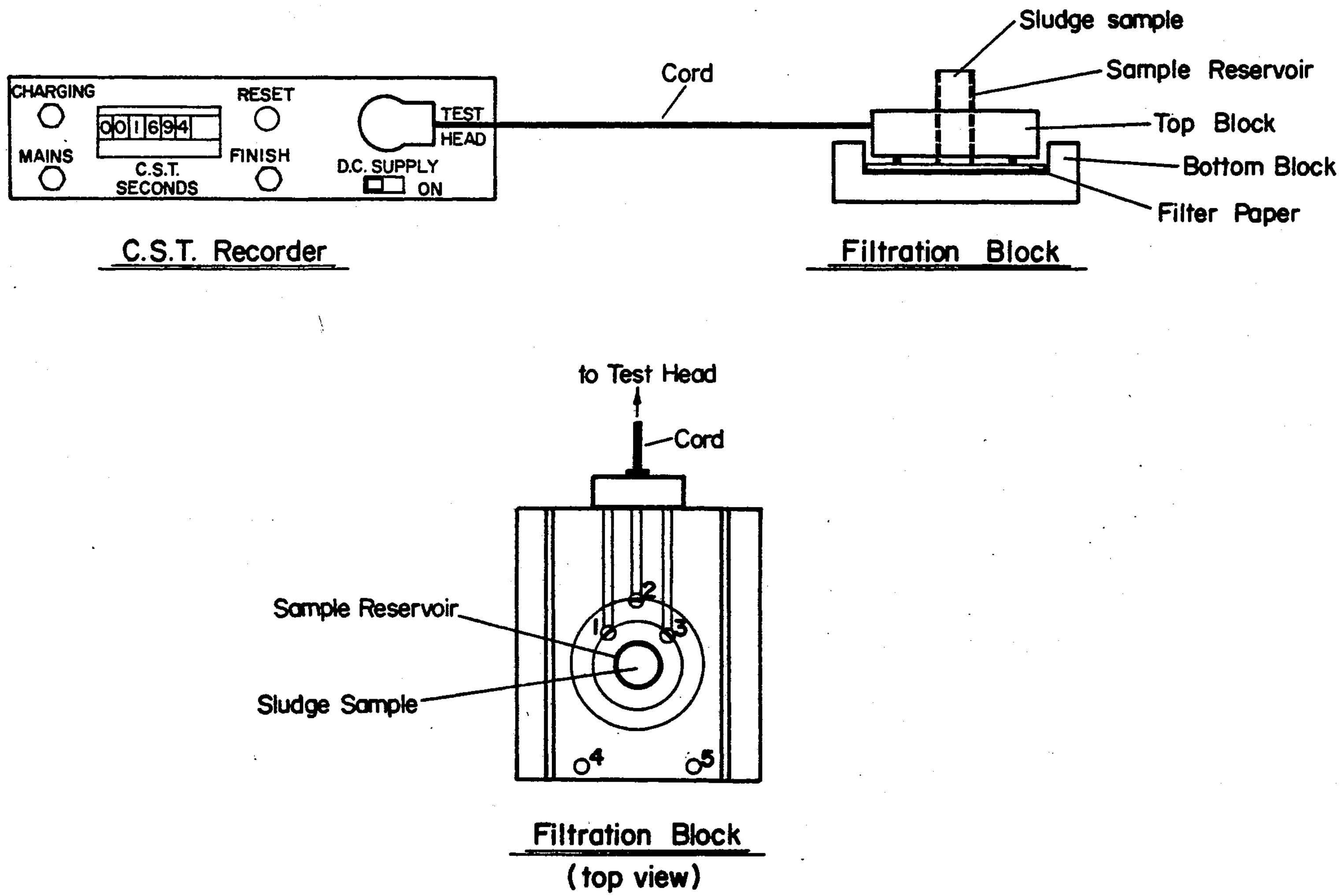

Figure 2. Schematic Diagram of Filterability Instrument

block parallel with the filter paper.

B. Digested Sludge Used

The sludge used for this study was obtained from:

1. Aerobic Pilot Plant Digestors

Each pilot plant unit was set up at the Stillwater Municipal Sewage Treatment Plant, which is located five miles southeast of the Oklahoma State University campus, to investigate the effects of different detention times on the characteristics of primary sludge digested aerobically.

It consists of four polyethelene, cylindrical tanks 42 inches in diameter, 200 gallon capacity, each holding 180 gallons of primary sludge, operated on a continuous flow system, except for Run Number Four, which was operated as a batch unit. Each tank was placed in a larger tank, 48 inches in diameter, which served as a constant temperature bath. The temperature was controlled by means of heating-cooling units, which pumped water into the baths by means of a centrifugal pump and returned it to the unit be gravity. Temperature in the reactors was held at a constant $25^{\circ} \pm 2^{\circ}$ C throughout this study.

Air was supplied to each reactor by simple pipe diffusers placed at the base of each digester, where four ½ inch outlets in the diffuser system (one outlet to each quadrant of the digester base) produced air bubbles large enough to keep the sludge well mixed and at the same time supplying enough oxygen to the microbial population.

The quantity of air supplied to each digester was controlled with the aid of a monometer mounted to the wall and kept at 88 cfm/1000 cu ft of digester capacity throughout the study.

Sludge used in these reactors was primary sludge with physical and chemical characteristics as shown in Tables 1 and 2.

The four reactors were operated with different detention times. These were 2, 4, 8, and 12 days for the first phase; 4, 4, 8, and 12 days for the second phase, and 12, 18, 24, and 30 days for the third phase of the study.

For the first run period, which lasted approximately six months, primary sludge was fed to the digesters by means of Moyno Cavity Progressing Pumps. Each had an electric timer attached to it, which was set for each specific detention time. However, due to the difficulties experienced with the operation of the sludge pumps, in the third run period primary sludge was hand-fed twice a day to each reactor as an approximation of continuous flow, when flow at the plant was in the upper flow levels.

A batch aerobic digester was added to the operation holding the same amount of sludge (180 gallons) including 10 per cent seed from the operating units. Air flow was set

TABLE I

GENERAL PHYSICAL PROPERTIES OF SLUDGE USED

Characteristic	Raw	Detention Time of Digested Sludge Used							Anaerobic
		2-Day	4-Day	8-Day	12-Day	18-Day	24-Day	30-Day	
Total Solids mg/1	31,359	18,566	22,924	18,534	16,650	23,833	19,166	20,125	96,088
Volatile Solids mg/1	14,790	7,998	12,281	10,183	8,952	7,667	6,583	6,750	
Fixed Solids mg/1	16,569	10,568	10,643	8,351	7,698	16,166	12,583	13,375	
Moisture Content mg/1	96.9	98.2	98.1	98.2	98.4	95.8	98.5	97.9	91.5
Filterability (CST)	194	478	514	523	535	576	637	563	630
Settleability Per cent	90	53	61	61	68	79	50	61	100
Temperature Degrees C.	29	24	24	25	25	25	25	25	

Capillary Suction Time (CST) is expressed in seconds throughout this report.

the same as the air flow in the other units, 88 cfm/1000 ft^3 of digester cavity and it was operated at the same constant temperature (25^o C $\pm$ 2^o C). This unit was placed in Oklahoma State University's Bioenvironmental Engineering laboratories, where no additions of sludge were made to this digestor. Physical and chemical tests were made on 0, 2, 4, 8, 12, 18, 24, and 30 day detention times. Drainage experimentation was made on 4, 12, and 30 day detention times.

The purpose of this unit was to compare the drainabilities of batch aerated sludge with that of the continuous flow unit. Many investigations reported in the past were based on batch studies.

2. The Stillwater Municipal Sewage Treatment Plant

This plant serves a community population of about 35,000. It is a typical biological treatment plant consisting of trickling filters in two stages, anaerobic digesters, sand drying beds, etc.

The anaerobically digested sludge was analyzed throughout this study so as to compare it with sludge from the aerobic pilot plant digesters.

The physical properties of sludge used in this study are listed in Table 1. Note that the values listed are general ranges of values from numerous tests performed throughout this study.

The chemical characteristics of sludge used in this study are listed in Table 2. Note that the figures listed are average values of numerous tests performed throughout this study.

C. Experimental Set-Up

The sludge used in this study was obtained from the pilot plant and Stillwater sewage plant. The grab-sampling technique was used in collecting the sludge from the aerobic digesters of the pilot plant. Sludge was settled for a period of four hours. The supernatant was decanted and the settled sludge was poured on top of the sand beds, two liters at a time, using very extreme care particularly in the very first applications, in order not to disturb the leveled sand surface.

The filtrate drained from each container was collected and measured in graduated cylinders to the nearest 1 ml. Simultaneously, the depth of the sludge remaining was recorded to the nearest 1/16 of an inch with the aid of a 12-inch ruler taped to the side wall of each container. Observations and data were taken initially at 0, 1, 2, 4, 6, and 12 hours. Then observations were made twice a day for approximately two weeks. After which, representative samples were collected from the remaining dried sludge for each bed to test for moisture content. Finally, the dried sludge was discarded and the sand beds were cleaned and the sand adjusted for

TABLE II

GENERAL CHEMICAL PROPERTIES OF SLUDGES USED

Characteristic	Raw		Detention Time of Sludge Used																Anaerobic	
			2-Day		4-Day		8-Day		12-Day		18-Day		24-Day		30-Day					
	M.L	Fil.	M.L	Fil.	M.L	Fil.	M.L	Fil.	M.L	Fil.	M.L	Fil.	M.L	Fil.	M.L	Fil.			M.L	Fil.
COD mg/l	42070	2055	2280	2640	34710	1440	26730	2520	25180	2580	39495	5200	33900	4070	27365	3900			77143	410
BOD mg/l	N.D	1625	N.D	1310	N.D	790	N.D	1090	N.D	1805	N.D	1710	N.D	1385	N.D	540			N.D	56
P mg/l	305	80	255	85	305	90	280	95	265	60	375	145	325	85	325	80			500^{+}	45
NH_3-N mg/l	550	100	365	170	305	155	280	210	310	140	105	85	85	80	75	100			1370	670
NO_3-N mg/l	15	0.8	15	1.6	16	2.3	14	1.7	25	1.4	31	1.4	31	1.4	36	1.5			111	0.6
pH	5.87	N.D	6.42	N.D	6.43	N.D	6.70	N.D	6.90	N.D	6.30	N.D	6.60	N.D	7.25	N.D			6.97	N.D
DO mg/l	N.D	N.D	0.6	N.D	0.43	N.D	0.60	N.D	0.48	N.D	0.49	N.D	0.45	N.D	0.43	N.D			N.D	N.D

M.L - Mixed Liquor

Fil. - Filter Paper Filtrate

other applications.

The sludge depths applied for each run were eight inches with the exception of two runs made with six-inch and four-inch sludge depths.

The depths of the sand and gravel in the containers were maintained constant at 12 inches and 3 inches respectively.

The sludge samples applied to each drying bed were examined for total solids and volatile solids content at the beginning of each experimentation, and for total solids and moisture content at the end of each experimentation.

The filtrate drained through the sand was analyzed both physically and chemically by taking a representative sample from the drained filtrate.

The sand beds were placed in an isolated backroom in O.S.U.'s Bioenvironmental laboratories, where an ambient temperature was maintained approximately at 25^{o} C $\pm$ 2^{o} C.

Simultaneously with this work, measurements of the filterability of sludge from each digester plus the anaerobic and the raw sludge, were taken on the mixed liquor and four-hour settled sludge, using the simple automatic instrument (1), illustrated previously.

D. Analytical Methods

1. Total and volatile solids

Total solids as well as volatile solids were determined using a 103^{o} C drying oven as described in FWPCA Methods for Chemical Analysis of Water and Wastes (3). On a few occasions large nonhomogenous materials were encountered and were excluded from the test sample.

2. Filterability

Filterability of mixed and four-hour settled sludges were determined, using a 1.0 cm. cone as described in the Manual for a Simple Automatic Instrument for Determining the Filterability of Sewage Sludges (1).

3. Settleability

In this study settleability was evaluated by quiescent settling in a one-liter graduated cylinder. The percentages of settled sludge were noted for a four-hour settling time.

4. Ammonia-Nitrogen

Ammonia-Nitrogen was measured on the sludge filtrate through Whatman filter paper No. 40 and on the sand beds filtrate using the distillation procedure as described in FWPCA Methods for Chemical Analysis of Water and Wastes (3).

5. Nitrate-Nitrogen

Nitrate-Nitrogen was measured on the sludge filtrate through Whatman filter paper No. 40 and on the sand beds filtrate (no filter paper used) using the Brucine Method as described in FWPCA Methods for Chemical Analysis of Water and Wastes (3).

6. Orthophosphate

Orthophosphate was measured on the sludge filtrate through Whatman filter paper No. 40 and on the sand beds filtrate (no filter paper used) using the single reagent method as described in FWPCA Methods for Chemical Analysis of Water and Wastes (3).

7. pH

The pH of the sludge was measured by using the Beckman Expandomatic SS-2 pH Meter. The pH meter was standardized to pH 7.0 every time a run was made.

CHAPTER IV

EXPERIMENTAL RESULTS

The physical and chemical characteristics of the sludge applied on the sand beds in runs 1, 2, 3, 4, 5, and 6 are shown in Tables III, V, VII, IX, XI, and XIII respectively. An average value of all runs is tabulated in Table XV.

The characteristics of the sludge drainability, such as volume of water removed (as percentage of initial volume of sludge applied) versus time, and sludge depths versus time for runs 1 through 6 are plotted in Fig. 1 through 15. Average values of all runs are plotted in Fig. 16. These same data are shown in tabulated form in

The chemical characteristics of the filtrates from the sand beds for runs 1 through 6 are shown in Tables IV, VI, VIII, X, XII, and XIV. Average values of all runs are tabulated in Table XVI.

The average values of the filterability of sludge as measured by the automatic instrument (1) for runs 1 through 6 are plotted in Fig. 17 as Capillary Suction Time (CST, in seconds) versus detention time in days.

The average values of the settleability of sludge for runs 1 through 6 are plotted in Fig. 18 as percentage of sludge settled in four hours versus detention time in days.

A. Run Number One

Stillwater's anaerobic digested sludge and pilot plant's aerobic digested sludge with detention times of 2, 4, 8, and 12 days were applied on the sand beds (with an initial sludge depth of 6.0 inches) simultaneously within one hour, under the same conditions. An average ambient temperature of 24° C $\pm$ 2° C was maintained during the experimental period of two weeks.

Table III lists the physical and chemical characteristics of the sludge when applied on the sand beds. Figure 3 shows the drainage characteristics of the sludge versus time, while Fig. 4 shows the depths of sludge on the sand beds versus time in hours.

Table IV lists the chemical characteristics of the sand beds' discharge collected after the fourth observation had been made. As shown in Fig. 3, sludge digested four days had drained very rapidly on the first day of the experiment; followed by the same, but slower drainage pattern of sludge digested two days.

Sludge digested eight and twelve days drained slowly. However, the drainage rate of the sludge digested twelve days had increased four days after application due to a layer

TABLE III

SLUDGE CHARACTERISTICS - RUN 1

Characteristic	Detention Time of Digested Sludge				Anaerobic
	2-Day	4-Day	8-Day	12-Day	
Total Solids mg/l	146,600	26,000	24,000	32,400	180,000
Volatile Soids mg/l	59,400	16,000	15,200	22,000	12,000
Filterability (CST)	524.5	587.0	621.0	480.7	465.9
NH_3-N mg/l	100.8	72.8	128.8	184.8	694.0
NO_3-N mg/l	1.9	1.9	1.2	1.7	0.8
P mg/l	103	67	109	109	43
COD mg/l	2768	1664	1984	2256	384
pH	5.75	6.61	6.59	6.98	N.D
Settleability Per cent	31	46	90	66	100

Determination of all chemical analyses is based on the filter paper filtrate.

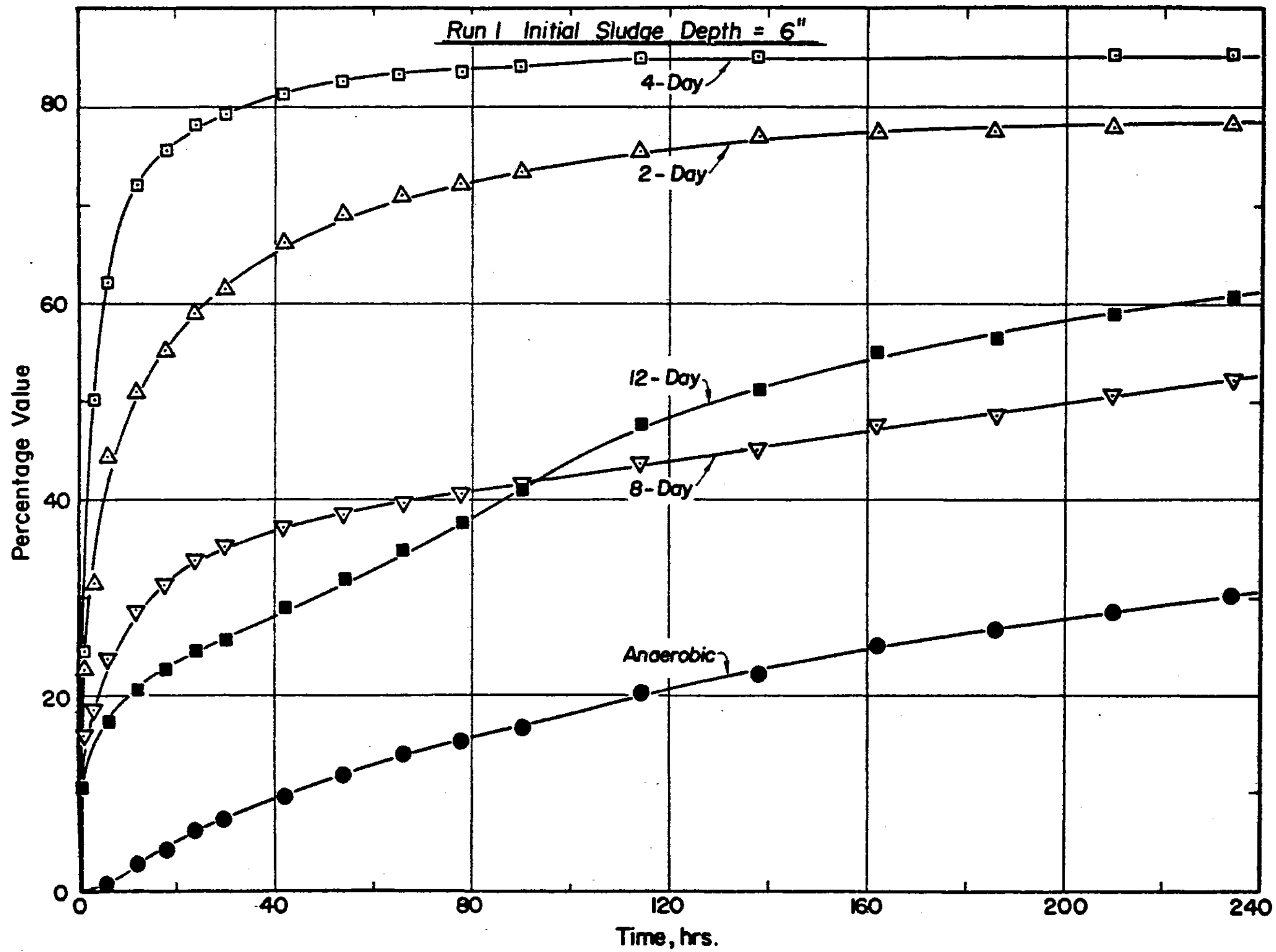

Figure 3. Percentage of Water Volume Drained to the Total Sludge Volume Applied Versus Time Curves - Run 1

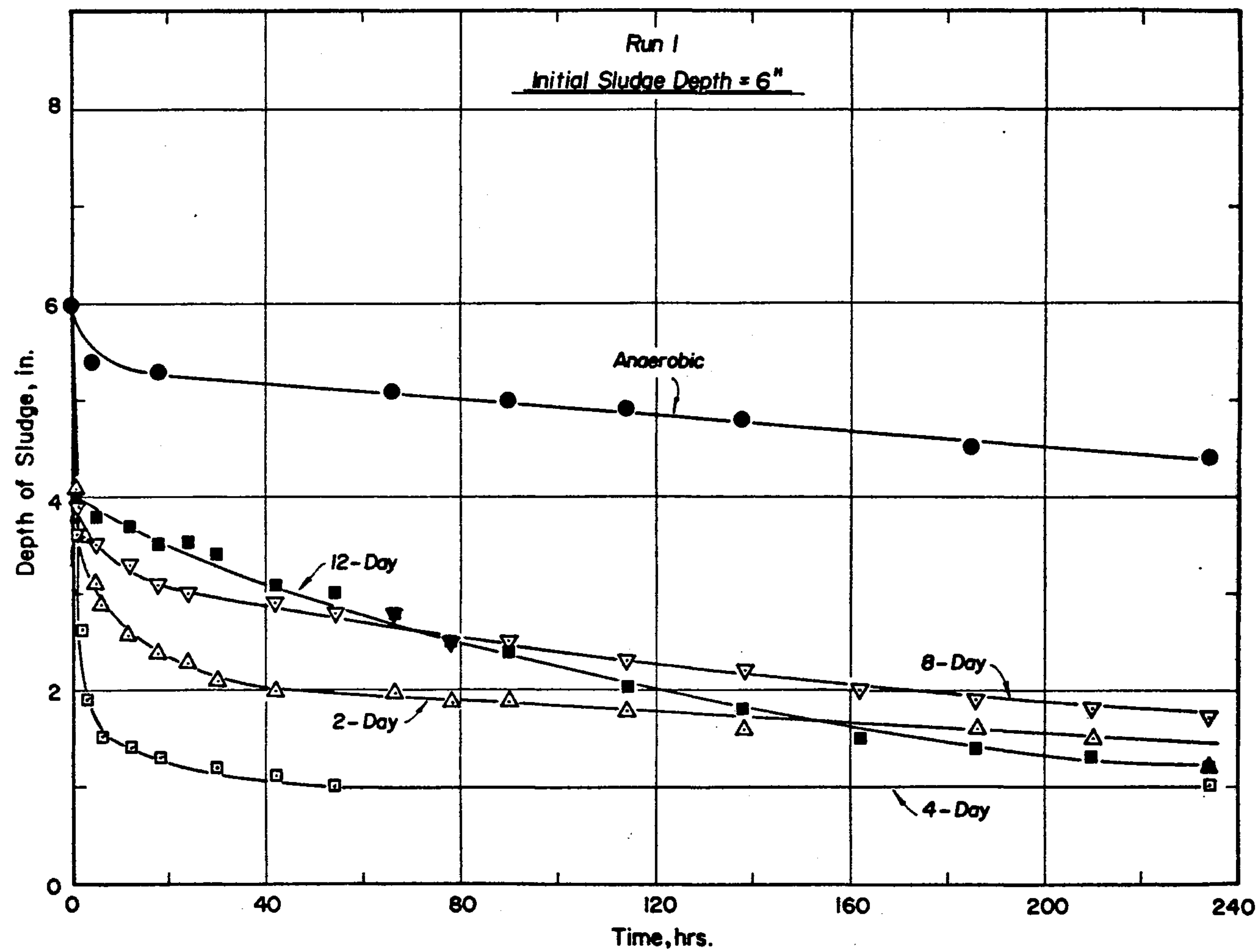

Figure 4. Sludge Depth Versus Time Curves - Run 1

TABLE IV

SAND BEDS FILTRATE CHARACTERISTICS - RUN 1

Characteristic	Detention Time of Digested Sludge				Anae-robic
	2-Day	4-Day	8-Day	12-Day	
NH_3-N mg/l	140	134	184	140	N.D
NO_3-N mg/l	4.1	6.3	6.5	4.0	N.D
P mg/l	75	60	66	30	24
COD mg/l	3616	3648	5840	1920	576

of supernatant, which had accumulated to a maximum depth of two inches and had seeped through the sludge layer into the sand causing a surge in the drainage flow.

The anaerobic sludge did not discharge any filtrate in the first five observations. Drainage was slow throughout the two-week period of the experiment. The filtrate appearance was clear and yellowish in color, in contrast to the filtrate of the 2, 4, 8, and 12 days digested sludge, which appeared to be turbid and gray in color throughout all the observations.

The odor was pungent in the area where the sand beds were placed, particularly on the first day of application. When close observations were made, 2-day digested sludge had the most penetrating odor of all sludges applied.

The sludge layer of the anaerobic digested sludge showed several cracks twelve days after application. These cracks varied from ¼ inch to ½ inch in width and from two inches to four inches in length. However, no cracks appeared on the aerobic digested sludge layers during the two week period of the experiment. The sludge layers were in one piece resting loosely on top of the sand layers.

B. Run Number Two

Sludge depths of 4.0 inches were applied in this run. There was no specific reason for using a four-inch sludge depth. However, the four later runs were applied in 8.0 inch sludge depths.

Raw, anaerobic, 2, 4, 8, and 12 day digested sludges were used. All sand beds were kept in the same area where the same conditions applied to all sand beds. The temperature on top of the sludge averaged 22^{o} C $\pm$ 2^{o} C.

Table V records the physical and chemical sludge characteristics. Figures 5 and 6 indicate the sludge drainage and depths versus time, respectively.

Chemical characteristics of the sand beds filtrate are tabulated in Table VI. Again, the four-day aerobically digested sludge drained rapidly; following the same drainage pattern as in the first run. However, the raw sludge--which was used here as a guide to how raw sludge behaves on sand beds--drained more rapidly than all other digested sludges in the first six hours of application. Thereafter, drainage decreased and ceased on the fourth day.

Supernatant was noticed on the aerobically treated sludge the first five days of application; with a maximum depth of 1.0 inch on the 12-day sludge. Anaerobically treated sludge had no supernatant layer during the experiment.

Odor was very pungent the first three days of application, due to the raw sludge which turned sour on the second day of the experiment. A white film had been observed on the semi-dry top of the raw sludge layer after three days

TABLE V

SLUDGE CHARACTERISTICS - RUN 2

Charac-teristic	Raw	Detention Time of Digested Sludge				Anae-robic
		2-Day	4-Day	8-Day	12-Day	
Total Solids mg/l	37,314	44,155	41,568	30,977	14,800	147,295
Volatile Solids mg/l	14,121	20,103	15,666	14,988	5,423	10,941
Filterability (CST)	145.6	270.5	520.6	389.4	191.0	825.8
NH_3-N mg/l	140	235.4	89.2	179.2	308.0	666.4
NO_3-N mg/l	2.5	3.5	1.0	3.5	2.0	3.5
P mg/l	91	40	100	35	91	43
BOD mg/l	1116	1600	133	1167	1000	67
COD mg/l	2640	2976	656	2144	1712	128
pH	5.3	6.1	7.3	6.6	7.4	7.0
Settleability Percent	99	26	28	50	99	100

Determination of all chemical analyses is based on the filter paper filtrate.

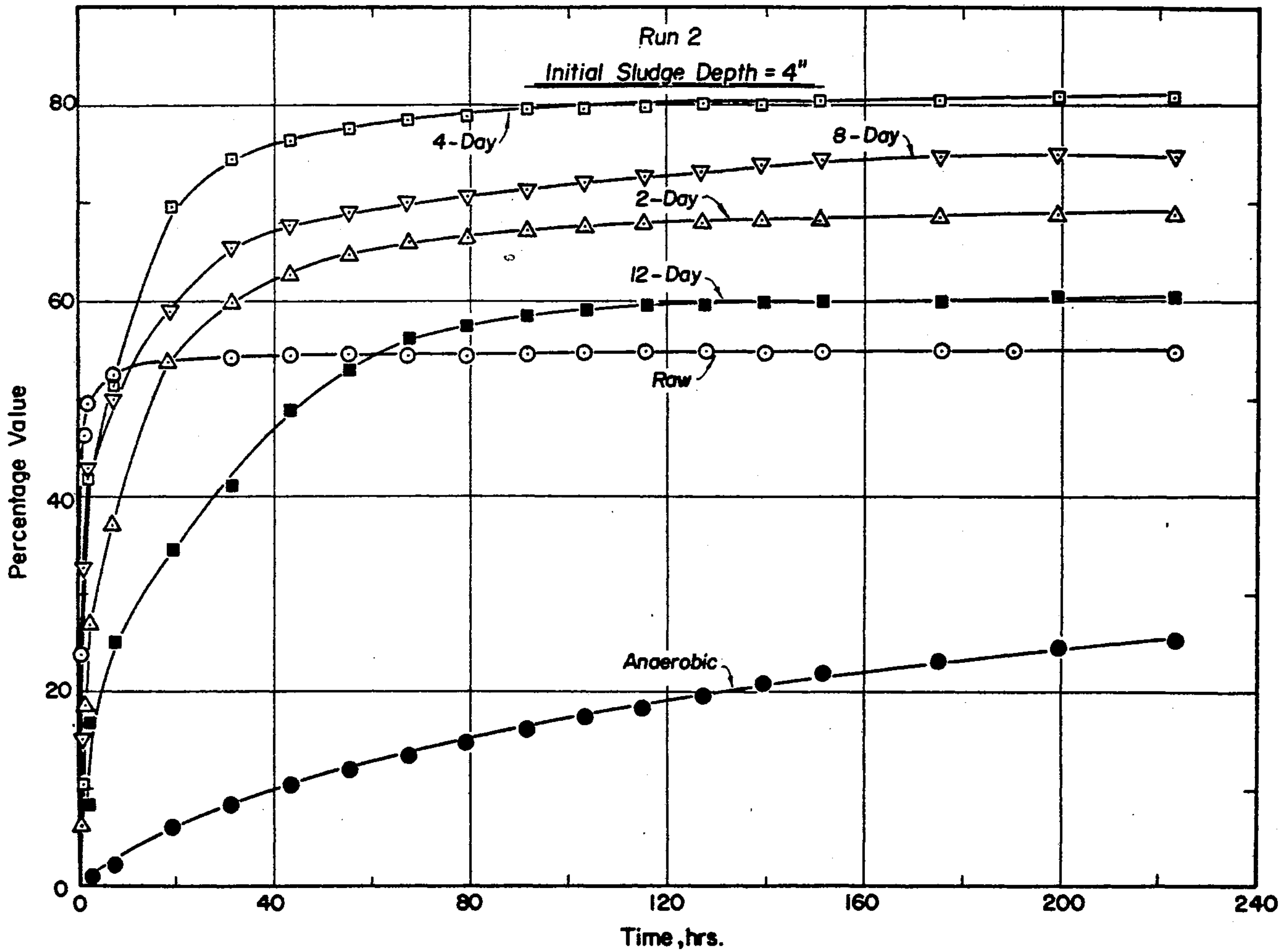

Figure 5. Percentage of Water Volume Drained to the Total Sludge Volume Applied Versus Time Curves - Run 2

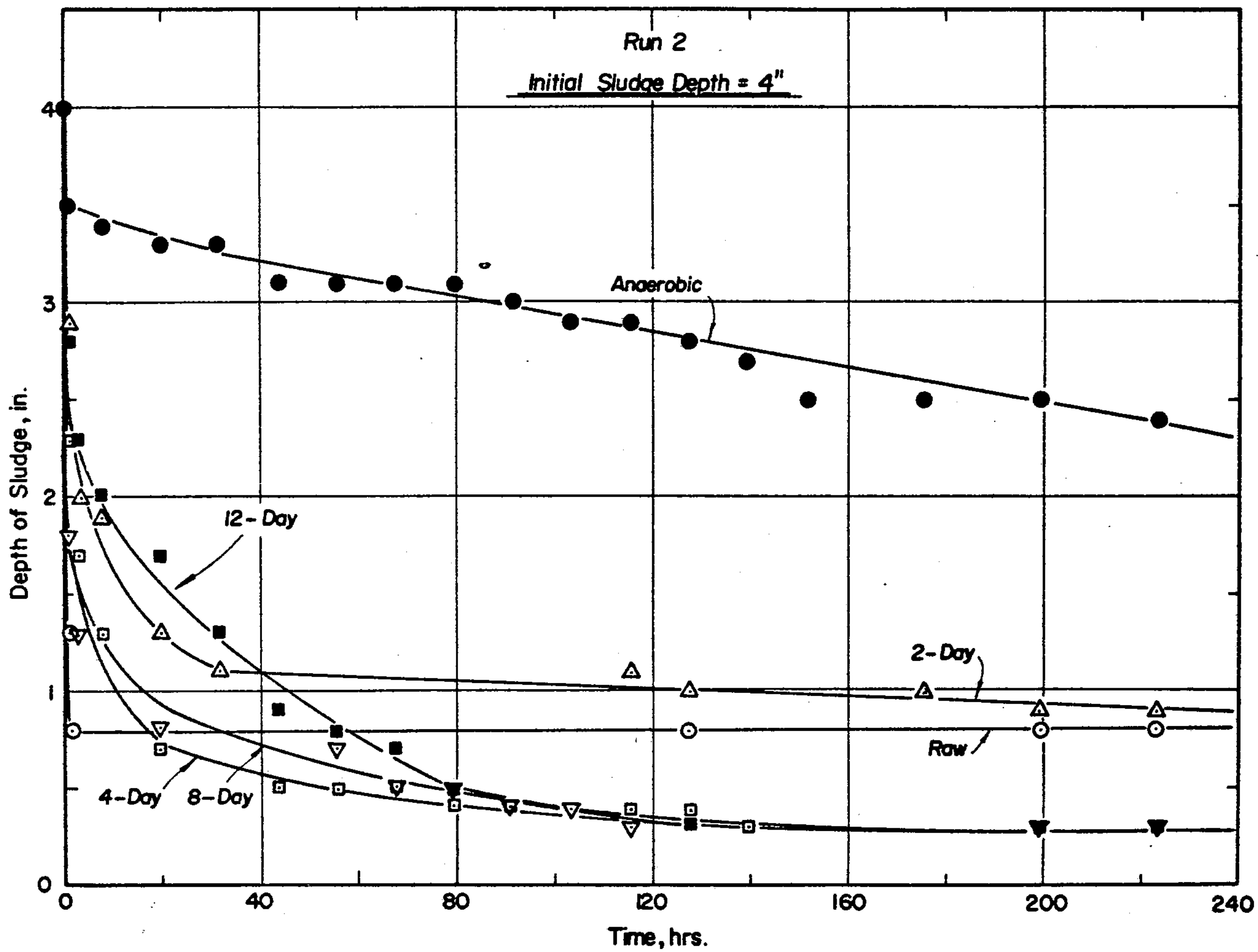

Figure 6. Sludge Depth Versus Time Curves - Run 2

TABLE VI

SAND BEDS FILTRATE CHARACTERISTICS - RUN 2

Charac-teristic	Raw	Detention Time of Digested Sludge				Anae-robic
		2-Day	4-Day	8-Day	12-Day	
NH_3-N mg/1	117.6	156.8	56.0	145.6	201.6	330.4
NO_3-N mg/1	0.7	2.6	3.1	3.0	2.7	0.7
P mg/1	N.D	72	46	78	28	15
COD mg/1	N.D	3,200	3,600	2,200	3,200	800

of application.

Again, no cracks were observed on the raw or aerobically digested sludge left on the sand beds. Anaerobic sludge had cracked ten days after application.

The raw sand bed's filtrate was white and cloudy; the anaerobic sand bed's filtrate continued to be clear, yellowish in color; while the 2, 4, 8, and 12 day sand beds' filtrates were turbid, light to dark gray in color, except for the 12-day filtrate, which cleared up at the beginning of the second week of the experiment.

C. Run Number Three

A sludge depth of 8.0 inches was applied to the sand beds in this run and the remaining runs to follow.

Anaerobic, 4, 8, and 12 day aerobically digested sludges were used. The same assigned sand bed for each type of sludge was used so that mixing of beds was avoided; i.e. anaerobic sludge was applied on sand bed No. 1 in the first, second, and third runs. Likewise, the 2-day aerobically digested sludge was applied on sand bed No. 2 in the first, and second runs, and so on.

Table VII shows the physical and chemical sludge characteristics before application onto the sand beds. An ambient temperature of 24° C $\pm$ 1° C was maintained during the experiment.

Figures 7 and 8 are plots of sludge drainage and depth versus time respectively. Chemical analysis of the sand beds filtrate are listed in Table VIII.

Twelve-day aerobically digested sludge dewatered rapidly through drainage during the first thirty hours of the experiment; followed by the 4-day and 8-day digested sludge respectively. As expected, the anaerobically digested sludge drained slowly.

Four-day and 12-day digested sludge had a dried surface with no appearance of cracks within a week of experimentation; while the 8-day digested sludge surface had some supernatant (.1 inch) at the end of two weeks.

Sand bed No. 3, which contained the 4-day digested sludge had some microbial growth throughout the depth of the sand in scattered places on the third day of the experiment, which possessed a dark red color, which in turn changed the color of the filtrate to a light pink. Two days after the growth had appeared on the above mentioned sand bed, some growth was observed on all sand beds in that area, except the 12-day sand bed, which showed a light green microbial growth all over the sand and gravel in the sand bed.

D. Run Number Four - Batch Unit

Sludge used in this run was sampled at detention times of 4, 12, and 30 days. Sand beds had been washed with tap

TABLE VII

SLUDGE CHARACTERISTICS - RUN 3

Characteristic	Detention Time of Digested Sludge			Anaerobic
	4-Day	8-Day	12-Day	
Total Solids mg/1	33,000	40,000	37,000	68,500
Volatile So-lids mg/1	24,500	27,000	26,000	30,500
Filterability (CST)	253	561	551	727
NH_3-N mg/1	358	325	381	627
NO_3-N mg/1	1.6	1.4	0.7	0.3
P mg/1	125	118	112	N.D
BOD mg/1	N.D	1273	1939	N.D
COD mg/1	5840	2920	3960	784
pH	5.9	6.4	6.2	6.9
Settleability Per cent	98	31	56	100

Determination of all chemical analyses is based on the filter paper filtrate.

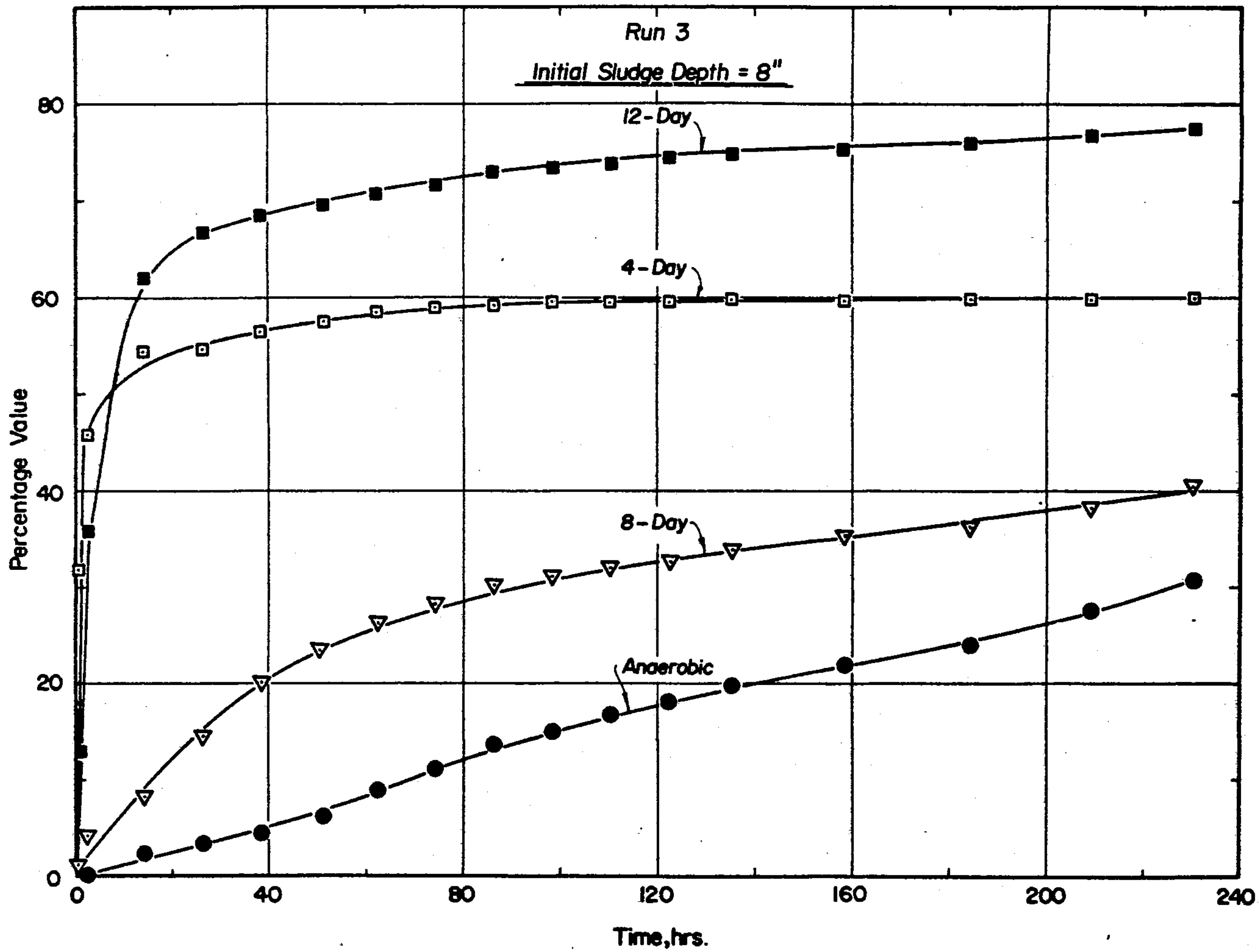

Figure 7. Percentage of Water Volume Drained to the Total Sludge Volume Applied Versus Time Curves - Run 3

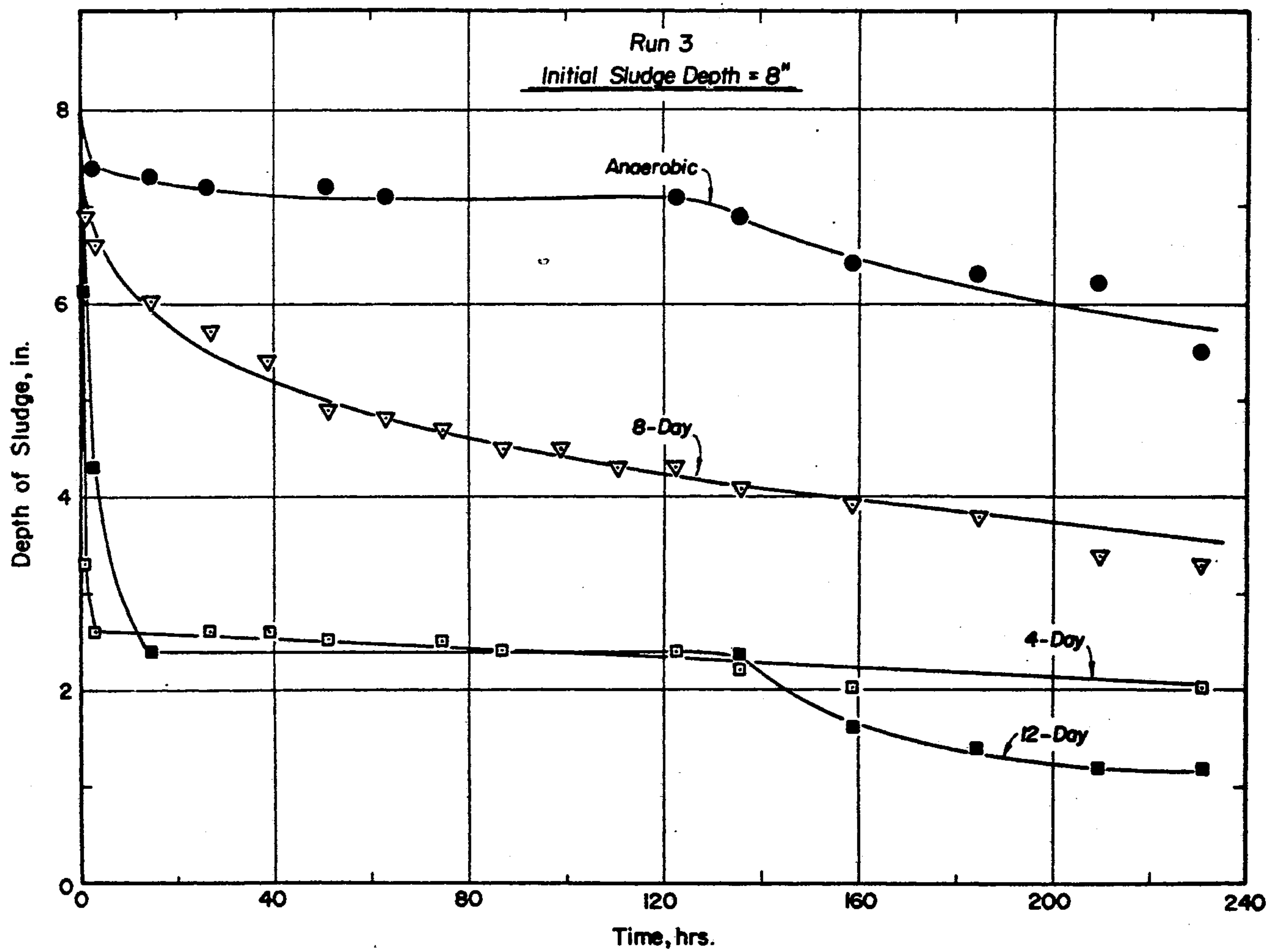

Figure 8. Sludge Depth Versus Time Curves - Run 3

TABLE VIII

SAND BEDS FILTRATE CHARACTERISTICS - RUN 3

Characteristic	Detention Time of Digested Sludge			Anaerobic
	4-Day	8-Day	12-Day	
NH_3-N mg/l	336	338	336	224
NO_3-N mg/l	3.0	4.0	2.0	0
P mg/l	101	67	90	23
COD mg/l	4,600	3,920	3,560	400

water to remove the growth which had accumulated on the sand bed and gravel.

Table IX lists the physical and chemical sludge characteristics. Sludge drainage and depth versus time are shown in Fig. 9 and 10. Table X lists the chemical analysis of the sand bed filtrates.

Drainage was substantially slow for all sludges. However, 30-day digested sludge showed a slight increase in drainage on the second day of application; followed by a slightly increased drainage pattern throughout the experimental period.

The supernatant in the 4-day digested sludge sand bed had built up to 2.4 inches, which took about twelve days from initial application to seep through the sludge blanket formed on top of the sand, while the supernatant in the 12-day digested sludge sand bed had a maximum depth of 3.75 inches and decreased to 1.5 inches after two weeks of application. No microbial growth was observed on any of the beds.

Sand bed filtrates of all sludges were cloudy, but light in color.

E. Run Number Five

The sand beds were washed with tap water long enough so that the effluent water was clear, making sure that the sand was clean and, hopefully there would be no interference

TABLE IX

SLUDGE CHARACTERISTICS - BATCH UNIT

Characteristic	Detention Time of Digested Sludge		
	4-Day	12-Day	30-Day
Total Solids mg/l	19,125	25,125	13,250
Volatile Solids mg/l	5,125	8,000	4,500
Filterability (CST)	486.6	450	304.2
NH_3-N mg/l	70	75.6	82.6
NO_3-N mg/l	1.8	1.6	2.3
P mg/l	80	75	30
BOD mg/l	1636	1606	362
COD mg/l	3253	2940	367
pH	6.3	6.9	8.0
Settleability Per cent	76	43	99

Determination of all chemical analyses is based on the filter paper filtrate.

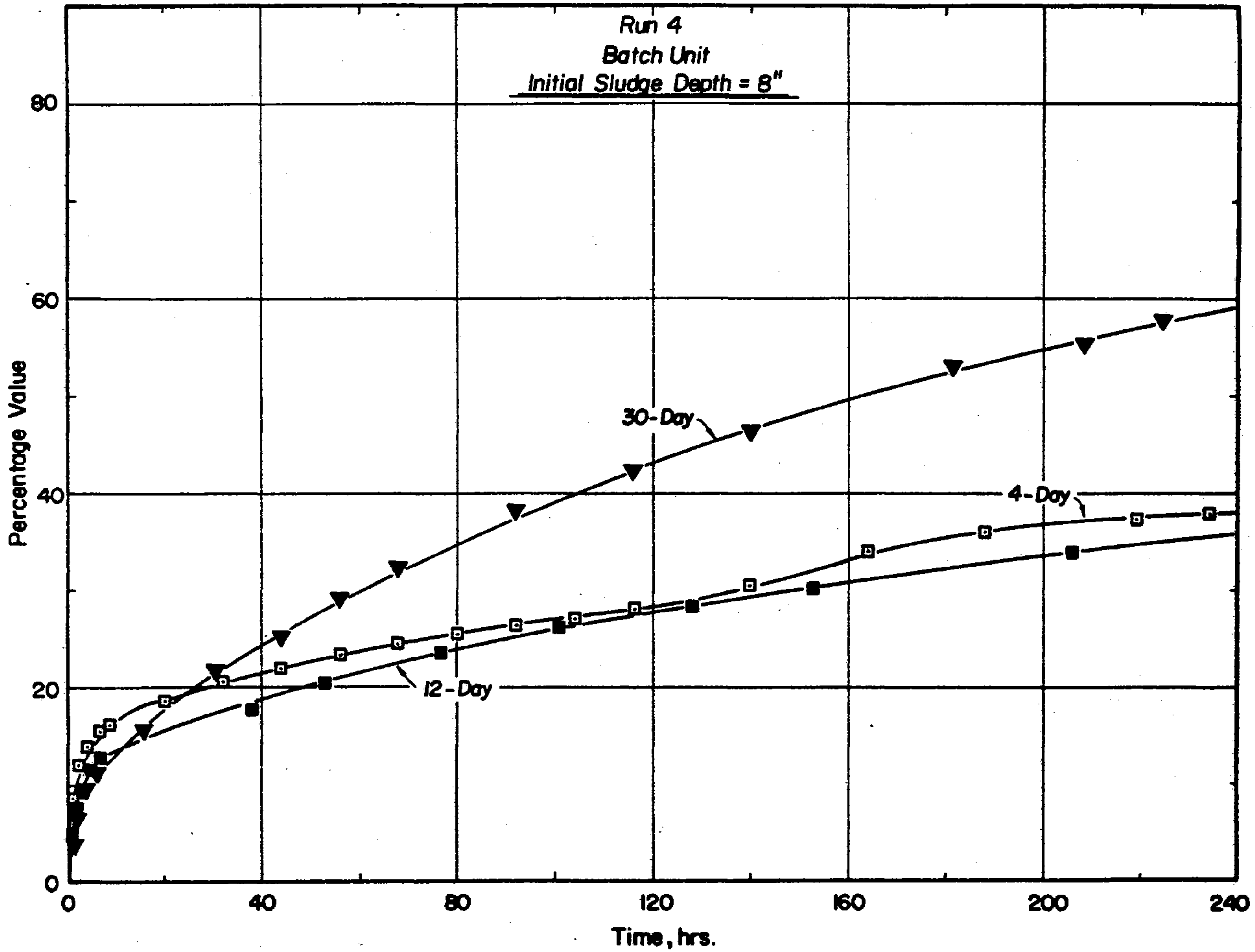

Figure 9. Percentage of Water Volume Drained to the Total Sludge Volume Applied Versus Time Curves - Run 4 - Batch Unit

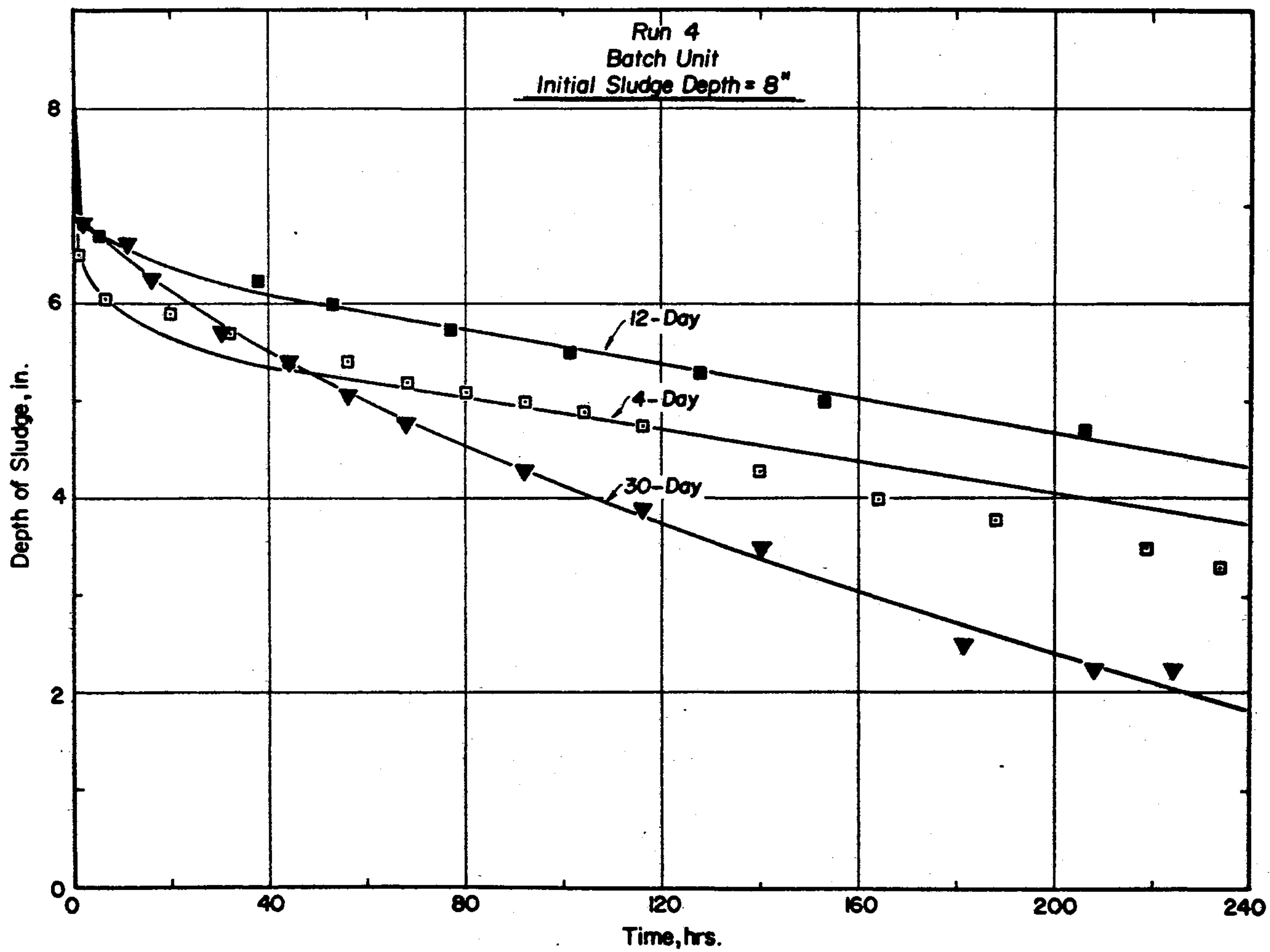

Figure 10. Sludge Depth Versus Time Curves - Run 4 - Batch Unit

TABLE X

SAND BEDS FILTRATE CHARACTERISTICS - BATCH UNIT

Characteristic	Detention Time of Digested Sludge		
	4-Day	12-Day	30-Day
NH_3-N mg/l	58.8	19.6	26.6
NO_3-N mg/l	7.4	1.6	0.0
P mg/l	120	6	12
COD mg/l	4573	1480	1303

of past sludge material on the new sludge to be applied.

In this run digested sludges with 12, 18, 24, and 30 day detention times were used.

Physical and chemical sludge characteristics are tabulated in Table XI. Sludge drainage characteristics and depth of sludge remaining on the sand beds versus time are shown in Fig. 11 and 12. Sand bed filtrate analyses are listed in Table XII.

Twelve-day and 30-day digested sludges had similar drainage behavior patterns with supernatant two inches in depth on each of the sludges on the second day of application. However, the third day of the experiment the supernatant of both sludges had seeped through the sludge layer causing a surge in the flow, resulting in an increase in the rate of drainage.

There was no supernatant observed the fourth day, while the 18 and 24 day sludges had a supernatant depth of 1.0 inch and .75 inch respectively at the end of the experiment.

No microbial growth was observed during the time of the experiment.

F. Run Number Six

The remaining sludge from Run 5 had been removed and discarded, and sand levels had been adjusted to their original depth (12 inches) before the second series of aero-

TABLE XI

SLUDGE CHARACTERISTICS - RUN 5

Characteristic	Detention Time of Digested Sludge			
	12-Day	18-Day	24-Day	30-Day
Total Solids mg/1	29,250	27,500	31,500	30,500
Volatile Solids mg/1	6,125	8,000	10,000	11,000
Filterability (CST)	660	608	586	482
NH_3-N mg/1	63	109	92	101
NO_3-N mg/1	0.0	1.7	1.9	1.1
P mg/1	110	145	85	N.D
BOD mg/1	1575	1756	1651	606
COD mg/1	3000	5780	3870	3170
pH	5.9	6.2	6.2	7.4
Settleability Per cent	67	88	51	62

Determination of all chemical analyses is based on the filter paper filtrate.

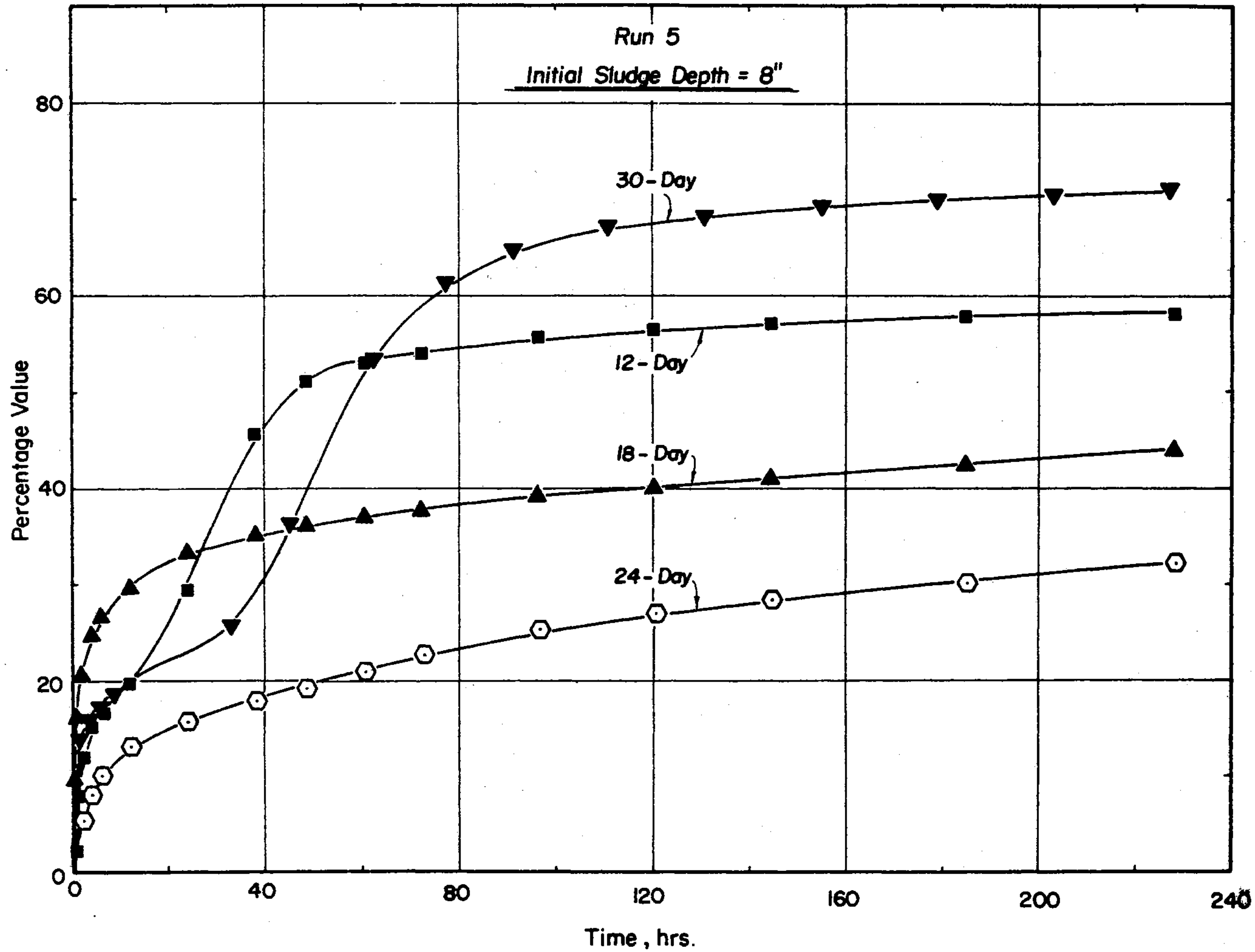

Figure 11. Percentage of Water Volume Drained to the Total Sludge Volume Applied Versus Time Curves - Run 5

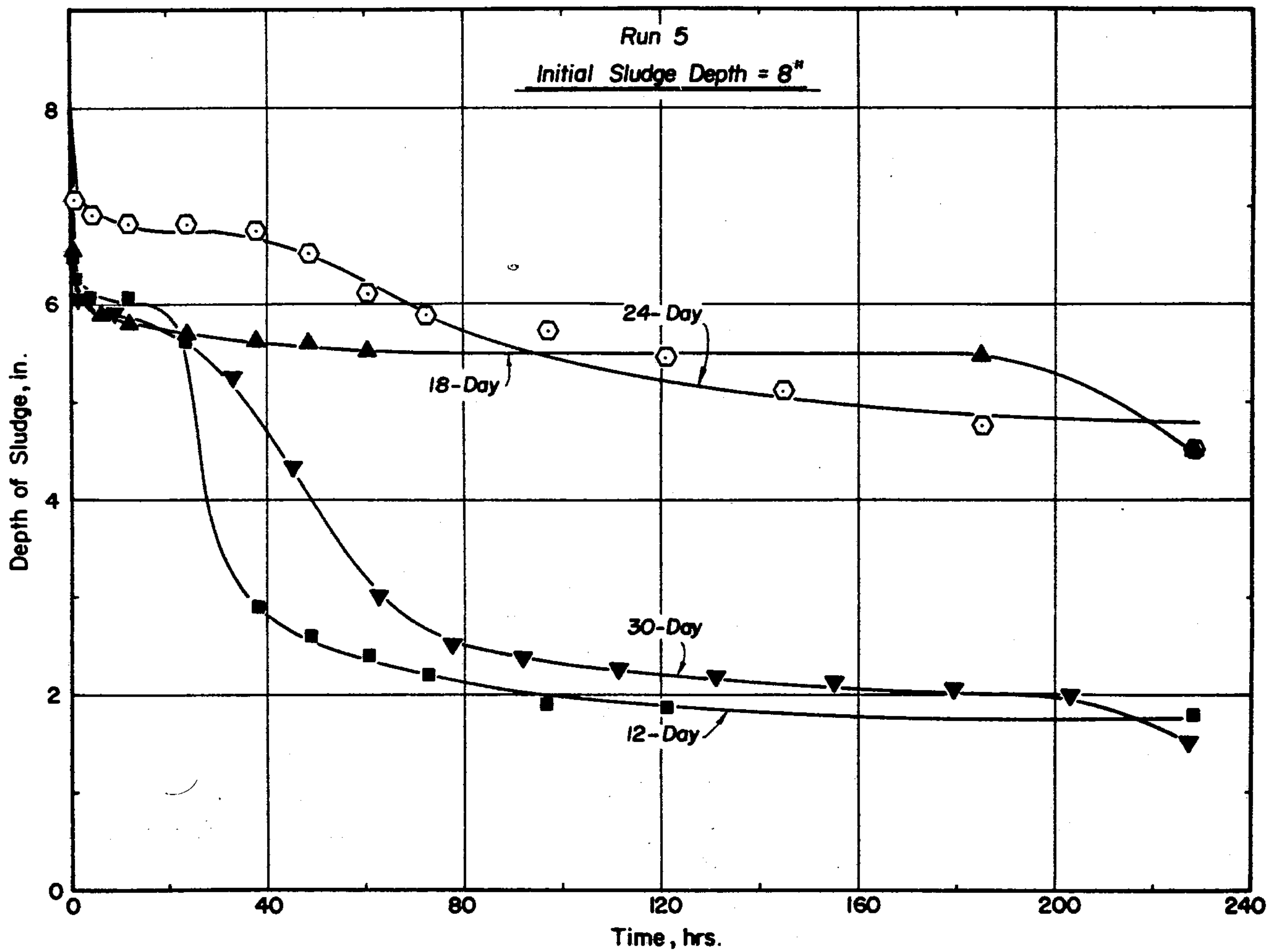

Figure 12. Sludge Depth Versus Time Curves - Run 5

TABLE XII

SAND BEDS FILTRATE CHARACTERISTICS - RUN 5

Characteristic	Detention Time of Digested Sludge			
	12-Day	18-Day	24-Day	30-Day
NH_3-N mg/l	48	74	12	85
NO_3-N mg/l	2.2	3.2	1.9	1.1
P mg/l	110	95	30	N.D
COD mg/l	6300	6230	3560	3610

bically digested sludges with 12, 18, 24, and 30 day detention times was applied.

Table XIII shows the characteristics of the applied sludge. Figures 13 and 14 show the drainage characteristics and depths of sludge versus time respectively. Filtrates of the sand beds have been analyzed chemically and analyses are listed in Table XIV.

The average ambient temperature was maintained at 25° C $\pm 2^{\circ}$ C.

The 18-day sludge had a supernatant of 2.25 inches during the first three days of application, but eventually drained through the sand and an abrupt change in depth was observed.

Sludge digested 30 days had bulked and the drainage rate was very slow. This sludge had been left on the sand bed for a two-week period after the experiment had terminated, just to observe the behavior of the drainage and sludge depth change. However, a 0.5 inch change in depth and a volume of 225 ml had drained in two weeks time. No moisture content sample was taken as the sludge was in a fluid state.

G. Average of All Runs

Data accumulated for runs 1, 2, 3, 5, and 6 have been compiled and averaged for each sludge on different runs.

TABLE XIII

SLUDGE CHARACTERISTICS - RUN 6

Characteristic	Detention Time of Digested Sludge			
	12-Day	18-Day	24-Day	30-Day
Total Solids mg/1	51,500	36,000	38,000	29,000
Volatile Solids mg/1	17,000	11,000	13,000	11,500
Filterability (CST)	683	555	681	595
NH_3-N mg/1	74	78	59	N.D
NO_3-N mg/1	2.4	1.7	1.5	1.8
P mg/1	145	N.D	N.D	N.D
BOD mg/1	1975	1727	1576	560
COD mg/1	6430	4880	4700	4630
pH	7.0	6.4	6.6	7.1
Settleability Per cent	64	62	43	60

Determination of all chemical analyses is based on the filter paper filtrate.

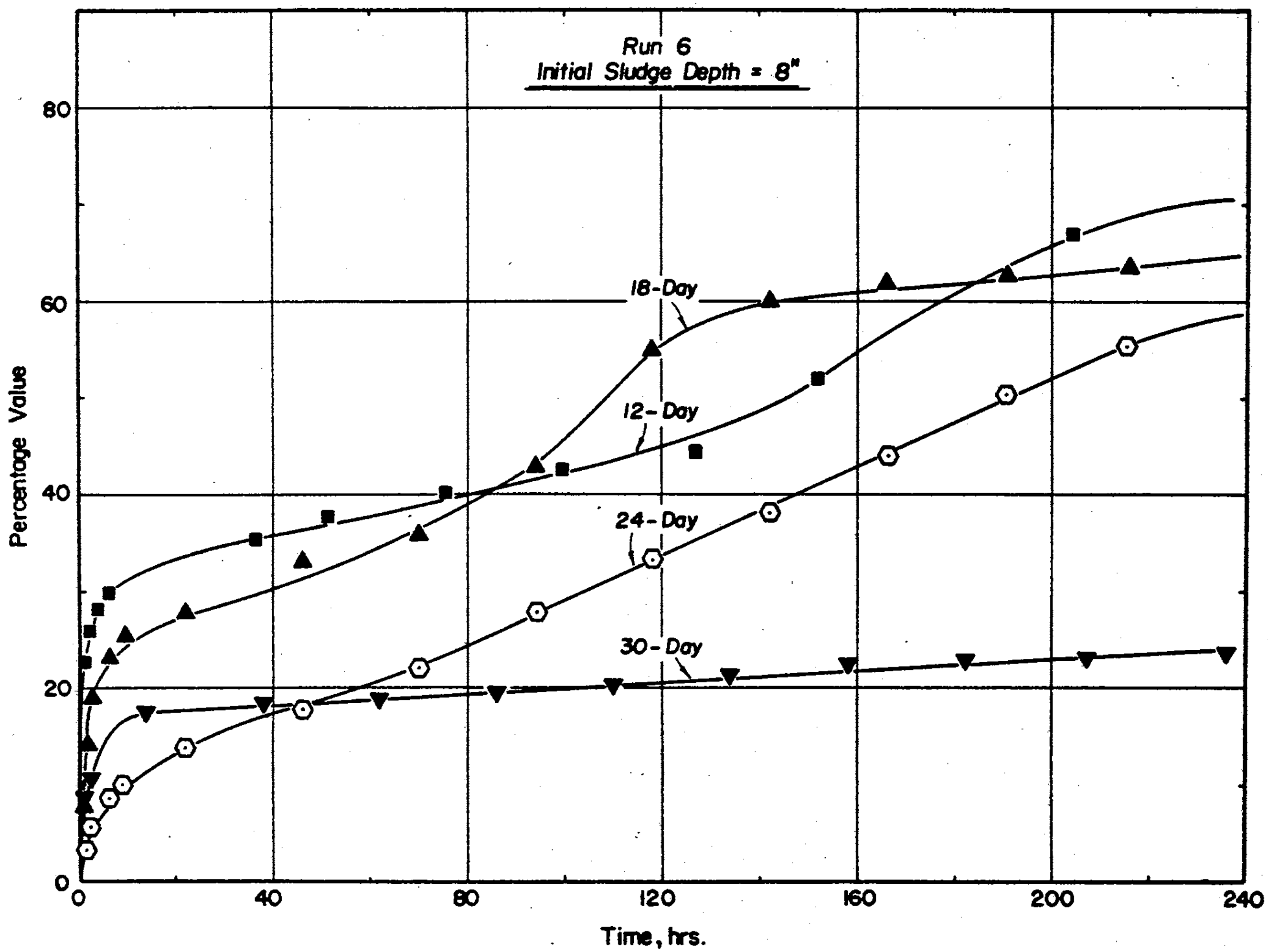

Figure 13. Percentage of Water Volume Drained to the Total Sludge Volume Applied Versus Time Curves - Run 6

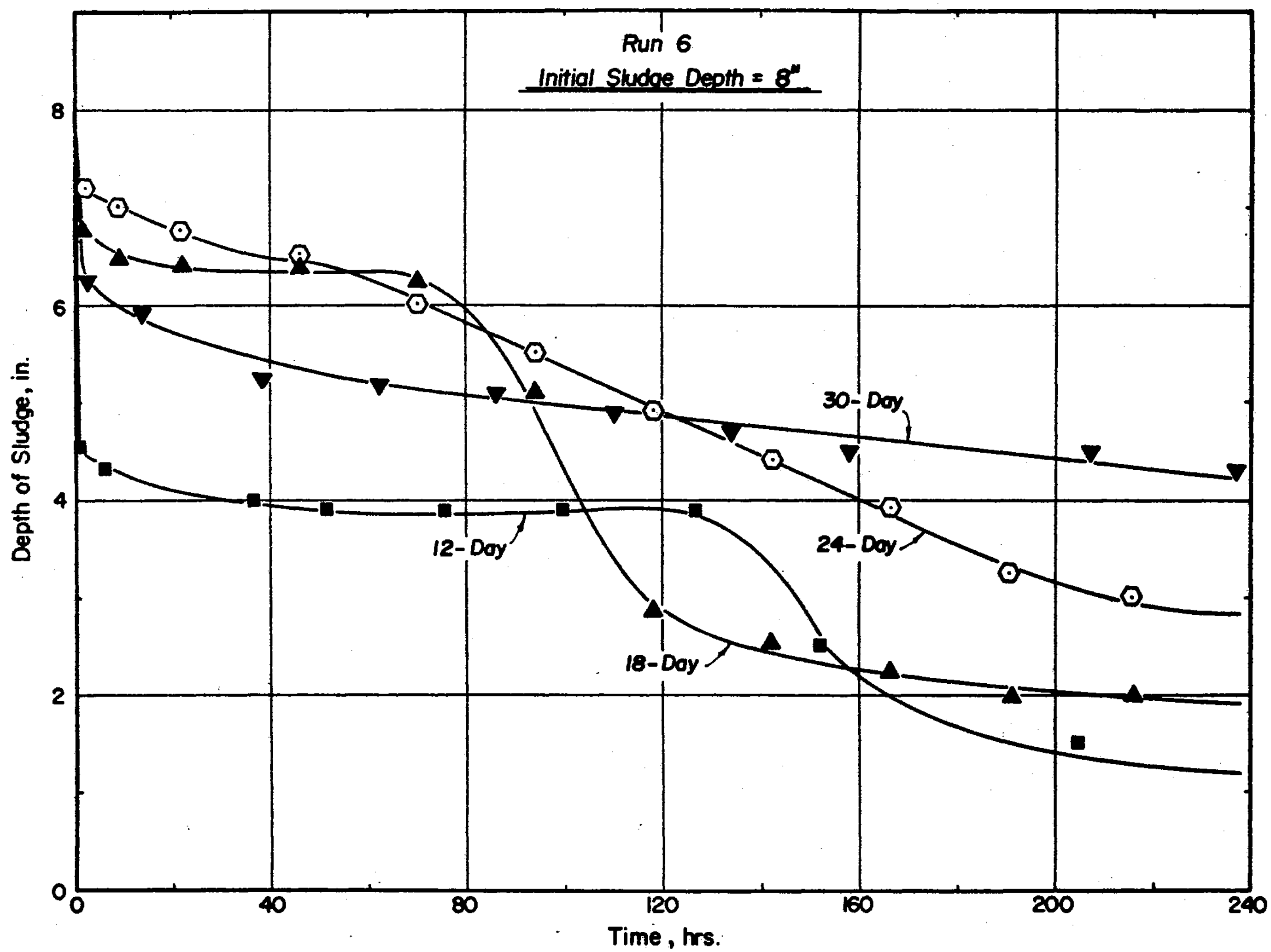

Figure 14. Sludge Depth Versus Time Curves - Run 6

TABLE XIV

SAND BEDS FILTRATE CHARACTERISTICS - RUN 6

Characteristic	Detention Time of Digested Sludge			
	12-Day	18-Day	24-Day	30-Day
NH_3-N mg/l	62	50	20	50
NO_3-N mg/l	1.8	3.4	4.6	4.0
P mg/l	105	N.D	N.D	N.D
COD mg/l	6490	5140	4880	4590

Average data for the chemical and physical characteristics of sludges are tabulated in Table XV. Average drainage curves of sludges are shown in Fig. 15.

Since drained water from drying beds must be returned for full treatment, its chemical composition is of considerable interest. Average data for the analysis of the water drained is given in Table XVI.

Average values of filterability, as measured by the simple automatic instrument (1), of all runs performed are plotted in Fig. 16. Also, settleability characteristics of the average value calculated from all runs performed are shown in Fig. 17.

TABLE XV

SLUDGE CHARACTERISTICS - AVERAGE OF ALL RUNS

Characteristic	Raw	Detention Time of Digested Sludge							Anaerobic
		2-Day	4-Day	8-Day	12-Day	18-Day	24-Day	30-Day	
Total Solids mg/l	37,314	95,378	33,523	31,659	32,990	31,750	34,750	29,750	131,931
Volatile Solids mg/l	14,121	39,752	18,722	19,063	15,310	9,500	11,500	11,250	17,814
Filterability (CST)	146	398	454	524	513	582	634	539	673
NH_3-N mg/l	140	168	173	211	202	94	76	101	663
NO_3-N mg/l	2.5	2.3	1.5	2.0	1.4	1.7	1.7	1.5	1.5
P mg/l	91	72	97	87	113	145	85	N.D	43
BOD mg/l	1116	1600	133	1175	1577	1266	1175	583	67
COD mg/l	2640	2870	2720	2349	3472	5330	4285	3900	432
pH	5.3	5.9	6.6	6.5	6.7	6.3	6.4	7.2	7.0
Settleability Per cent	99	29	57	57	70	75	47	61	100

Determination of all chemical analyses is based on the filter paper filtrate.

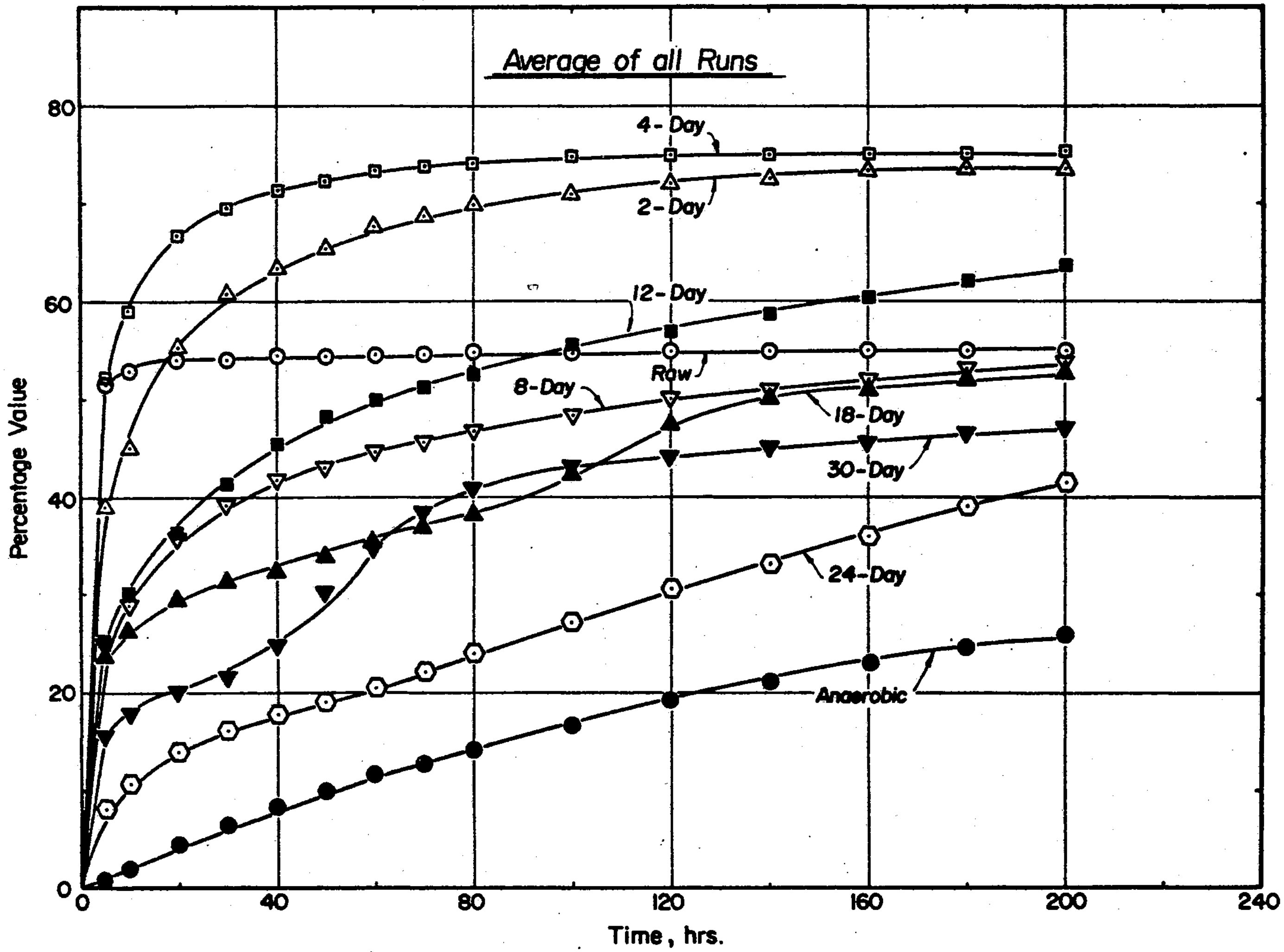

Figure 15. Percentage of Water Volume Drained to the Total Sludge Volume Applied Versus Time Curves - Average of Runs 1, 2, 3, 5, and 6

TABLE XVI

SAND BEDS FILTRATE CHARACTERISTICS - AVERAGE OF ALL RUNS

Characteristic	Raw	Detention Time of Digested Sludge							Anaerobic
		2-Day	4-Day	8-Day	12-Day	18-Day	24-Day	30-Day	
NH_3-N mg/l	118	148	175	222	158	62	36	58	277
NO_3-N mg/l	0.7	3.5	4.1	3.5	2.5	3.3	3.3	2.6	0.4
P mg/l	N.D	73.5	69.0	70.0	72.5	95.0	30.0	N.D	20.7
COD mg/l	N.D	3408	3949	3987	4314	5685	4220	4100	592

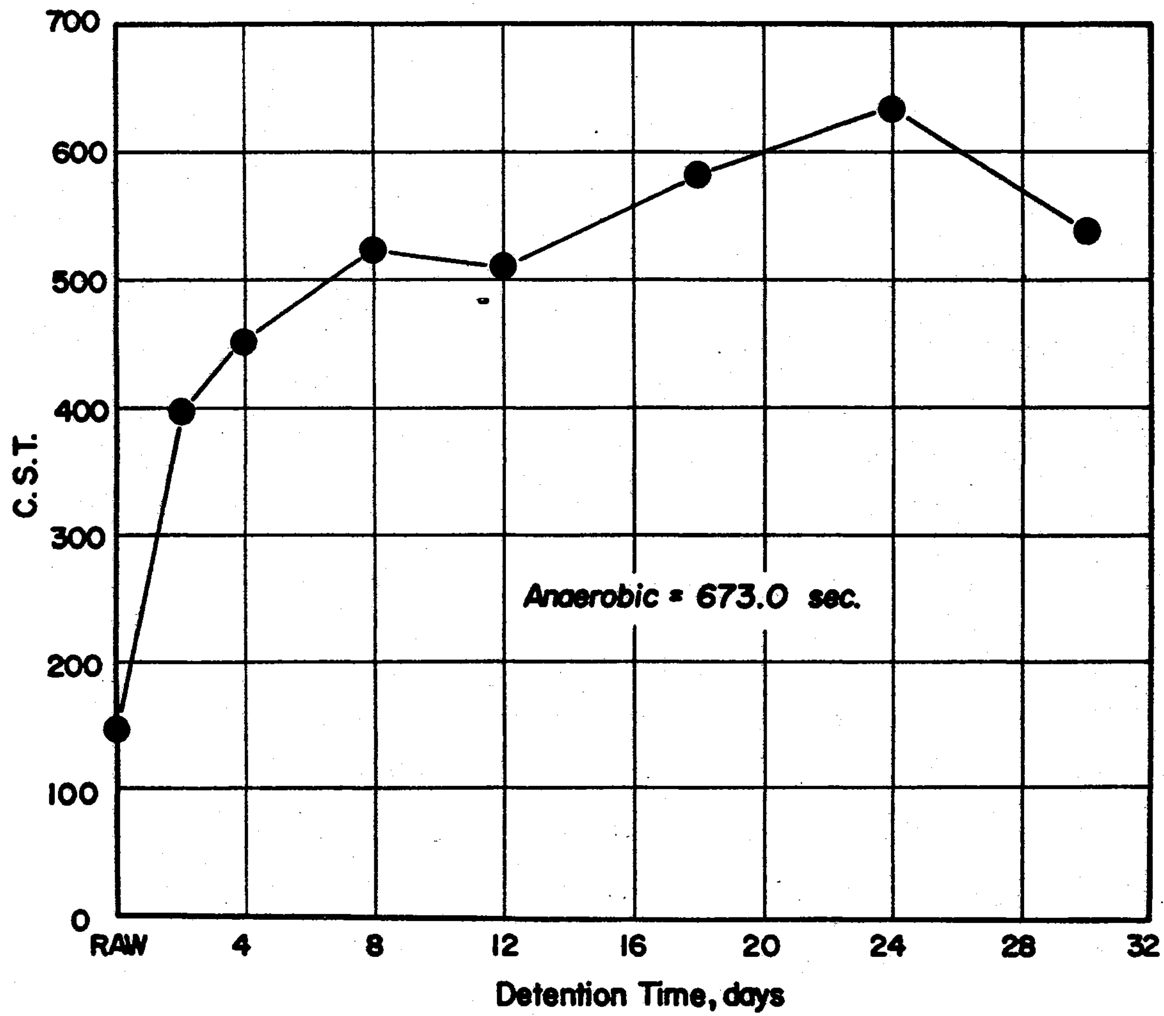

Figure 16. Capillary Suction Time Versus Detention Time - Average of Runs 1, 2, 3, 5, and 6

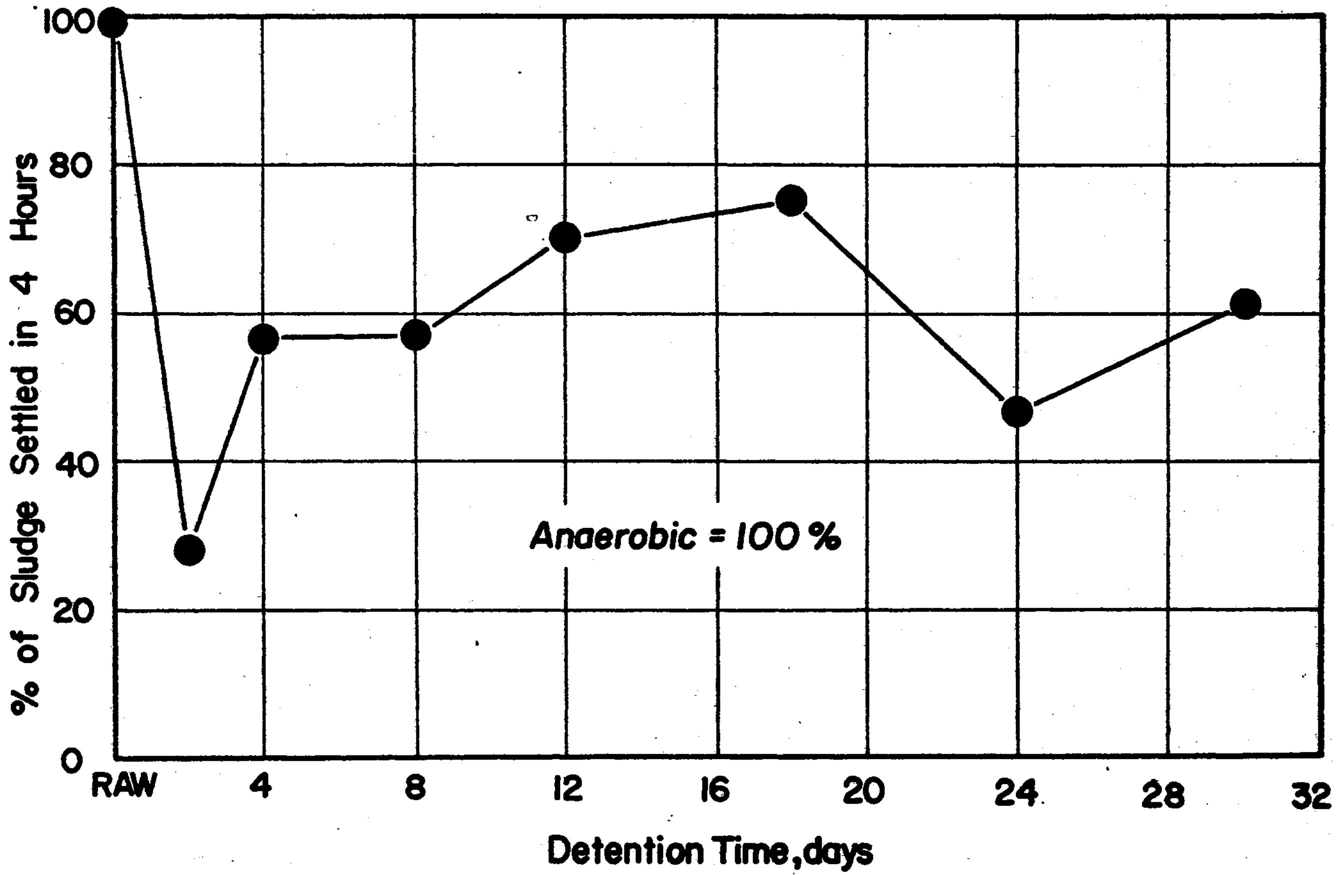

Figure 17. Percent of Sludge Settled at Four Hours Versus Detention Time - Average of Runs 1, 2, 3, 5, and 6

CHAPTER V

DISCUSSION

A. Drainability and Sludge Depth

The shape and pattern of the average drainage curves of all runs performed for this study as shown in Fig. 15, were typical of all drainage curves obtained in each run regardless of the applied sludge depth, since each of the curves for each sludge type was averaged on the basis of water drained as percentage of the volume of sludge applied. It is of interest to note, however, that on the average there was a slight difference in drainage characteristics when different initial sludge depths were applied.

The results show that aerobically digested sludges had drained extremely well when compared to the anaerobically digested sludge as illustrated in Fig. 3, 5, 7, and 15. However, a wide gap did occur between the drainage characteristics of the 2 and 4 day digested sludges as a group and the other digested sludges as another group. See Fig. 15.

As illustrated in Fig. 3. 5, 7, and 15, the raw, 2-day, and 4-day digested sludges had a high initial drainage rate on the first day of application, which gradually decreased with time and finally came to a complete stop before the experiment period (two weeks) had ended.

The apparent cause for the rapid drainage flow, which was observed on the first day of the experiment for the above mentioned sludges could be generally explained in this manner: the physical appearance of the raw sludge could be described as consisting of many, small to large lumps of fibers and particulate matter suspended in the water. These lumps do not tend to form a layer of sludge solids, which in turn allows the free water to seep through these lumps into the sand layer faster. However, since digestion of two or four days destroys only a small percentage of the fibers and particulate matter, the rapid drainage of the 2-day and and 4-day aerobically digested sludges could have the same explanation as mentioned above.

The levels of the sludge had sharply lowered when the initial drainage flow was high. When the drainage flow slowed down the sludge levels decreased at a slower rate, as indicated in Fig. 4, 6, and 8. This phenomenon could explain the fact that a direct relationship between the decreasing sludge depth and the drainage flow does exist. It is important to mention however, that as the drainage flow came to a complete stop after several days of the experiment no significant decrease in depth was observed throughout the two-week period of the experiment as shown in Fig. 4, 6, and 8. This indicates that evaporation played no signigicant part in the dewatering process in this case, since this study was investigated under normal ambient conditions.

This finding was in complete disagreement with results and conclusions of several workers: Tang (17), Randall and Koch (12), Nebiker (9), and Swanwick and Baskerville (16).

Sludge digested twelve days or more, in one way or another had a different pattern of drainage than sludge digested less than twelve days, as indicated in Fig. 11, 13, and 15. The drainage curves for the above mentioned sludge had a plateau approximately two to three days after application, when a maximum rate of drainage occured.

As indicated in Fig. 12 and 14, an abrupt decrease in the level of the sludge surfaces was observed simultaneously for the detention times of 12, 18, 24, and 30 days. This surge phenomenon in the sludge could be explained in this manner: the formation of supernatant on top of the sludge layer occured due to the rapid settlement and compaction of the sludge solids, which surpassed the drainage flow from the mixed liquor. This compacted layer consisting of fine sludge particles, in turn hindered the drainage flow. However, after approximately two days anaerobic conditions in the sludge cake developed and gas formation was observed. Hence, cracks and empty pockets resulted, allowing the entrapped supernatant to drain through and a maximum rate of drainage was then observed.

Quon (10) in his study of sludge drainage on sand beds, observed the surge phenomenon. This, he explained, is attributed to the inability of the air entrapped in the pores of the sand beds to be dispersed mechanically, and the porosity of the bed is restored only when the entrapped air has been absorbed, after two or three days.

Tang, et al. (17) also observed the surge phenomenon in his studies in moisture transport in sludge dewatering. He explained the phenomenon as a sudden break of the free water through the impass formed by the fine sludge particles on the surface of the sand layer, which was due to the pressure imbalance between the point on the surface on the sludge cake and that under the sludge cake.

B. Moisture Removal

The amount of water removed from sludges during the dewatering process on the sand beds varied from one type of sludge to the other and from one run to the other even for the same type of sludge. However, the maximum percentage removal of the initial moisture during the two-week period of application was 94.4 per cent and the minimum removal was as little as 4 per cent of the initial moisture content. This occured because of bad drainage characteristics. Again this is another phenomenon which illustrates the fact that evaporation had a very small part in the dewatering process throughout this study. The drainage phase of the dewatering process therefore, receives the credit for moisture removal in the sludge.

For the Batch Run the moisture removal was very insignificant. The drainage mechanism does not seem to apply very well with batch-digested sludges.

C. Sand Heaving

A significant, but unusual phenomenon was observed during this study. This was an increase in the sand depth, which was observed after the second run was terminated on almost all sand beds used. An increase in the sand level of 0.5 inch from the original mark was observed. This same observation was noticed again in the third run, but to a lesser extent. This strange phenomenon could be interpreted in this manner: as the water trickles down the sand layer, microorganisms in the water tend to stick to the discrete grains of sand. As more water trickles down, more food is provided to the microorganisms, and growth takes place as indicated in Chapter IV. This growth, in turn tends to force the sand particles apart and since the movement of the sand is limited to an upward direction, an increase in sand depth results.

D. Filterability

In comparing the filterability of the various sludges used in this study, an automatic instrument (1) was used which is based on the capillary suction method. A close look at Fig. 16 and Table XV. shows the filterability of sludges measured by the above mentioned instrument is closely related to the drainability of sludge on sand beds. In this capillary suction method, the lesser the value of capillary suction time (CST), the more filterable the sludge. Determination of filterability was done on two simultaneous runs for each sludge where very reasonable precision was obtained and an average value was computed and recorded.

Filterability results did vary in each run for every sludge. This inconsistency in results was probably due to the non-uniformity of the primary digested sludges, and also to the problems of feeding the units encountered when pumps were clogged and out of order for a significant length of time to cause a great variation in all physical and chemical parameters investigated throughout this study.

Results obtained from the batch studies showed that filterability and drainability were closely related. The 30-day digested sludge was expected to drain better than the 4-day or 12-day digested sludges since the (CST) value was lower, hence there was better filterability.

E. Settleability

This parameter was the most difficult to evaluate in this study. As indicated in Tables III, V, VII, XI, XIII, and XV, values were never repeated within a reasonable difference. A 60 per cent difference was observed for one type of sludge. In general, aerobically digested sludge showed good settling characteristics as compared to the raw and anaerobically digested sludges. However, settling studies with small laboratory equipment can hardly be compared to conditions in actual practice.

F. Other Parameters

Attempts to correlate parameters such as pH, total solids, and volatile solids were not very successful due to the inadequate data obtained for the runs performed because of the feeding problems involved.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The drainage characteristics of aerobically and anaerobically digested sludges have been studied. The experimental results establish the following:

(1) Drainage of aerobically digested sludge surpassed the drainage of anaerobically digested sludge. This is in complete agreement with results reported by Quon (10) and Randall (12).

(2) Sludge digested four days out-performed all other sludges used for almost every parameter considered.

(3) Evaporation had a very insignificant effect on the dewatering process under the conditions to which the sand filters were exposed.

(4) The drainage phase was responsible for removing almost 90 per cent of the total volume of water removed.

(5) Drainability of sludge on sand beds correlates fairly well with filterability as measured by the automatic instrument. With a simple test performed, this instrument can provide the plant operator with a basic idea of whether or not the

sludge in the digester is ready for application on the drying beds.

(6) The settling characteristics had no correlation whatsoever with the drainage behavior of sludge.

(7) After sand bed filtration, ammonia-N tends to decrease; nitrate-N tends to increase; orthophosphate tends to decrease; and COD tends to increase.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are recommended:

(1) Studies are needed on the composition, structure, and properties of aerobically digested sludge to promote a greater understanding of what affects the initial drainage rate.

(2) Investigations on dewatering of aerobically digested sludge utilizing mechanical dewatering methods, especially the vacuum filtration process would be helpful.

(3) The addition of chemical conditioners to aerobically digested sludge may improve sludge dewatering substantially.

(4) More studies are needed on the usage of coarser sand as a drainage medium.

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APPENDIX A

DRAINAGE DATE - RUN 1

Appendix A-1 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 2-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	22	6.0	0	0	0.00	85.3
1	22	4.1	2880	2880	22.60	
2	22	3.9	570	3450	27.07	
3	22	3.6	580	4030	31.62	
4	22	3.3	610	4640	36.41	
5	22	3.1	550	5190	40.72	
6	22	2.9	450	5640	44.25	
12	21	2.6	860	6500	51.00	
18	22	2.4	560	7060	55.39	
24	23	2.3	480	7540	59.16	
30	23	2.1	300	7840	61.51	
42	23	2.0	610	8450	66.30	
54	24	2.0	350	8800	69.05	
66	24	2.0	250	9050	71.01	
78	23	1.9	170	9220	72.34	
90	25	1.9	140	9360	73.44	
114	24	1.8	280	9640	75.64	
138	24	1.6	150	9790	76.81	
162	23	1.6	70	9860	77.36	
186	24	1.6	30	9890	77.60	
210	25	1.5	30	9920	77.83	
234	25	1.2	50	9970	78.23	
282	23	1.2	65	10035	78.74	
330	25	1.2	105	10140	79.56	6.0

Initial volume of sludge applied = 14160 ml.

Appendix A-2 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 4-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	22	6.0	0	0	0.00	97.4
1	22	3.6	3060	3060	24.46	
2	22	2.6	1410	4470	35.73	
3	22	1.9	1800	6270	50.12	
4	22	1.8	1180	7450	59.56	
5	22	1.6	300	7750	61.96	
6	22	1.5	360	8110	64.83	
12	21	1.4	910	9020	72.11	
18	22	1.3	440	9460	75.63	
24	23	1.3	336	9796	78.30	
30	23	1.2	105	9901	79.14	
42	23	1.1	270	10171	81.30	
54	24	1.0	165	10336	82.62	
66	24	1.0	75	10411	83.22	
78	23	1.0	70	10481	83.78	
90	25	1.0	60	10541	84.26	
114	24	1.0	80	10621	84.90	
138	24	1.0	11	10632	84.99	
162	23	1.0	0	10632	84.99	
186	24	1.0	0	10632	84.99	
210	25	1.0	23	10655	85.17	
234	25	1.0	10	10665	85.25	
282	23	1.0	38	10703	85.55	
330	25	1.0	35	10738	85.83	3.0

Initial volume of sludge applied = 14160 ml.

Appendix A-3 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 8-Day Sludge

Time (hrs)	Temp. ($^oC.$)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	22	6.0	0	0	0.00	97.6
1	22	3.9	1980	1980	15.81	
2	22	3.8	180	2160	17.27	
3	22	3.6	175	2335	18.67	
4	22	3.5	170	2505	20.03	
5	22	3.5	210	2715	21.70	
6	22	3.4	265	2980	23.83	
12	21	3.3	600	3580	28.62	
18	22	3.1	340	3920	31.34	
24	23	3.0	330	4250	33.98	
30	23	3.0	150	4400	35.17	
42	23	2.9	250	4650	37.17	
54	24	2.8	190	4840	38.67	
66	24	2.8	130	4970	39.73	
78	23	2.5	130	5100	40.77	
90	25	2.5	120	5220	41.73	
114	24	2.3	250	5470	43.73	
138	24	2.2	200	5670	45.33	
162	23	2.0	290	5960	47.63	
186	24	1.9	130	6090	48.68	
210	25	1.8	240	6330	50.60	
234	25	1.8	190	6520	52.12	
282	23	1.5	230	6750	53.96	
330	25	1.3	260	7010	56.04	86.5

Initial volume of sludge applied = 14160 ml.

Appendix A-4 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 12-Day Sludge

Time (hrs)	Temp. (°C)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	22	6.0	0	0	0.00	96.8
1	22	4.0	1300	1300	10.80	
2	22	3.9	160	1460	12.13	
3	22	3.9	0	1460	12.13	
4	22	3.8	170	1630	13.54	
5	22	3.8	200	1830	15.20	
6	22	3.7	240	2070	17.20	
12	21	3.7	400	2470	20.52	
18	22	3.5	250	2720	22.60	
24	23	3.5	230	2950	24.51	
30	23	3.4	140	3090	25.67	
42	23	3.1	405	3495	29.04	
54	24	3.0	360	3855	32.03	
66	24	2.8	350	4205	34.92	
78	23	2.5	340	4545	37.76	
90	25	2.4	410	4955	41.16	
114	24	2.0	810	5765	47.89	
138	24	1.8	400	6165	51.22	
162	23	1.5	460	6625	55.04	
186	24	1.4	190	6815	56.62	
210	25	1.3	290	7105	59.03	
234	25	1.2	200	7305	60.69	
282	23	1.0	410	7715	62.43	
330	25	1.3	240	7955	65.84	82.0

Initial volume of sludge applied = 14160 ml.

Appendix A-5 - Temperature, Depth of Sludge Drainage Volume, and Moisture Content of Anaerobic Sludge

Time (hrs)	Temp. (^{o}C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	22	6.0	0	0	0.00	98.2
1	22	5.4	0	0	0.00	
2	22	5.4	0	0	0.00	
3	22	5.4	0	0	0.00	
4	22	5.4	0	0	0.00	
5	22	5.3	0	0	0.00	
6	22	5.3	110	110	0.86	
12	21	5.3	260	370	2.90	
18	22	5.3	190	560	4.39	
24	23	5.1	240	800	6.28	
30	23	5.1	120	920	7.22	
42	23	5.1	330	1250	9.81	
54	24	5.1	270	1520	11.93	
66	24	5.1	210	1730	13.57	
78	23	5.0	220	1950	15.30	
90	25	5.0	190	2140	16.79	
114	24	4.9	440	2530	20.24	
138	24	4.8	270	2850	22.36	
162	23	4.7	380	3230	25.34	
186	24	4.5	170	3400	26.68	
210	25	4.4	250	3650	28.64	
234	25	4.4	190	3840	30.13	
282	23	4.2	250	4090	32.09	
330	25	3.3	255	4345	34.09	74.6

Initial volume of sludge applied = 14160 ml.

APPENDIX B

DRAINAGE DATA - RUN 2

Appendix B-1 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of Raw Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.00	19	4.0	0	0	0.00	96.0
0.50	19	1.3	2260	2260	23.94	
1.25	17	0.8	2120	4380	46.39	
2.25	17	0.8	290	4670	49.47	
7.25	17	0.8	280	4950	52.43	
19.25	24	0.8	140	5090	53.91	
31.25	25	0.8	36	5126	54.30	
43.25	24	0.8	20	5146	54.51	
55.25	26	0.8	15	5161	54.67	
67.25	25	0.8	13	5174	54.80	
79.25	24	0.8	7	5181	54.88	
91.25	21	0.8	7	5188	54.95	
103.25	23	0.8	5	5193	55.00	
115.25	22	0.8	5	5198	55.06	
127.25	23	0.8	2	5200	55.08	
139.25	23	0.8	2	5202	55.10	
151.25	23	0.8	0	5202	55.10	
175.25	24	0.8	0	5202	55.10	
199.25	21	0.8	0	5202	55.10	
223.25	22	0.8	0	5202	55.10	
271.25	23	0.8	0	5202	55.10	
343.25	24	0.8	0	5202	55.10	
439.25	23	0.8	0	5202	55.10	N.D

Initial volume of sludge applied = 9440 ml.

Appendix B-2 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 2-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.00	19	4.0	0	0	0.00	91.8
0.50	19	2.9	610	610	6.46	
1.25	17	2.1	1160	1770	18.75	
2.25	17	2.0	780	2550	27.01	
7.25	17	1.9	980	3530	37.39	
19.25	24	1.3	1550	5080	53.81	
31.25	25	1.1	580	5660	59.95	
43.25	24	1.1	290	5950	63.02	
55.25	26	1.1	170	6120	64.83	
67.25	25	1.1	130	6250	66.20	
79.25	24	1.1	60	6310	66.84	
91.25	21	1.1	60	6370	67.47	
103.25	23	1.1	35	6405	67.84	
115.25	22	1.1	32	6437	68.18	
127.25	23	1.0	17	6456	68.36	
139.25	23	1.0	17	6471	68.54	
151.25	23	1.0	15	6486	68.70	
175.25	24	1.0	21	6507	68.92	
199.25	21	0.9	13	6520	69.06	
223.25	22	0.9	9	6529	69.16	
271.25	23	0.8	7	6536	69.23	
343.25	24	0.8	5	6541	69.28	
439.25	23	0.8	15	6556	69.40	N.D

Initial volume of sludge applied = 9440 ml.

Appendix B-3 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 4-Day Sludge

Time (hrs)	Temp. ($^oC.$)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.00	19	4.0	0	0	0.00	95.5
0.50	19	2.3	950	950	10.06	
1.25	17	1.9	1340	2290	24.26	
2.25	17	1.7	1660	3950	41.84	
7.25	17	1.3	930	4880	51.69	
19.25	24	0.7	1700	6580	69.70	
31.25	25	0.7	460	7040	74.57	
43.25	24	0.5	190	7230	76.58	
55.25	26	0.5	110	7340	77.75	
67.25	25	0.5	100	7440	78.81	
79.25	24	0.5	35	7475	79.16	
91.25	21	0.5	36	7511	79.56	
103.25	23	0.5	20	7531	79.77	
115.25	22	0.5	19	7550	79.97	
127.25	23	0.5	17	7567	80.15	
139.25	23	0.3	21	7588	80.37	
151.25	23	0.3	16	7604	80.54	
175.25	24	0.3	24	7628	80.80	
199.25	21	0.3	31	7659	81.12	
223.25	22	0.3	12	7671	81.25	
271.25	23	0.3	25	7696	81.52	
343.25	24	0.3	30	7726	81.83	
439.25	23	0.3	4	7730	81.88	N.D

Initial volume of sludge applied = 9440 ml.

Appendix B-4 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 8-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.00	19	4.0	0	0	0.00	96.3
0.50	19	1.8	1420	1420	15.04	
1.25	17	1.5	1645	3065	32.46	
2.25	17	1.3	980	4045	42.85	
7.25	17	1.3	660	4705	49.84	
19.25	24	0.8	870	5575	59.05	
31.25	25	0.7	600	6175	65.41	
43.25	24	0.7	210	6385	67.63	
55.25	26	0.7	130	6515	69.01	
67.25	25	0.5	105	6620	70.12	
79.25	24	0.5	50	6670	70.65	
91.25	21	0.4	77	6747	71.46	
103.25	23	0.4	62	6809	72.12	
115.25	22	0.3	58	6867	72.74	
127.25	23	0.3	66	6933	73.43	
139.25	23	0.3	67	7000	74.14	
151.25	23	0.3	34	7034	74.50	
175.25	24	0.3	14	7048	74.65	
199.25	21	0.3	40	7088	75.07	
223.25	22	0.3	6	7094	75.14	
271.25	23	0.2	55	7149	75.72	
343.25	24	0.1	135	7284	77.15	
439.25	23	0.1	120	7404	78.42	N.D

Initial volume of sludge applied = 9440 ml.

Appendix B-5 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 12-Day Sludge

Time (hrs)	Temp. (^{o}C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.00	19	4.0	0	0	0.00	97.1
0.50	19	2.8	310	310	3.28	
1.25	17	2.4	500	810	8.58	
2.25	17	2.3	760	1570	16.63	
7.25	17	2.0	800	2370	25.10	
19.25	24	1.7	930	3300	34.95	
31.25	25	1.3	700	4000	42.37	
43.25	24	0.9	620	4620	48.94	
55.25	26	0.8	390	5010	53.07	
67.25	25	0.7	290	5300	56.14	
79.25	24	0.5	120	5420	57.41	
91.25	21	0.4	110	5530	58.57	
103.25	23	0.4	59	5589	59.20	
115.25	22	0.4	40	5629	59.62	
127.25	23	0.3	22	5651	59.86	
139.25	23	0.3	16	5667	60.03	
151.25	23	0.3	10	5677	60.13	
175.25	24	0.3	14	5691	60.28	
199.25	21	0.3	24	5715	60.53	
223.25	22	0.3	22	5737	60.77	
271.25	23	0.2	77	5814	61.58	
343.25	24	0.1	73	5887	62.36	
439.25	23	0.1	100	5987	63.41	N.D

Initial volume of sludge applied = 9440 ml.

Appendix B-6 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of Anaerobic Sludge

Time (hrs)	Temp. (^{o}C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.00	19	4.0	0	0	0.00	N.D
0.50	19	4.0	0	0	0.00	
1.25	17	3.5	0	0	0.00	
2.25	17	3.5	100	100	1.06	
7.25	17	3.4	180	280	2.01	
19.25	24	3.3	280	560	6.04	
31.25	25	3.3	240	800	8.58	
43.25	24	3.1	185	985	10.54	
55.25	26	3.1	150	1135	12.13	
67.25	25	3.1	140	1275	13.61	
79.25	24	3.1	130	1405	15.00	
91.25	21	3.0	120	1525	16.26	
103.25	23	2.9	150	1675	17.85	
115.25	22	2.9	70	1745	18.59	
127.25	23	2.8	130	1875	19.97	
139.25	23	2.7	105	1980	21.08	
151.25	23	2.5	95	2075	22.08	
175.25	24	2.5	130	2205	23.46	
199.25	21	2.5	120	2325	24.73	
223.25	22	2.4	100	2425	25.79	
271.25	23	2.1	130	2555	27.17	
343.25	24	1.5	155	2710	28.81	
439.25	23	1.1	110	2820	29.98	N.D

Initial volume of sludge applied = 9440 ml.

APPENDIX C

DRAINAGE DATE - RUN 3

Appendix C-1 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 4-Day Sludge

Time (hrs)	Temp. ($^{o}C.$)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	23	8.0	0	0	0.00	96.7
0.7	23	3.3	6020	6020	31.88	
2.7	23	2.6	2600	8620	45.66	
14.7	24	2.6	1640	10260	54.34	
26.7	25	2.6	88	10348	54.81	
38.7	24	2.6	290	10638	56.35	
50.7	26	2.5	230	10868	57.56	
62.7	24	2.5	170	11038	58.47	
74.7	24	2.5	100	11138	58.99	
86.7	23	2.4	72	11210	59.38	
98.7	22	2.4	35	11245	59.56	
110.7	24	2.4	27	11272	59.70	
122.7	24	2.4	22	11294	59.82	
135.7	24	2.2	14	11308	59.90	
158.7	25	2.0	0	11308	59.90	
184.7	25	2.0	0	11308	59.90	
209.7	25	2.0	0	11308	59.90	
230.7	24	2.0	0	11308	59.90	
255.2	23	2.0	0	11308	59.90	
302.7	26	2.0	0	11308	59.90	28.6

Initial volume of sludge applied = 18878 ml.

Appendix C-2 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content, of 8-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	23	8.0	0	0	0.00	98.2
0.7	23	6.9	200	200	1.05	
2.7	23	6.6	580	780	4.13	
14.7	24	6.0	750	1530	8.10	
26.7	25	5.7	1200	2730	14.46	
38.7	24	5.4	1080	3810	20.18	
50.7	26	4.9	630	4440	23.51	
62.7	24	4.8	520	4960	26.27	
74.7	24	4.7	410	5370	28.44	
86.7	23	4.5	340	5710	30.24	
98.7	22	4.5	170	5880	31.14	
110.7	24	4.3	170	6050	32.04	
122.7	24	4.3	160	6210	32.89	
135.7	24	4.1	190	6400	33.90	
158.7	25	3.9	220	6620	35.06	
184.7	25	3.6	230	6850	36.28	
209.7	25	3.4	400	7250	38.40	
230.7	24	3.3	410	7660	40.57	
255.2	23	3.1	510	8170	43.27	
302.7	26	2.8	265	8435	44.68	87.5

Intial volume of sludge applied = 18878 ml.

Appendix C-3 - Tempterature, Depth of Sludge, Drainage Volume, and Moisture Content of 12-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	23	8.0	0	0	0.00	97.9
0.7	23	6.1	2440	2440	12.92	
2.7	23	4.3	4300	6740	35.70	
14.7	24	2.4	4970	11710	62.02	
26.7	25	2.4	910	12620	66.85	
38.7	24	2.4	310	12930	68.49	
50.7	26	2.4	230	13160	69.71	
62.7	24	2.4	220	13380	70.87	
74.7	24	2.4	190	13570	71.88	
86.7	23	2.4	200	13770	62.94	
98.7	22	2.4	110	13880	73.52	
110.7	24	2.4	110	13990	74.10	
122.7	24	2.4	100	14090	74.62	
135.7	24	2.4	82	14172	75.07	
158.7	25	1.6	110	14282	75.65	
184.7	25	1.4	80	14362	76.07	
209.7	25	1.2	150	14512	76.87	
230.7	24	1.2	115	14627	77.48	
255.2	23	1.2	105	14732	78.03	
302.7	26	1.2	5	14737	78.06	14.6

Initial volume of sludge applied = 18878 ml.

Appendix C-4 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of Anaerobic Sludge

Time (hrs)	Temp. (^{o}C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	23	8.0	0	0	0.00	93.2
0.7	23	7.4	0	0	0.00	
2.7	23	7.4	0	0	0.00	
14.7	24	7.3	450	450	2.38	
26.7	25	7.2	200	650	3.44	
38.7	24	7.2	220	870	4.60	
50.7	26	7.2	320	1190	6.30	
62.7	24	7.1	530	1720	9.11	
74.7	24	7.1	390	2110	11.17	
86.7	23	7.1	460	2570	13.61	
98.7	22	7.1	270	2840	15.04	
110.7	24	7.1	320	3160	16.73	
122.7	24	7.1	285	3445	18.24	
135.7	24	6.9	290	3735	19.78	
158.7	25	6.4	410	4145	21.96	
184.7	25	6.3	375	4510	23.94	
209.7	25	6.2	700	5220	27.65	
230.7	24	5.5	600	5820	30.82	
255.2	23	4.9	640	6460	34.21	
302.7	26	4.7	400	6860	36.33	67.4

Initial volume of sludge applied = 18878 ml.

APPENDIX D

DRAINAGE DATA,

CHEMICAL AND PHYSICAL PROPERTIES

RUN 4 - BATCH UNIT

Appendix D-1 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 4-Day Sludge

Time (hrs)	Temp. (°C)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	26	8.0	0	0	0.00	98.1
1	26	6.5	1630	1630	8.60	
2	27	6.3	630	2260	11.97	
4	27	6.2	375	2635	13.95	
7	27	6.1	350	2985	15.81	
9	27	6.0	120	3105	16.44	
20	27	5.9	410	3515	18.61	
32	29	5.7	380	3895	20.63	
44	28	5.4	290	4185	22.16	
56	27	5.4	240	4425	23.43	
68	27	5.2	240	4665	24.71	
80	27	5.1	160	4825	25.55	
92	29	5.0	175	5000	26.48	
104	28	4.9	140	5140	27.22	
116	25	4.8	170	5310	28.12	
140	26	4.3	520	5830	30.88	
164	27	4.0	610	6440	34.11	
188	26	3.8	240	6680	35.38	
219	26	3.5	280	6960	36.86	
234	24	3.4	180	7140	37.82	
258	18	3.2	280	7420	39.30	
282	27	3.0	320	7740	41.00	
309	27	2.8	300	8040	42.58	
334	27	2.5	480	8520	45.13	87.8

Initial volume of sludge applied = 18878 ml.

Appendix D-2 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 12-Day Sludge

Time (hrs)	Temp. ($^oC.$)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	27	8.0	0	0	0.00	92.5
1	27	6.9	890	890	4.71	
2	27	6.8	540	1430	7.57	
3	27	6.7	350	1780	9.42	
5	27	6.7	390	2170	11.49	
7	25	6.7	240	2410	12.76	
38	26	6.3	930	3340	17.69	
53	24	6.0	560	3900	20.65	
77	18	5.8	580	4480	23.73	
101	26	5.5	500	4980	26.37	
128	27	5.3	375	5355	28.36	
153	27	5.0	370	5725	30.32	
206	30	4.7	690	6415	33.98	
255	26	4.3	520	6935	36.73	
273	26	4.0	150	7085	37.53	14.5

Initial volume of sludge applied = 18878 ml.

Appendix D-3 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 30-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	25	8.0	0	0	0.00	98.7
1	25	6.9	730	730	3.86	
2	25	6.8	520	1250	6.62	
4	26	6.8	550	1800	9.53	
6	26	6.6	310	2110	11.17	
16	26	6.3	840	2950	15.62	
31	25	5.7	1150	4100	21.71	
44	25	5.4	665	4765	25.24	
56	25	5.1	730	5495	29.10	
68	25	4.8	590	6085	32.23	
92	25	4.3	1135	7220	38.24	
116	26	3.9	760	7980	42.27	
140	26	3.5	780	8960	46.40	
182	25	2.5	1230	9990	52.91	
209	24	2.3	450	10440	55.30	
225	24	2.3	470	10910	57.79	
256	25	2.0	480	11390	60.33	
275	25	1.8	235	11625	61.57	
299	25	1.6	250	11865	62.29	
323	24	1.5	225	12100	64.09	
347	25	1.4	200	12300	65.15	94.6

Initial volume of sludge applied = 18878 ml.

Appendix D-4 - Chemical Characteristics of the Batch Unit

Detention Time (Days)	COD		Ammonia		Nitrate		Phosphate		BOD	pH	D.O.
	Paper Filt.	S.B. Filt.	Paper Filt.	S.B. Filt.	Paper Filt.	S.B. Filt.	Paper Filt.	S.B. Filt.	Paper Filt.		
0	1,046	--	63.4	--	9.1	--	55	--	450	6.87	--
2	1,893	--	72.8	--	1.8	--	45	--	1,080	6.74	.50
4	3,253	4,573	70.0	58.8	1.8	7.4	80	120	1,636	6.27	.66
8	4,480	--	78.4	--	3.9	--	105	--	1,606	6.25	1.02
12	2,940	1,480	75.6	19.6	1.6	1.6	75	6	1,606	6.87	1.02
18	2,911	--	77.0	--	2.5	--	75	--	1,626	6.75	1.44
24	2,410	--	75.3	--	2.6	--	80	--	1,522	7.57	1.68
30	367	1,303	82.6	26.6	2.3	N.D	30	12	362	8.00	1.64

All chemical analyses expressed as mg/l, except pH.

Appendix D-5 - Physical Characteristics of the Batch Unit

Detention Time (Days)	Filterability		Settle-Ability Percent	Total Solids		Volatile Solids		Moisture Content	
	Mixed Liq.	Settled 4 Hours		Mixed Liq.	Settled 4 Hours	Mixed Liq.	Settled 4 Hours	Mixed Liq.	Settled 4 Hours
0	350.4	374.2	63	17875	29375	7000	7125	98.3	97.1
2	487.8	395.2	80	16125	18250	4000	4500	98.4	98.2
4	556.2	486.6	76	15250	19125	3750	5125	98.5	98.1
8	473.7	446.6	53	13625	21250	3750	6250	98.6	97.9
12	468.5	450.0	43	15325	25125	4125	8000	98.5	92.5
18	513.1	460.1	49	14000	23750	4000	7500	98.6	97.6
24	371.6	366.8	99	13625	13375	4125	3875	98.6	98.3
30	268.6	304.2	99	13000	13250	4750	4500	98.7	98.7

Filterability expressed in seconds.
Moisture Content expressed in per cent.
Total Solids and Volatile Solids expressed in mg/l.

APPENDIX E

DRAINAGE DATA - RUN 5

Appendix E-1 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 12-Day Sludge

Time (hrs)	Temp. (^{o}C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	24	8.0	0	0	0.00	97.1
0.5	24	6.5	750	750	3.97	
1.0	24	6.3	780	1530	8.10	
2.0	25	6.2	740	2270	12.02	
4.0	25	6.1	600	2870	15.20	
6.0	25	6.1	330	3200	16.95	
12.0	24	6.1	520	3720	19.70	
24.0	26	5.6	1850	5570	29.50	
38.0	25	2.9	3030	8600	45.55	
48.5	25	2.6	1020	9620	50.95	
60.5	24	2.4	390	10010	53.02	
72.5	25	2.2	220	10230	54.19	
96.5	25	1.9	300	10530	55.77	
120.5	25	1.9	150	10680	56.57	
144.5	26	1.8	115	10795	57.18	
185.0	24	1.8	120	10915	57.81	
228.0	22	1.8	75	10990	58.21	
259.0	24	1.8	65	11055	58.56	
276.0	24	1.8	60	11115	58.87	
300.0	25	1.8	35	11150	59.06	
324.0	26	1.8	15	11165	59.14	51.6

Initial volume of sludge applied = 18878 ml.

Appendix E-2 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 18-Day Sludge

Time (hrs)	Temp. ($^oC.$)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	24	8.0	0	0	0.00	97.3
0.5	24	6.6	1850	1850	9.79	
1.0	24	6.3	1200	3050	16.15	
2.0	25	6.1	880	3930	20.81	
4.0	25	6.0	750	4680	24.79	
6.0	25	5.9	380	5060	26.80	
12.0	24	5.8	570	5630	29.82	
24.0	26	5.7	620	6250	33.10	
38.0	25	5.6	400	6650	35.22	
48.5	25	5.6	195	6845	36.25	
60.5	24	5.5	165	7010	37.13	
72.5	25	5.6	130	7140	37.82	
96.5	25	5.6	250	7390	39.14	
120.5	25	5.6	190	7580	40.15	
144.5	26	5.6	170	7750	41.05	
185.0	24	5.5	290	8040	42.58	
228.0	22	4.5	270	8310	44.01	
259.0	24	4.1	220	8530	45.18	
279.0	25	4.1	85	8615	45.63	
303.0	25	4.0	95	8714	46.10	
327.0	24	3.9	85	8795	46.58	84.0

Initial volume of sludge applied = 18878 ml.

Appendix E-3 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 24-Day Sludge

Time (hrs)	Temp. ($^oC.$)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	24	8.0	0	0	0.00	96.9
0.5	24	7.2	80	80	0.42	
1.0	24	7.1	420	500	2.64	
2.0	25	7.0	500	1000	5.29	
4.0	25	6.9	530	1530	8.10	
6.0	25	6.9	360	1890	10.81	
12.0	24	6.8	580	2470	13.08	
24.0	26	6.8	510	2980	15.78	
38.0	25	6.8	380	3360	17.79	
48.5	25	6.5	260	3620	19.17	
60.5	24	6.1	360	3980	21.08	
72.5	25	5.9	290	4270	22.61	
96.5	25	5.6	490	4760	25.21	
120.5	25	5.4	350	5110	27.06	
144.5	26	5.1	260	5370	28.44	
185.0	24	4.8	340	5710	30.24	
228.0	22	4.5	410	6120	32.41	
259.0	24	4.4	380	6500	34.43	
279.0	25	4.3	140	6640	35.17	
303.0	25	4.1	120	6760	35.80	water
327.0	24	4.1	110	6870	36.39	on top

Initial volume of sludge applied = 18878 ml.

Appendix E-4 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 30-Day Sludge

Time (hrs)	Temp. ($^oC.$)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	25	8.0	0	0	0.00	96.9
0.5	25	6.3	1800	1800	9.53	
1.5	25	6.1	850	2650	14.03	
3.5	26	6.0	410	3060	16.20	
9.0	25	5.9	460	3520	18.64	
33.0	26	5.3	1320	4840	25.63	
45.0	24	4.3	2025	6865	36.36	
62.5	24	3.0	3200	10065	53.31	
77.5	23	2.5	1550	11615	61.52	
91.5	22	2.4	620	12235	64.81	
111.0	24	2.3	470	12705	67.30	
131.0	25	2.2	215	12920	68.40	
155.0	25	2.1	155	13075	69.26	
179.0	25	2.1	130	13205	69.94	
203.0	25	2.0	125	13330	70.61	
227.0	26	1.5	100	13430	71.14	
251.0	26	1.3	80	13510	71.56	
275.0	26	1.3	55	13565	71.85	
299.5	24	1.3	52	13617	72.13	73.2

Initial volume of sludge applied = 18878 ml.

APPENDIX F

DRAINAGE DATA - RUN 6

Appendix F-1 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 12-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	27	8.0	0	0	0.00	94.9
1	27	4.6	4280	4280	22.67	
2	27	4.5	600	4880	25.85	
4	27	4.4	450	5330	28.23	
6	25	4.3	310	5640	29.87	
37	26	4.0	1020	6660	35.27	
52	24	3.9	470	7130	37.76	
76	18	3.9	480	7610	40.31	
100	26	3.9	420	8030	42.53	
127	27	3.9	375	8405	44.52	
152	27	2.5	1420	9825	52.04	
205	30	1.5	2850	12675	67.14	
254	26	1.0	450	13125	69.52	
271	26	0.9	55	13180	69.81	
319	25	0.8	30	13210	69.97	51.6

Initial volume of sludge applied = 18878 ml.

Appendix F-2 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 18-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	25	8.0	0	0	0.00	96.4
1	24	6.8	1340	1340	7.09	
2	24	6.8	1340	2680	14.19	
3	24	6.6	890	3570	18.91	
7	24	6.5	800	4370	23.14	
10	25	6.5	400	4770	25.26	
22	25	6.4	460	5230	27.70	
46	25	6.4	1030	6260	33.16	
70	24	6.3	550	6810	36.10	
94	26	5.1	1320	8130	43.06	
118	26	2.9	2250	10380	54.98	
142	26	2.6	960	11340	60.06	
166	26	2.3	340	11680	61.87	
191	24	2.0	200	11880	62.93	
216	24	2.0	130	12010	63.61	
245	25	1.8	100	12110	64.14	
288	24	1.8	75	12185	64.50	
317	25	1.8	55	12240	64.80	58.9

Initial volume of sludge applied = 18878 ml.

Appendix F-3 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 24-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0	25	8.0	0	0	0.00	96.2
1	24	7.3	490	490	2.59	
2	24	7.2	560	1050	5.56	
6	24	7.0	600	1650	8.74	
9	25	7.0	240	1890	10.01	
22	25	6.8	700	2590	13.71	
46	25	6.5	760	3350	17.74	
70	24	6.0	820	4170	22.08	
94	26	5.5	1110	5280	27.96	
118	26	4.9	1060	6340	33.58	
142	26	4.4	860	7200	38.13	
166	26	3.9	1100	8300	43.96	
191	24	3.3	1240	9540	50.53	
216	24	3.0	860	10400	55.09	
245	25	2.9	520	10920	57.84	
264	24	2.8	440	11360	60.17	
293	25	2.8	220	11580	61.34	86.9

Initial volume of sludge applied = 18878 ml.

Appendix F-4 - Temperature, Depth of Sludge, Drainage Volume, and Moisture Content of 30-Day Sludge

Time (hrs)	Temp. (°C.)	Sludge Depth (in)	Filt. Vol. (ml)	Cumm. Vol. (ml)	% of Vol. Appl.	M.C. (%)
0.0	25	8.0	0	0	0.00	97.1
0.5	25	6.5	1450	1450	7.68	
1.0	25	6.3	180	1630	8.63	
2.5	25	6.3	380	2010	10.64	
14.0	25	5.9	1300	3310	17.53	
38.0	25	5.3	160	3470	18.38	
62.0	25	5.2	100	3570	18.91	
86.0	25	5.1	140	3710	19.65	
110.0	26	4.9	140	3850	20.39	
134.0	26	4.7	210	4060	21.50	
158.0	26	4.5	200	4260	22.56	
182.5	23	4.5	100	4360	23.09	
207.5	24	4.5	50	4410	23.36	
236.5	25	4.3	80	4490	23.78	
255.5	24	4.0	45	4535	24.02	water
284.5	25	3.8	130	4665	24.71	on top

Initial volume of sludge applied = 18878 ml.

VITA

Yousif Antone Badra

Candidate for the Degree of

Master of Science

Thesis: DRAINAGE CHARACTERISTICS OF AEROBICALLY DIGESTED PRIMARY SLUDGE ON SAND BEDS

Major Field: Bioenvironmental Engineering

Biographical:

Personal Data: Born May 5, 1945, in Amman, Jordan the son of Antone and Kaleopie Badra.

Education: Graduated from Terra Sancta College, Amman, Jordan, in June, 1963; completed the ordinary and advanced level of the General Certificate of Education of Applied Sciences from the University of London, London, England December, 1964; received the Degree of Bachelor of Science in Civil Engineering from Oklahoma State University, Stillwater, Oklahoma January, 1970; completed requirements for the Degree of Master of Science from Oklahoma State University, Stillwater, Oklahoma July, 1971.

Professional Experience: Undergraduate Research Assistant, Oklahoma State University, Stillwater, Oklahoma July, 1968 - May, 1969; Soils Mechanics Laboratory Technician with Twin Cities Testing, St. Paul, Minnesota June, 1969 - August, 1969; Bioenvironmental Engineering Graduate Research Associate at Oklahoma State University, Stillwater, Oklahoma January, 1970 - July, 1971.

Membership in Professional Societies: American Society of Civil Engineers, American Water Works Association, Water Pollution Control Federation, Chi Epsilon.