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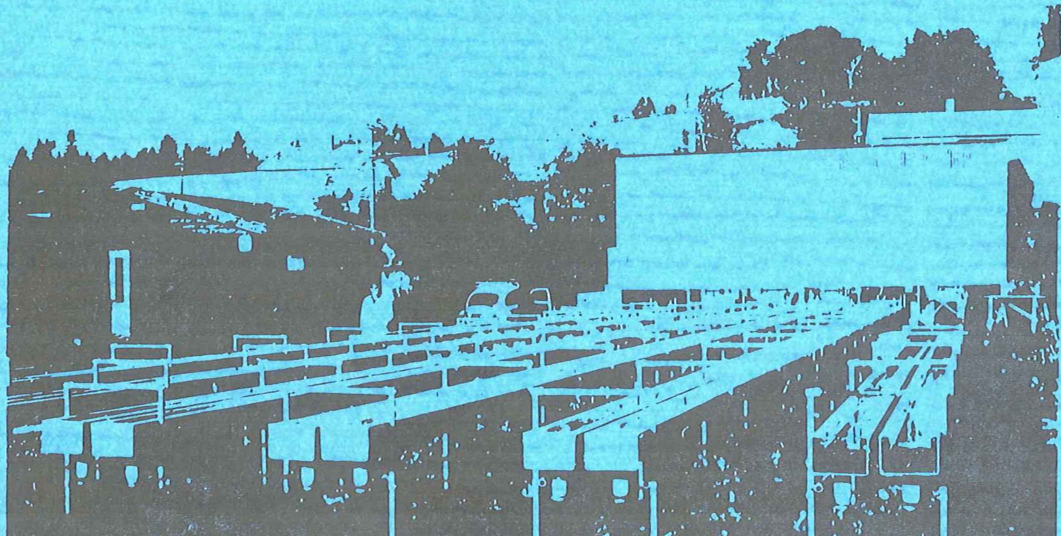

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AEROBIC STABILIZATION OF PRIMARY AND MIXED PRIMARY/CHEMICAL (ALUM) SLUDGE

by

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ABSTRACT

AEROBIC STABILIZATION OF PRIMARY AND MIXED PRIMARY/CHEMICAL (ALUM) SLUDGE

This study was conducted to investigate the feasibility of using aerobic digestion as a method for the stabilization of mixed primary-chemical (alum) sludge from a physical-chemical treatment plant. The results obtained provide valuable information in the design of aerobic digesters treating primary or mixed primary-chemical sludge.

Aerobic digestion was carried out in twenty cylindrical reactors, each containing 15 liters of sludge. Two large galvanized steel tanks served as water baths and each contained 10 reactors.

The experiments were conducted on a continuous flow system. According to the predetermined detention time (5-35 days) for each reactor, the proper volume of sludge was withdrawn once each day and the same volume of raw sludge was added.

The influence of temperature and detention time on the removal of the total suspended solids (TSS), volatile suspended solids (VSS) and chemical oxygen demand (COD) was studied. Temperature was found to have a slightly greater influence on the reduction of volatile suspended solids in primary sludge than in mixed primary-chemical sludge. Based on the Q_{10} concept, the values were determined to be 2.72 for primary sludge and 2.19 for mixed primary-chemical sludge. The Rate of Decay Constant (K_T) at 25 °C was 0.109 for primary sludge and 0.096 for mixed primary-chemical sludge.

Nitrification took place in the reactors treating both primary and mixed primary-chemical sludge. The high content of aluminum in the mixed primary-chemical sludge did not inhibit the nitrifiers. The nitrogen content as percentage of dry volatile suspended solids increased with increasing detention time for both types of sludge investigated.

The oxygen-uptake rate varied between approximately 5.0 mg O_2/gVSS · hr and 1.0 mg O_2/gVSS · hr depending on the detention time and the reactor temperature. Higher organisms in the heterogenous population were found to influence the oxygen-uptake rate and thus make it less valuable as a parameter for measuring sludge stability.

Adenosine Triphosphate (ATP) content per unit volatile suspended solids indicated a low content of active biomass during aerobic digestion.

Filtration properties, measured as specific resistance to filtration or capillary suction time generally improved woth increasing detention time except for mixed primary-chemical sludge stabilized at temperatures below 12°C.

Sludge compressibility increased with increasing detention time for both types of sludge investigated.

During anoxic storage of primary sludge at different degrees of stability, phosphorus was always released from the solids phase to the liquid phase. No release of orthophosphate during anoxic storage of mixed primary-chemical sludge took place.

Higher organisms were found in all reactors regardless of temperature and type of sludge. High concentrations of aluminum did not inhibit the growth of these organisms.

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INTRODUCTION

Problem Definition

The sludge handling process in a wastewater treatment plant is generally more costly and contains more problems than other plant processes. In spite of this sludge handling receives the lowest research priority of all unit processes.

A world-wide research effort to remove phosphorus from domestic wastewater has been initiated to solve the eutrophication problems of lakes, streams and salt water estuaries. Iron, lime and alum have proven to be effective chemical agents. Numerous plants that include a chemical step in the treatment process are in operation in the western world and more are in the planning stage.

Because of the chemicals added in the process, the nature and quantity of sludge produced has changed. Conventional sludge handling facilities, such as aerobic and anaerobic digesters, now have to process a type of sludge significantly different in nature from what they were intended to handle. Treatment plant designers and operators suddenly are faced with more unknowns.

This research will investigate the feasibility of using aerobic digesters for the treatment of mixed primary-chemical (alum) sludge. Attention will be given to the possibility of phosphorus release to the supernatant during the digestion process and during anoxic storage of the sludge prior to dewatering.

The Norwegian Institute for Water Research (NIVA) in Oslo, Norway made funds and laboratory facilities available to enable the author to carry through this project.

Object of Research

The primary objective of this research was to investigate the feasibility of using aerobic digestion as a possible method for stabilization of mixed primary-chemical (alum) sludge. Tests on primary sludge were carried out simultaneously to make sure that factors other than the alum sludge were not inhibiting the digestion process.

In order to meet the primary objective of this research project, the author felt that several factors had to be investigated.

First of all, the influence of temperature on the removal of total suspended solids (TSS), volatile suspended solids (VSS) and chemical oxygen demand (COD) for both primary and mixed primary-chemical sludge was studied. By using theoretical equations the rate of decay constant (K_T) and the temperature coefficient, theta, were derived.

Second, the oxygen-uptake rate and Adenosine Triphosphate (ATP) were used to measure the biological activity at different detention times and temperatures in the reactors. The object of this, of course, was to find any inhibitory effects of the high concentrations of aluminum in the mixed primary-chemical sludge.

Also the degree of nitrification and the nitrogen loss during the stabilization process were investigated.

In a physical-chemical treatment process, phosphorus is removed with the sludge stream. This phosphorus-rich sludge usually is stored at the plant prior to dewatering or it is transferred to a centrally located dewatering station. A major concern of environmental engineers is the possible release of this phosphorus during anoxic storage of the sludge and its possible reentry into the receiving water. The purpose of this investigation was to develop information during the sludge storage to insure a minimum recycling of phosphorus along with the supernatant.

Since dewatering is the normal procedure after the digestion process, sludge characteristics such as sedimentation, drainage and filtration properties must be known to enable design engineers to select the proper unit operations.

Therefore, complete sedimentation tests were performed at different temperatures and detention times to determine the effect of these parameters on the sedimentation properties. Changes in sludge volume index (SVI) and interface velocity also were compared.

Because drying beds are quite often the only practical dewatering alternative at small treatment plants, the drainage characteristics of stabilized primary- and mixed primary-chemical sludges were investigated. The quality of the filtrate was studied to determine whether the filtrate should be recycled to the treatment plant inlet or whether it could be released directly to the receiving water. Solids concentration in the sludge cake after drainage was determined so that final sludge quantities requiring disposal could be estimated.

The filtration properties were investigated by using the specific resistance to filtration method and the capillary suction time (CST) method, developed in England approx. 1966. The influence of detention time and temperature on the filtration properties was considered as a very important part of this research project.

Compressibility of sludges is important since many types of dewatering equipment will apply high pressures to the sludge during the dewatering process. For this reason, this parameter was measured for both types of sludges investigated. A general classification of microorganisms was attempted to learn if there were any major differences in the abundance of higher organisms in the two sludges stabilized.

The second objective of this research is twofold. First, the practical problems that can be expected during normal operation of aerobic digesters were studied and a comparison between the process efficiency in full-scale operation and pilot studies was made.

Finally, a limited effort was made to investigate existing methods for measuring the degree of stability of sludges in order to give plant operators a tool in determining the performance of aerobic digesters.

LITERATURE REVIEW

General

Aerobic digestion of sludge is not commonly used in larger waste treatment plants. In recent years, however, there seems to be increasing interest in this type of sludge stabilization (Burd, 1968). Package treatment plant manufacturers have used this method for several years because it has a low capital cost, is easy to operate and makes the sludge acceptable for disposal (Ecodyne Corp. 1971).

The literature review revealed that most of the research on aerobic sludge digestion was done in the United States although several German researchers have also worked on aerobic digestion. No work on aerobic stabilization of mixed primary-chemical sludges was found in the literature.

Reduction of Organic Material

The main purpose of aerobic sludge digestion is to reduce the organic content of the sludge in addition to improving the handling characteristics of the sludge.

The growth phase in which cells use their own cell material and release nutrients from dead cells for food, is termed the endogenous respiration phase. It occurs when the supply of nutrient is too low to support the bacterial culture. The following equation represents this relationship (Kambhu 1969):

$$\text{Vol. solids} + O_2 \xrightarrow[\text{Nutrients}]{\text{Microorganisms}} CO_2 + H_2O$$

Reynolds (1967), Kambhu (1959), Benedek et al. (1972), and others (Bokil et al., 1970, Simpson, 1965) represented endogenous decay by a first order biochemical equation:

$$dS/dt = K_T S \qquad (1)$$

dS/dt = change of biodegradable cell material per unit of time

S = concentration of biodegradable cell material (g/m^3)

K_T = rate of decay constant ($days^{-1}$)

$$S_t/S_o = e^{-K_T t} \tag{2}$$

S_t = concentration of biodegradable cell material at time t

S_o = initial concentration of biodegradable cell material

The equation given above will be valid for batch fed tanks or continuously fed, plugflow systems only. For continuously fed, completely mixed tanks, Benedek et al. (1972) gave the following expression:

$$\frac{S_t}{S_o} = \frac{1}{1-K_T t} \tag{3}$$

Because S_t never becomes zero, Eckenfelder et al. (1961) and Okasaki et al. (1966) introduced a term S_i for the inert organic residue. Equation 2 will then become:

$$\frac{S_t-S_i}{S_o-S_i} = e^{-K_T t} \tag{4}$$

For a mixture of primary and secondary sludge, Kambhu (1969) found the rate of decay to be 0.094 $days^{-1}$ at 20°C. This is much lower than values reported by Reynolds (1967) for waste activated sludge. These values ranged between 0.53 to 0.85 $days^{-1}$. Reynolds did not report the temperature. The temperature would change the reaction rate K_T by several orders of magnitude between 20°C and 40°C (Long et al., 1971). The rate of decay constant at different temperatures was determined by Benedek et al. (1972) as shown in

Table I below:

°C	10	12	15	20	28	30
Measured range	0·02	0·02	0·05	0·06	0·14	0·18
of K_T		0·05	0·07	0·10	0·20	0·20

Table 1. VALUES OF K_T AT DIFFERENT TEMPERATURES
(Benedek et al., 1972)

This value for 20°C agrees quite well with Kambhu's result.

Jaworski et al. (1963) made both batch and continuous flow studies on aerobic digestion. They found that aeration for six days at 20°C of mixed primary and activated sludge, which had initial total solids concentrations of 7,500 g/m^3 and 30,600 g/m^3, gave reductions of chemical oxygen demand (COD) of 50 and 12 per cent respectively.

In their continuous flow studies, digestion was carried out until equilibrium conditions were attained before analyses were made. A mixture of primary and secondary sludge was used in this study. Reductions of volatile solids ranged between 30 and 40 per cent after 10 days of aeration at temperatures of 15°C and 20°C respectively.

Rüffer (1966) carried out research on aerobic sludge stabilization in Germany. He found that the organic fraction (VSS) in activated sludge could be reduced 74 per cent after 15 days of aeration. For mixed primary and biological sludge (volume ratio 3:2), he found that 36 days of aeration would reduce the total solids concentration approximately 33 per cent and the organic solids concentration 61.8 per cent. Rüffer also found that the composition of the sludge would change during the digestion process. Of course this is expected, since only the degradable fraction in the raw sludge is reduced and the inorganic fraction and the inert fraction is constant or even increased.

Coakley et al. (1966) performed batch studies on anaerobically digested sludge. This research team found that 35 days of aeration would reduce volatile suspended solids 55 to 60 per cent provided the batch reactor was seeded with activated sludge.

Krauth (1969) investigated the reduction of volatile suspended solids for different types of sludges as a function of detention time in the aerobic digester. His data is given in Table 2 below:

Detention time (days)	Type of Sludge	Reduction of VSS (%)	Comments
3-5	Act. sludge (est. aeration)	15	Pilot plant
10	Act. sludge	35-40	" "
15-20	" "	50-60	" "
15-20	" "	40-50	Full-scale plant
2	Primary sludge	6	Pilot plant
4	" "	8	" "
8	" "	13	" "
16	" "	13	" "
32	" "	13	" "

Table 2. REDUCTION OF VOLATILE SUSPENDED SOLIDS vs. DETENTION TIME (Krauth, 1969)

Irgens et al. (1965) investigated aerobic digestion of anaerobically digested sludge using a continuous flow digester. They found that volatile suspended solids aerated for 20 days at 30°C would be reduced from 25,490 mg/l to 17,500 mg/l (31 per cent reduction). Their data, however, indicates higher removal of volatile suspended solids at 23°C than at 30°C. Since experiments made by Irgens et al. (1965) and Coackley et al.(1966) were run on anaerobically digested sludge, the result has only academic value. These processes would not normally be used in series.

Singh et al. (1972) tried to improve the digestion rate by solubilizing the waste sludge prior to subjecting it to aerobic treatment. A higher reduction of VSS was found for solubilized sludge, but a comparison with non-solubilized sludge was not found appropriate since part of the VSS reduction was due to the solubilizing process itself.

A wide variation in results on volatile suspended solids reductions during aerobic sludge stabilization is found in the literature. There are several reasons for this, but the characteristics of the sludge used and experimental procedures seem to be the major ones.

Oxygen Requirements during Aerobic Stabilization

During aerobic stabilization of biodegradable organic material, the oxidation rate and thus the oxygen consumption will change with time (Eckenfelder et al., 1961 and 1966; Bisogni, 1971). As the oxidation of organic solids proceeds, cellular nitrogen is released to the solution in the form of ammonia. Under continuous oxidation, the ammonia is oxidized to nitrate (See Figure 1).

Reynolds (1967) determined the oxygen-uptake rate in a completely mixed system to be:

$$dO_2/dt = 1.42 \frac{(S_o - S_t)}{T} \tag{5}$$

dO_2/dt = change in oxygen concentration per unit time

T = theoretical detention time (days)

S_o = biodegradable organics at time $0 (g/m^3)$

S_t = biodegradable organics at time $t (g/m^3)$

The factor 1.42 kg O_2 required per kg organic material oxidized originates from the empirical equation for bacterial cells, $C_5 H_7 O_2 N$. This factor would change with changes in the cell composition.

Mudrack (1966) investigated the oxygen uptake using primary sludge from VSK Dusseldorf-Lorrik, Germany. His data is recorded as oxygen used per gram organic solids. The shape of the oxygen uptake rate curve vs. days of aeration is a rapid decrease during the first 6 hours and then a fairly constant oxygen uptake rate at 6.67 g O_2/kg VS/hr. After 4 days of aeration, the oxygen uptake rate drops to 5.00 g O_2/kg VS/hr, and Mudrack proposes this as the limit for a well-stabilized sludge. Sludges with higher oxygen uptake rates would then be only partly stabilized. However, the temperature and type of sludge would influence the value of the oxygen uptake rate that should be used as a limit between stabilized and non-stabilized sludges.

Mudrack also drew the following conclusions from his investigation with primary sludge:

A. The easily degradable organics are removed during the first 6 hours

B. Oxidation of the hard degradable organics will occur between 6 hours and 2.5 days.

C. After 2.5 days, auto-oxidation will take place until the digestion process is complete.

Barnhart (1961) aerated mixed primary and activated sludge for 15 days and his data confirms the findings of Mudrack (1966).

Kehr (1966) discusses the use of aerobic sludge stabilization in Germany. While it is used, often the aerobic stabilization process is integrated in the activated sludge plant itself, the "Totalkläranlage." A total aeration time of only 6 hours is used with a sludge concentration of 10,000-14,000 mg/l MLSS. Kehr also studied aerobic sludge stabilization as a separate process. The city of Nordhorn in Germany (waste load estimate = 50,000 people) utilizes this process for sludge stabilization. Oxygen uptake rates were given by Kehr for four different types of sludge. The oxygen uptake rate for mixed primary and biological sludge began at a higher rate than for biological sludge, but decreased at a faster rate until it stabilized for both types of sludge at 6.3 - 3.3 g O_2/kg VS/hr after 5 days of aeration.

Malina (1964) summarized data observed during a laboratory evaluation and comparison of aerobic and anaerobic stabilization of primary wastewater sludge. Test units were operated for 15 days at 35°C. He stresses the importance of the initial volatile solids of the sludge to be treated. It was assumed all oxygen supplied to the aerobic system containing primary sludge was used by the microbial system. This assumption is not valid. Based on the volatile solids added, Malina then found approximately 40 kg O_2/kg VS was required. This value seems extremely high considering the ranges of 0.8 to 1.2 kg O_2/kg VS given by Kehr (1966).

An oxygen uptake rate for activated sludge during aerobic stabilization, reported by Okazaki et al. (1966) agrees with data by Kehr (1966). Okazaki et al. found the oxygen uptake rate would be 1.67 g O_2/kg VS/hr after 7 days of aeration.

Irgens et al. (1965) determined the quantity of oxygen consumed per liter of treated sludge per day by calculating the 24-hour decrease in chemical oxygen demand (COD) per liter. They found that when the daily loading of raw sludge was increased (or detention time reduced), less oxygen was consumed per liter of raw sludge added. During a 40-day detention time, 750 mg O_2 per liter sludge was consumed. This is in agreement with work previously discussed.

Bokil et al. (1970) investigated the influence of mechanical blending on aerobic digestion of waste-activated sludge. They found the oxygen uptake rate would increase with mixing intensity the first 4 days of aeration. The oxygen uptake rate in excess of 4 days would not be influenced by mixing and would stay at 4.0 g O_2/kg VSS/hr after 10 days of aeration. It was also concluded that the day to day variations in the oxygen uptake rate were attributable to the predominance of different species of bacteria at different times.

Bhatla et al. (1965) investigated oxygen uptake in heterogenous populations. Valuable information on the role of higher organisms on uptake can be gained from their study. They concluded the higher oxygen uptake rate resulting from the presence of protozoa must be directly ascribed to the respiration of the protozoa feeding on the bacterial population.

Sekulov et al. (1970) investigated the influence of household detergents on the oxygen uptake rate of activated sludge. This research team found detergents do have a negative effect on the oxygen uptake rate, but that this negative effect is counteracted by an increasing solids concentration.

Eckenfelder (1956) studied the oxidation kinetics of biological sludges and found that 14 days of aeration of pulp and paper waste activated sludge would reduce the oxygen uptake rate from 6.5 to 3.4 mg O_2/g VSS/hr. These values agree very well with those given by Kehr (1966).

Change in pH during Aerobic Stabilization

The changes in pH during stabilization of primary and/or biological sludges are well documented in the literature. However, no work on the degree pH will vary during stabilization of mixed primary/chemical sludge, has been found. The author of this dissertation believes a discussion of the pH changes during the treatment of primary and/or waste activated sludge will be beneficial in evaluating the changes that will occur during aerobic stabilization of a mixture of primary and chemical sludges.

Lawton (1964) found that with a pH as low as 5.0 no significant effect was shown on the digestion efficiency.

Randall et al. (1969) experienced retardation of biological activity in some of their aerobic digesters due to pH values of less than 5.7. Digesters with low pH showed low removal of volatile organic solids. The researchers' results also indicated a gradual decrease of pH during the digestion process except in one case where sludge from a plant with low organic loading was used. In this case, pH increased over the first 6 days and then gradually decreased to approximately 6.0. This might have been due to the rapid utilization of organic acids present in the untreated waste and deamination. Other researchers have had the same experience (Jenkins et al., 1971).

Moore (1971) performed batch studies to determine the effects of pH on aerobic digestion of waste activated sludge. Detention time of at least 20 days was used. He found that total and volatile solids reduction was not affected over a pH range of from 3.5 to 9.5. This result does not agree with work by Randall et al. (1969), which was previously discussed. Moore also found somewhat higher solids reductions were realized when the pH was kept constant. Different microbial composition might account for the different results obtained.

Other research groups (Jaworski et al., 1963, Rüffer, 1966) also found a gradual increase in pH followed by a gradual decrease during aerobic stabilization. Jaworski et al. (1963) mention the pH dropped as low as 5.0, but only in one case did this low pH affect the aerobic metabolism. In this study the change in alkalinity was also investigated.

Rüffer (1963) found pH would increase from an initial value of 8.0 to as high as 9.15 after 12 days of aeration. This relatively large increase was primarily due to an increase in ammonia content. As the aeration time exceeded 12 days, the pH would gradually decrease again.

Coackley et al.(1966) kept the pH constant at different levels during their study, and it was concluded that the amount of solids destroyed at each level of pH (from 8.4 to 4.0) was the same although it appears from their work that pH 4.0 does inhibit the activity.

Kempa (1969) found pH would increase from its initial 7.3 to 8.0 after 7 days of aeration. It would then gradually decrease to 7.2 after 31 days of aeration.

The change of pH during the stabilization process is due to CO_2 production caused by respiratory activity and deamination. The alkalinity, however, is unaffected by CO_2 production (Stumm et al., 1970). The change in alkalinity would most likely be caused by nitrification. The reasons for this will be discussed below.

Change of Nitrogen Forms and Alkalinity During Aerobic Stabilization

During primary-chemical treatment of wastewater, removal rates of only 10-30 per cent of the total nitrogen entering the treatment plant can be expected. This data indicates most of the nitrogen entering a wastewater treatment plant will not be captured in the sludge stream, but will go out with the effluent.

The fraction that enters the sludge stream will undergo changes in the aerobic digestion process and influence the whole environment under which the aerobic stabilization takes place.

The primary solids will add nitrogen to the system and this organic nitrogen will also undergo changes in the process.

A large portion of the nitrogen entering an aerobic digester, which is treating mixed primary-chemical sludge, will be in the form of organic nitrogen and ammonium (NH_4). Through the aerobic treatment process, the organic nitrogen will first be converted to NH_4 and then oxidized to NH_3. The pathways for oxidation of ammonium to nitrite and then from nitrite to nitrate were given by Eckenfelder et al. (1961).

In sewage treatment Nitrosomonas and Nitrobacter are the most important nitrifiers (Eikum, 1967). There are two species of Nitrosomonas, namely *Nitrosomonas europaea* and *Nitrosomonas moncella*. The two species of Nitrobacter are known: *Nitrobacter winogradskyi* and *Nitrobacter agilis* (Alexander, 1961).

Several authors have discussed the influence of nitrification on alkalinity. A detailed study of this can be found in work by Lijklema (1969, 1971). Only a short discussion of the interaction between nitrification and alkalinity will be given in this literature review. Ammonia will be oxidized to NO_3 as shown in Figure 1. and thus produce $2H^+$ and NO_3^-. Hydrogen will then combine with HCO_3^- alkalinity to form CO_2 and H_2O. During the vigorous aeration in the aerobic digester, some of the CO_2 will be stripped off. The end result is a reduction in alkalinity.

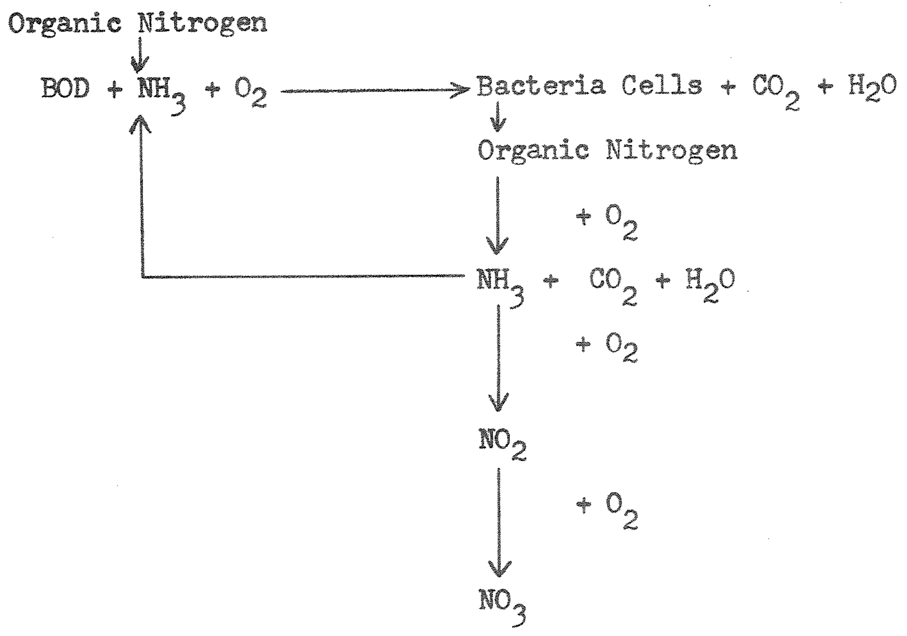


Figure 1. Forms of Nitrogen during Oxidation.

The author of this dissertation is not aware of any information on tests where mixed primary-chemical sludge has been used. Using primary, biological or a mixture of these two sludges, alkalinity changes have been recorded.

Moore (1971) found a gradual decrease of alkalinity from 200 mg/l as $CaCO_3$ to 20 mg/l as $CaCO_3$. This has been experienced by other researchers also (Eckenfelder, 1961), except that the alkalinity decreased from 700 mg/l as $CaCO_3$ down to 20 mg/l as $CaCO_3$.

Malina et al. (1964) found that the alkalinity in the digester effluent was less than in the influent. He also found that the alkalinity reductions were greater for higher organic loadings to the digester, quite contrary to what would be expected. No other research work seems to confirm this.

Jaworski et al. (1963) investigated the different nitrogen forms during the digestion process. He found a rapid decrease of ammonium in the first 10 days and an increase of nitrite (NO_2) prior to a decrease. This was because nitrite is finally oxidized to nitrate (NO_3). The same result was obtained by Rüffer (1966) and Hamm et al. (1965).

Kempa (1969) found during his studies on aerobic digestion that the NH_4 content would increase the first 5 days of aeration. Nitrite (NO_2) would then start to increase up to a maximum concentration after approximately 13 days of aeration. Nitrite (NO_2) would then gradually be oxidized to nitrate (NO_3). According to his work, the alkalinity first increased to a maximum of 450 mg/l $CaCO_3$ after 6-8 days of aeration and then gradually decreased to 150 mg/l $CaCO_3$ after 31 days of aeration.

Randall et al. (1969) support the findings by Kempa (1969) regarding both the forms of nitrogen and alkalinity although their final alkalinity was approximately 20 mg/l $CaCO_3$. Randall and his coworkers noticed that if the pH in the digesters dropped below pH 5.6, there was a rapid increase in ammonium concentration and a sudden decrease in nitrite concentration, indicating the nitrite forming organisms had been inhibited.

It appears from this brief literature review on nitrogen and alkalinity changes during the aerobic digestion process that the work which has been done agrees quite well on the changes that take place and why, even though the final concentrations reported vary several orders of magnitude.

Change in Phosphorus Forms During Aerobic Stabilization

Because the sludge stream is the only stream in which phosphorus is removed from a treatment plant, the conditions under which phosphorus is released must be considered in the design and operation of these treatment systems.

Wells (1970) suggested that an equilibrium, somewhat similar to a chemical equilibrium, exists between the soluble orthophosphates in the liquid phase and the organically bound phosphorus. When treating a mixture of primary and chemical sludges, an equilibrium would be expected to exist between organically bound phosphorus, chemically bound phosphorus and the phosphorus content in the liquid phase. The mechanism of how these forms of phosphorus will interact is somewhat obscure because the work done on aerobic digestion has dealt with primary and/or biological sludges only. Researchers have not been concerned with supernatant phosphorus content. Wells (1970) aerated activated sludge for 5 days to investigate the possibility of "bleed back" of phosphorus to the supernatant. Supernatant (filtered) phosphorus values increased from less than 1 mg/l P to 50 mg/l P after 5 days of aeration. The raw sludge contained approximately 7.5 per cent of P by weight prior to aeration. This is quite high compared to phosphorus contents of sludges given by Rüffer (1966), who reports 2 per cent P (by weight) for biological sludge and 1 per cent for mixed primary and activated sludge.

Luxury uptake of phosphorus might have occured in the sludge used by Wells in his study and thus higher release of phosphorus would be expected. However, phosphorus release from activated sludge has been found by numerous investigators (Levin, 1965; Minton, 1970; Randall et al., 1970). Selected literature reviewed by Minton (1970) is recommended for further study of phosphorus release during aeration.

Leaching of phosphate from the sludge into the liquid phase when aeration was turned off has been experienced. Wells (1970) found that 15 per cent of the phosphorus in the sludge leached into the liquid during the first 8 hours and 35 per cent after 24 hours. This information would be valuable in the day to day operation of aerobic digesters since normal practice is to turn the air off and let the solids settle to the bottom for several hours. Supernatant is then replaced with excess sludge from the plant.

Irgens et al. (1965) found that during aerobic digestion of sludge from a conventional wastewater treatment plant, the phosphorus content in the sludge mass (solids and water) remained constant. No drastic changes of PO_4-P in the supernatant were found. He also found the phosphorus content in the sludge solids was fairly constant during the digestion process. After 20 days of aeration, the sludge solids had decreased in phosphorus content approximately 3 per cent while at 40 days of aeration the phosphorus content had increased 3 per cent.

Rüffer (1966) determined the phosphorus content of different types of sludges during aerobic stabilization. He found for activated sludge from a treatment plant with high organic loading, the phosphorus content increased from 2 per cent to 4.5 per cent after 12 days of aeration. Then is decreased gradually to 3.0 per cent. No change was experienced when he used sludge from an extended aeration plant. Eventually, he tried 3 parts of primary sludge to 2 parts of activated sludge. The result indicated a gradual increase in phosphorus content of the sludge from 1 per cent to 1.8 per cent after 35 days of aeration. His work indicated there was no release of phosphorus from the sludge to the supernatant over the total digestion period.

Sekikawa (1966) and his co-workers examined the biochemical behavior of soluble orthophosphate under unfavorable conditions such as deficiency of nutrient, lack of dissolved oxygen, admixing of poisonous substances, etc. The ultimate goal of their study was to learn whether the phosphate change could be applied for practical plant control. They state in their work that phosphorus exists in the form of nucleic acids, nucleotides and inorganic phosphates in the cells, but that mono- or poly-phosphate is presumed in the activated sludge floc. The following conclusions can be drawn from their study:

A. Phosphate concentration decreased with consumption of available nutrients (measured as BOD). Release of phosphate would occur when the nutrients in the mixed liquor were consumed.

B. Phosphate uptake was hardly affected by initial sludge concentration within 4 to 5 hours of the aeration period. The release of phosphate from the sludge during aeration increased remarkably in accordance with the initial concentration of sludge.

C. Orthophosphate concentration will increase with increasing detention time during aerobic digestion. Approximately 20 per cent of the phosphorus content would be released. Orthophosphate can be used as a reliable index in determining the degree of aerobic stabilization.

D. Dissolved phosphate concentration increased at the initial stage of anaerobic storage. The maximum phosphate release after 10 days of storage was 50 per cent of the total phosphorus in the sludge. Phosphate release could probably be attributed to autolysis or microbial destruction of sludge organisms.

E. Marked release of phosphate was observed if the pH was adjusted to 4.0 in the mixed liquor.

Shapiro et al. (1967) studied anoxically induced release of phosphate in wastewater treatment. They made extensive field observations and found while uptake by the sludge reduced the dissolved phosphate concentration, subsequent release allowed the dissolved phosphate to increase. In other words, phosphate taken up during aeration can be released during settling. This is obviously disadvantageous to the production of low phosphate effluents. The major information from their study is listed below:

A. Periodic mixing during anoxic storage will increase the release of orthophosphate.

B. An increase in storage temperature will increase the anoxic release of orthophosphate.

C. Higher concentrations of solids will give a higher release of orthophosphate.

Shapiro et al. (1967) also mention that the release is not due to decomposition of the sludge or to lysis of microorganisms. The phenomenon is completely reversible if aeration is restored. The author of this dissertation believes, although this will give information on the reasons for phosphorus release, it is of minor importance since aeration is seldom restored prior to dewatering of a stored sludge.

Hopson et al. (1973) investigated cellular phosphorus changes under low carbon stress using pure culture system. They state that cellular composition and therefore phosphorus content undergo changes due to culture age, phase of growth and composition of the media. In their study, they found in cultures operating under carbon-limited conditions, which allowed no cell divisions, the organisms were capable of taking up phosphorus. This could increase the phosphorus content by 31 per cent in 7 hours. Most of the increase was attributed to an increase in nucleic acids. On a percentage basis the maximum phosphorus levels attained were 7.0 per cent under log-growth and 3.25 per cent under carbon-limiting conditions.

Randall et al. (1970) made a study of the factors that affect activated sludge phosphate release. Their study indicates storage of phosphate will take place during substrate utilization, but the release is directly related to the amount of stress the organisms are subjected to. They also conclude that the anoxic release is due to cell lysis and the amount of phosphorus released per unit of sludge solids is relatively constant.

No work on phosphorus uptake and release during stabilization of mixed of mixed primary-chemical sludge was found. However, Hsu (1970) discusses the interaction between aluminum and phosphate in aqueous solutions. His work might provide additional insight into the complex interaction between pH and concentrations of phosphorus and aluminum. He found hydroxy-aluminum polymers and Al yielded different reaction products with phosphate. With increasing ratios of H_2PO_4/Al in the solution, he found an increasing P/Al molar ratio in the precipitate. This agrees with work by Stumm et al. (1962). Hsu (1970) states that the net positive charge per aluminum atom gradually decreases with the addition of phosphate and at the isoelectric point the polymers are completely neutralized by the phosphate ions. Both Al and polymers will react with phosphate, however, they will react differently. The reaction product will, therefore, depend greatly on the nature of the aluminum present in the solution.

From the discussion it is not obvious what will happen to the phosphorus in the supernatant during aerobic stabilization of mixed primary-chemical sludge. The author of this dissertation believes since so many processes are interdependent, only an educated guess can be made. It seems probable that a biological release of phosphorus will occur. Assuming phosphorus is released to the supernatant, it is likely phosphorus will exchange sites with ions and thus be tied up chemically in the solid phase.

Change of Sludge Characteristics during Aerobic Stabilization

It would seem reasonable to expect the sludge characteristics, like sedimentation, filtration and drainage properties, to change to a greater or lesser degree during the digestion process. No research team has investigated the change of these properties for mixed primary-chemical sludge, but the author of this dissertation believes knowledge will be gained by reviewing work done on primary- and mixed primary-biological sludge.

Bisogni et al. (1971) measured the Sludge Volume Index (SVI) at different sludge ages. A rapid increase in SVI was experienced the first three days and then a rapid decrease between the third and the fifth day. The SVI values for higher sludge ages stayed at 100 ml/g or lower. Since one ordinarily has higher values of sludge age than those investigated by Bisogni et al. (1971), SVI values below 100 ml/g would be expected.

Randall et al. (1969) used waste-activated sludge in their study on aerobic digestion. They found that aerobic digestion does not necessarily improve the drainage characteristics, although it may do so. Also the drainage is retarded by the presence of large amounts of fibrous material and may be physically hampered by some type of microorganisms, expecially an <u>Arcella</u> specie which has a rigid, circular sectioned, chitinous shell about 50 microns in diameter.

Rüffer (1966) found practically no change in SVI values during digestion of waste-activated sludge. From an initial value of 80 ml/g, the SVI fluctuated between 80 ml/g and 120 ml/g during an aeration period of 32 days. Rüffer's result does not agree with that given by Bisogni et al. (1971).

Hartmann (1963) relates the organic nitrogen content of the biomass with the settling characteristics of the sludge. The higher the nitrogen content, the poorer the settling properties will be. No other research work investigated seems to substantiate this finding.

Tenney (1965) worked on the addition of chemicals to biological sludges to improve their filterability. This might give us some insight as to what effect the aluminum sludge might have on the mixed sludge filterability in the aerobic digester. This research team found that the addition of aluminum sulphate greatly increased the filterability of biological sludges. Increased dosage of chemical resulted in the formation of a stronger flocculation lattice which, in the presence of a vacuum, maintains porosity for the effectual withdrawal of water. The pH was also found to influence the dewaterability. When using aluminum sulphate additions, a pH 4.0 was found to be optimum. The sludge dewatered better at low pH values.

Lawton et al. (1964) experienced the same as Bisogni et al. (1971): aerobic digestion longer than 5 days would increase sludge drainability.

Jaworski et al. (1963) measured the drainability on gravity sand filters supported by filter paper in Buchner funnels. This research team found that sludges digested for 5 days usually exhibit poorer drainability than undigested sludge. This finding is quite in agreement with others (Bisogni, 1971; Lawton, 1964). Sludges digested for 10 days or longer showed improved drainability. The improvement in drainability with detention times longer than 10 days seemed to be of minor importance. Few of the sludges investigated by this research team seemed to have good settling characteristics. Sludges digested at low temperature for a short period of time showed poor settleability. When detention times exceeded 30 days, gas bubbles caused the sludge to float.

Irgens et al. (1965) did filtration and centrifugation tests on digested sludge. The supernatant fluids obtained from these two methods were free from visible solids. The sludges also showed good settleability.

Laubenberger et al. (1971) worked on the physical structure of activated sludge in aerobic stabilization. They found that as time of stabilization is increased, the particle sizes are reduced. Flocs are formed by agglomeration of these particles. The amount of water present in the sludge flocs will, therefore, vary with the particle sizes. Laubenberger et al. stress the importance of the three "types" of water in a floc: the organically-bound water, the capillary water in each particle and the stagnant water between each particle.

Mudrack (1966) did not find improved dewaterability for increased detention times up to 5 days. No data was available on aeration times in excess of 5 days.

Kempa (1967) looked at the sedimentation properties of aerobically stabilized sludge. He found an increase in detention time in the digester would decrease the sludge volume after 30 minutes settling. This was due to better flocculation properties with increasing detention time. However, sludge aerated for 60 days would settle very poorly due to a complete loss of its ability to flocculate.

Müller-Neuhaus (1971) pointed out in his study that higher digestion temperatures produced improved settleability. The influence of detention time on the sludge-volume-index (SVI) was also investigated and there seemed to be an initial increase and then a gradual decrease.

Müller-Neuhaus (1971) also tested the drainage properties of digested sludge. The drainage period was 2 hours. No obvious relationship between aeration period and drainage properties could be found. At low temperature (5°C, 15°C) there was an increase in drained water volume with longer detention time, but this was not the case at higher temperatures.

Kempa (1969) found in his later work that the Sludge Volume Index (SVI) would increase from an initial value at 95 ml/g to 155 ml/g after 9 days of aeration. Then, a sudden decrease in SVI to 40-50 ml/g would occur between 10 and 14 days of aeration. An aeration period in excess of 14 days would not change the SVI.

Bokil et al. (1970) found that settleability of aerobically digested sludge is improved as a result of blending during the digestion period. This was attributed to more rapid mineralization of the blended sludge as well as some decrease in the quantity of bound water due to reduction in particle size.

Lindstedt et al. (1970) made pilot plant studies to find the amount of solids reduction that could be achieved through aerobic digestion. They applied flotation as the unit process for solid-liquid separation and they found that fresh waste-activated sludge compacted about 30 per cent better than the aerobically digested sludge.

Tenney et al. (1965) carried out a study to investigate to what extent chemical flocculation methods can complement or substitute the biological treatment process. Valuable information on biological flocculation that can partly explain changes in sedimentation and dewatering properties during aerobic digestion can be gained from this work. Non-flocculant growth is generally observed at short detention times. After long aeration times with very low concentrations of organic substrate, conditions for excellent flocculation occurs. Most microorganisms evidently have, under certain circumstances, the ability to flocculate. According to Tenney and Stumm (1965), natural polymers such as complex polysaccharides and polyamino acids excreted or exposed at the surface predominantly during the declining growth and the endogenous respiration phases. It is possible, however, that polymeric substances are excreted during the log-growth phase, but that new cell surfaces are created at a faster rate and thus will not be covered by such polymers. Tenney et al. (1965) also state that substantial amounts of polysaccharides will be accumulated during the endogenous phase and that these represent a large fraction of the residual organic material.

Gale (1971) studied the dewatering properties of different types of sludges and, it is interesting to note, he found sewage sludges generally have higher specific resistance to filtration than sludges encountered in any industry. Gale used both the ordinary specific resistance to filtration test and the capillary suction time (CST) apparatus. Since the CST apparatus is widely used in this research project, the author of this dissertation thinks some of the features mentioned by Gale should be recognized. These are

1. Batch to batch variations in the paper may give variations up to 2 s at low CST (say 10 s) and up to 40 s at higher CST (say 200 s). Within-batch variations are considerably less and thus for important comparisons the same batch of paper should be used (batch numbers are marked on packets).

2. The sensitivity of the apparatus is of course poor when readings are close to the blank reading (i.e. the reading obtained with clear filtrate alone). This occurs with sludges of very low specific resistance or solids content. With very high doses of high viscosity polyelectrolytes which have been inadequately stirred, the blank may be much higher than with water, because of the presence of unadsorbed polymer in the liquid phase.

3. It is very important to remember the effect of solids content on CST. If a low CST is obtained with a high solids content sludge then excellent filtration properties are indicated. On the other hand, if the same CST is obtained with a low solids content sludge the specific resistance will be higher. This combination of higher specific resistance and lower solids content will of course indicate a much lower output from, say a rotary vacuum filter.

Zeper et al. (1972) studied the dewatering characteristics of aerobically stabilized sludge using centrifuge and belt-press filter. The sludge used was taken from an oxidation ditch. This research team found that a decanting centrifuge could be used successfully for the dewatering of aerobically stabilized sludge. The dosage of polymers was 4 kg/metric ton of dry solids with 90 per cent recovery and 20 per cent solids in the cake. This dosage is quite high and would of course increase the total cost of dewatering this type of sludge. The sludge was also successfully dewatered in the belt-press filter. A dosage of 3 kg/metric ton of dry solids was required to obtain 90 per cent recovery and 15 per cent solids in the cake. Since these types of sludges normally have a high compressibility, high pressures had a negative effect on the performance of the filter.

It appears from this literature review that a certain amount of information on the characteristics of aerobically digested sludge is available.

However, sedimentation properties have often been described by changes in the sludge volume index (SVI). Since the SVI defines only one point on the settling curve, it is not a precise measure of settling characteristics. This is discussed in detail by Dick et al. (1969). It is, therefore, no surprise to find discrepancies in the results published by different authors.

Change in Adenosine Triphosphate (ATP) Content During Aerobic Stabilization

No work on changes in ATP content during aerobic digestion was found in the literature. However, valuable information can be gained from work on ATP in activated sludge. Stanier et al. (1971) state in their book:

> ...that the fraction of the substrate converted to cell material may range, depending on the organism, from 20 to 50 per cent. The differences between aerobes with respect to the growth yield at the expense of a given carbon source probably reflect differences in the efficiency with which the substrate can be used to generate ATP.

They also say the growth yields, as a function of ATP formed, are remarkably constant. They approximate 10 g of cell material per gram mole of ATP.

Weddle et al. (1971) investigated the viability and activity of activated sludge using ATP as a parameter. They found that ATP content per unit volatile suspended solids would vary with the growth rate. At low growth rates (0.1 - 0.2 days^{-1}) the ATP concentration was approximately 0.3 - 0.8 mg ATP/gVSS. At high growth rates (2.0 days^{-1}) the ATP content seemed to reach a limit of 1.0 to 1.5 mg ATP/gVSS. They also found the ATP content per viable cell did not vary significantly (10^{-9} - 10^{-8} µg/cell) and they concluded that ATP content is a rapid and convenient indicator of viable organisms in activated sludge.

Patterson et al. (1970) apply ATP as a specific indicator of cell viability. Among other things, the effects of some heavy metals on ATP levels in activated sludge were investigated. Another experiment was designed to determine the pattern of ATP pool response to a change in metabolic activity of an activated sludge culture. They found the ATP pool is affected by the metabolic activity of an activated sludge culture. It will respond rapidly to an increase in substrate concentration, while only gradually being reduced as the organisms enter the endogenous phase. ATP analyses taken on activated sludge from batch- and continuously-fed reactors would consistently yield ATP values of 1.4 to 2.0 mg/gVSS. These values are higher than would be found during the endogenous phase. Experiments conducted at the University of Florida with sludge taken from a contact stabilization plant gave ATP values of such low magnitude that only 15-20 per cent of the mixed liquor volatile suspended solids (MLVSS) was active biomass.

Cost of Aerobic Stabilization

Reliable information on the cost of aerobic digestion is hard to find in the literature. The main reason for this is that aerobic digestion is usually used in connection with smaller package plants and the cost of aerobic digestion is seldom separated from the total cost. Aerobic digesters are fairly simple in their design. The mechanical equipment involved is mainly diffusors and blowers or mechanical aerators; no heaters or mixers are necessary as in an anaerobic digester. There are no additional construction costs to prevent odor problems or danger of explosions. On the other hand, an anaerobic digester will produce methane gas that can be utilized as an energy source.

Smith (1971) discusses the costs of aerobic digestion vs. anaerobic digestion and concludes that for plants up to 8 mgd design flow, aerobic digestion is less costly than anaerobic digestion. However, he does not show through calculation how he reached this particular plant size as the breaking point.

Loehr (1965) discusses the advantages and disadvantages of aerobic digestion compared to anaerobic digestion. Among the advantages that should be considered in cost estimates are (1) there is no need for tank insulation, (2) there is no need for sludge thickening, and (3) the solid residue and the liquid effluent produced have a low oxygen demand. Among the disadvantages are (1) the cost of supplying air, (2) no usable methane gas is produced, and (3) there is a lack of optimum microbial metabolism due to fluctuations in temperature.

Lindstedt et al. (1970) discuss the cost of aerobic digestion at the Metropolitan Denver Sewage Treatment Plant. The goal of the aerobic digestion in this case was to reduce the amount of sludge to be processed by the vacuum filters and incinerators. During the digestion process, 26.5 per cent of the sludge solids was destroyed. The direct savings in chemicals for flotation and filtration, according to Lindstedt, is $20/ton of solids removed. The direct power cost amounted to approximately $0.35/mil. gal. of waste treated in the plant or each ton of solids destroyed by aerobic digestion required $1.33 for air. These costs given by Lindstedt are for power only and do not include blowers and aeration facilities.

Müller-Neuhaus (1971) estimated the relative digester volumes required at different process temperatures for aerobic digestion and compared this with the volume required for anaerobic digestion (heated to 30-35°C). This is shown in Table 3.

Temperature	5°C	10°C	15°C	20°C	25°C	30°C	35°C
Aerobic digest. vol. 1/p	364	221	143	100	72	52	42
Anaerobic dig. 1/p	220	220	220	220	220	220	220
Anaerobic/ Aerobic	0.6	1.0	1.5	2.2	3.1	4.2	5.2

Table 3. RELATIVE DIGESTER VOLUMES vs. PROCESS TEMPERATURE (Müller-Neuhaus, 1971)

This table emphasizes the importance of the process temperature when estimating costs for these processes. With an average temperature of 10°C, the specific volume (1/p) of the two types of digesters would be the same. As the process temperature increases, the aerobic digester would be more favorable in volume and thus the capital cost would decrease. Müller-Neuhaus compared the costs for an anaerobic and aerobic unit, both treating 100 m^3 sludge per day. The process temperature was 10°C and unit construction cost per m^3 volume of aerobic and anaerobic digester was 300 DM/m^3 (\$100/m^3). Power and maintenance cost for the anaerobic digester was set at 45 DM/m^3 year (\$15/m^3 year). The total costs for the two types of digestion were 81,000 DM/year (\$27,000/year) for anaerobic digestion and 100,000 DM/year (\$33,300/year) for aerobic digestion. It must be recognized that a unit treating 100 m^3 sludge per day would be a very large plant in Scandinavia and the cost comparison would change if the plants were smaller.

Ritter (1970) concluded in his work that 85-150 l/person is adequate as aerobic digester volume and the air supply used in practice is 25-30 l/min/m^3 (25-30ft^3 per 1000ft^3 per min). Ritter states that operating costs, which are mainly power costs, are reasonably low considering the effectiveness of aerobic digestion. Average power costs in the plants studied by Ritter was \$2.18/yr/lb BOD received or \$0.37/yr/person.

Measurements of the Degree of Stability of Aerobically Digested Sludge

In "Korrespondenz Abwasser" (1971), a summary of a meeting held in Germany regarding degree of stabilization was published. The possible methods discussed will only be listed in this literature review because very little data is available to evaluate one method against another.

1. Per cent reduction of volatile suspended solids.
2. Change in percentage volatile suspended solids as a fraction of total suspended solids.

3. Fat content in the sludge measured by an extraction process.
4. H_2S evolution during storage.
5. Oxygen-uptake rate.

All of these methods have their advantages and disadvantages, but are undoubtedly parameters that can be used to measure the degree of stability.

Kempa (1967) introduced a new parameter for measuring the degree of stability. Since both the carbon (C) content and hydrogen (H) content in the sludge change during the digestion process, he proposed to use the product of C and H divided by the ash content (total solids minus volatile solids). This C•H/ash content ratio would then decrease during the stabilization process and a certain "break" in the curve would, according to Kempa, indicate that the sludge had been fully stabilized.

Kempa (1967) also used the expression developed by Rawn and Bant. This expression is shown below:

$$M = 100\left(1 - \frac{v_1\, m_o}{v_o\, m_1}\right) \qquad (6)$$

M = degree of stability (%)

v_o, v_1 = organic solids content as per cent of total solids in raw and treated sludge respectively.

m_o, m_1 = inorganic solids content as per cent of total solids in raw and treated sludge respectively.

This expression was originally meant to be used for anaerobic digestion. However, its use has been expanded to include aerobic digestion. The main fallacy, in the author's opinion, is that this expression will never give a fully stabilized sludge ($M = 100\%$) and the result, therefore, can be misleading.

Rüffer (1966) used the lead acetate test as an indicator of sludge stability. This simple test method is described under "Analytical Procedures" in this dissertation. A sludge was considered stable if no color could be detected earlier than 6 weeks. A standard procedure is needed before this method can be used universally.

DESCRIPTION OF EQUIPMENT

Pilot Plant

Aerobic digestion was carried out in 20 cylindrical reactors, each containing 15 liters of sludge. Each reactor had a diameter of 25 cm and a height of 50 cm. Two large, galvanized steel tanks served as waterbaths. Each bath contained 10 reactors (see Figures 2 and 3).

Compressed air was supplied from a compressor, type Spellna, also serving the biological treatment plant at Kjeller Research Station. One 20 mm Pyrex diffuser stone with no. 1 porosity was placed in each reactor, approximately 40 mm from the reactor bottom. Due to clogging, each diffuser was replaced with a clean diffuser approximately once a week. Air flow was measured with a Fischer and Porter type rotameter (No. 6612N) with maximum capacity 360 l/min. The air supply to each unit was kept constant at 12.6 l/min ± 0.6 l/min (5%). Once, during the six months testing period, the air supply was shut off because of a 2-hour and 10-minute power outage.

Two heating units (one Haake-Thermostat E52 and oneHeto, type 50E623) each with a capacity of 0-1000 watts were used for temperature control of waterbaths at 25°C, 18°C and 12°C. Each unit was equipped with a pump (capacity 12 l/min) to circulate water in the bath. Thermostats were replaced twice during the test period due to malfunctioning. Temperature in the waterbath was always slightly different from the temperature in the reactors. Evaporation and the temperature of the compressed air were probably the major reasons for this. A close control of the temperature in the reactors was kept at all times.

A refrigeration unit (type Alfa-Laval) served two purposes in this project: it kept the cold storage bath for raw sludge at 4°C ± 0.5° and it controlled the temperature in the 7°C waterbath. A thermostat placed in the 7°C waterbath activated a pump that supplied water from the 4°C cold storage bath whenever the temperature in the 7°C bath increased above this set temperature. No problem was encountered with this set-up.

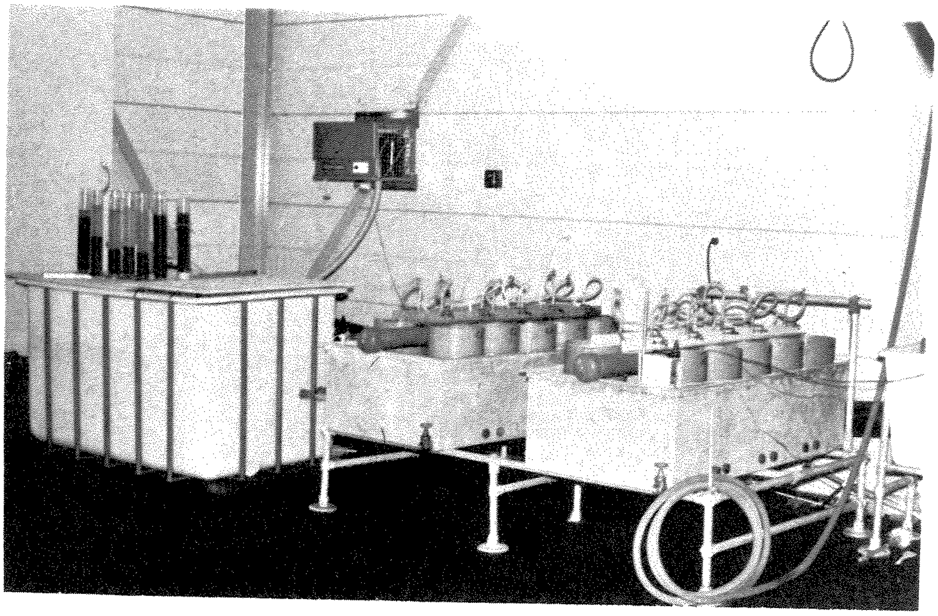


Figure 2. Pilot Plant

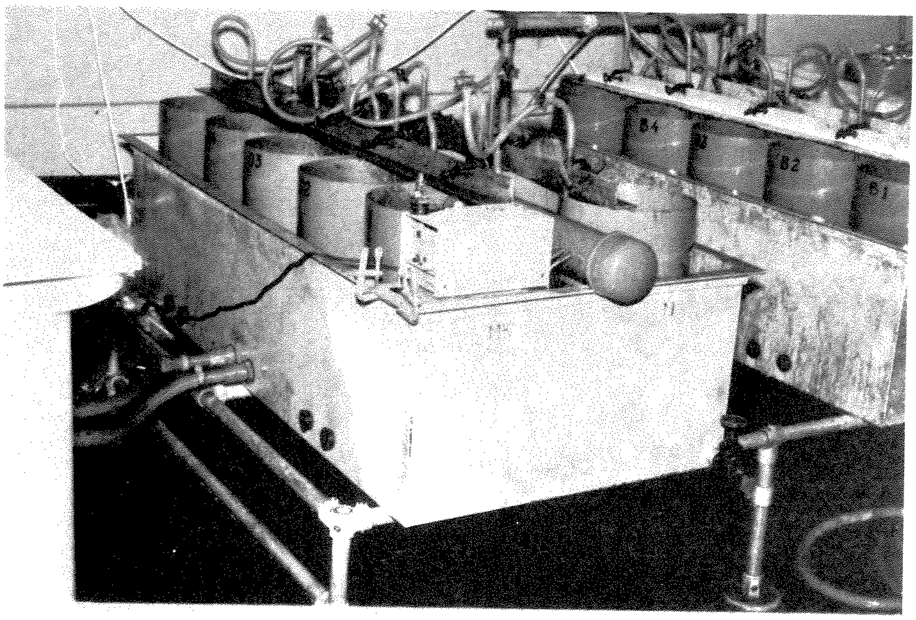


Figure 3. Water Bath with 10 Reactors

The temperature in the 4°C cold storage bath was thermostatically controlled also. The submersible cooling unit was equipped with a propeller to keep good circulation in this tank at all times.

The pilot plant required daily maintenance seven days a week because the experiments were carried out on a continuous flow system. The daily routine, when no tests were conducted, was to check the temperature in the reactors and the 4°C cold storage bath and adjust the thermostats, if necessary. The next step was to check the aerators for signs of clogging and, if necessary, they were replaced with clean ones. The walls of each reactor were scraped clean of solids that always had a tendency to fasten to the walls. This was particularly true with the units treating primary sludge and having a short detention time. The volume of each reactor was controlled and water lost due to evaporation was replaced with tap water. Very little water was lost during the 7°C and 12°C tests. At 25°C and 18°C tests approximately 100-400 ml were lost in 24 hours. The proper volume of sludge was then withdrawn from each unit, according to the set detention times and new sludge was taken from the cold storage and added to the units. At times foaming was a problem in some of the units. This did not seem to follow any pattern and it disappeared after a few days.

A set routine was also followed when an extensive testing program was carried out. Tests on 5 reactors only were conducted in one day because of the amount of laboratory work involved. The general procedure was to measure temperature, pH, oxygen content and the oxygen uptake rate in each unit. This was always done before the walls of the reactor were scraped down. The walls were then scraped down, volume adjusted and the treated sludge (mixed liquor) was withdrawn from each unit into one-liter plastic bottles. Gentle stirring with a wooden paddle was provided during sludge withdrawal. The new raw sludge was then added.

In the field laboratory, samples for total phosphorus, orthophosphate, Kjeldahl-nitrogen, nitrite plus nitrate (NO_2+NO_3), adenosine triphosphate (ATP) were prepared and brought to the main laboratory of the Norwegian Institute for Water Research (NIVA) in Oslo. All tests on sludge characteristics, like capillary suction time (CST), specific resistance to filtration, drainage, sedimentation, etc., were carried out at the field laboratory. An effort was made to do these tests as soon as possible after the samples were withdrawn from the reactors.

Full-Scale Aerobic Digesters

The 3 aerobic digesters located outside were constructed out of timber with a structural steel frame at the top and the bottom of the walls. Each digester measured approximately 3.80 m by 3.70m with a depth of 2.0m. The effective water depth was 1.50 m, which gave each reactor a capacity of 21.1m^3.

A walkway was placed across all 3 digesters. This walkway supported the 3 surface aerators and provided access to skimmers for supernatant withdrawal, valves and other appurtenances (See figures 4 and 5).

Two of the digesters were equipped with type APAG, 3HP, surface-type aerators operating on the airlift-pump principle. The third digester was not used for experiments, but served as a "buffer tank" for excess sludge produced at the test station.

The volume of sludge pumped from the treatment plant to the digester was measured with a scale fastened to the wall of each digester. Since the aerators were not floating, the volume in each unit had to be kept fairly constant to prevent a change in oxygenation capacity of the aerators.

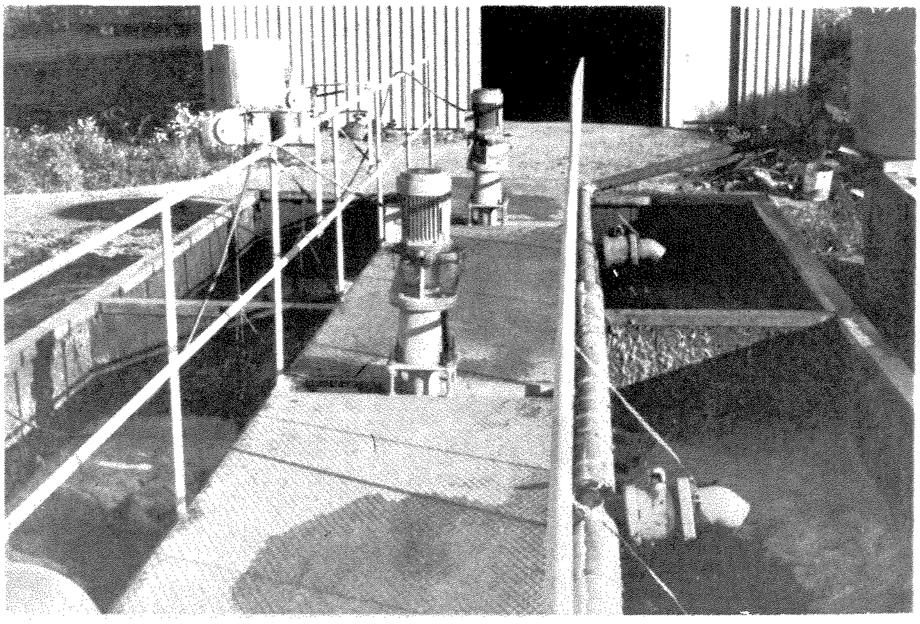


Figure 4. Full-scale Aerobic Digesters

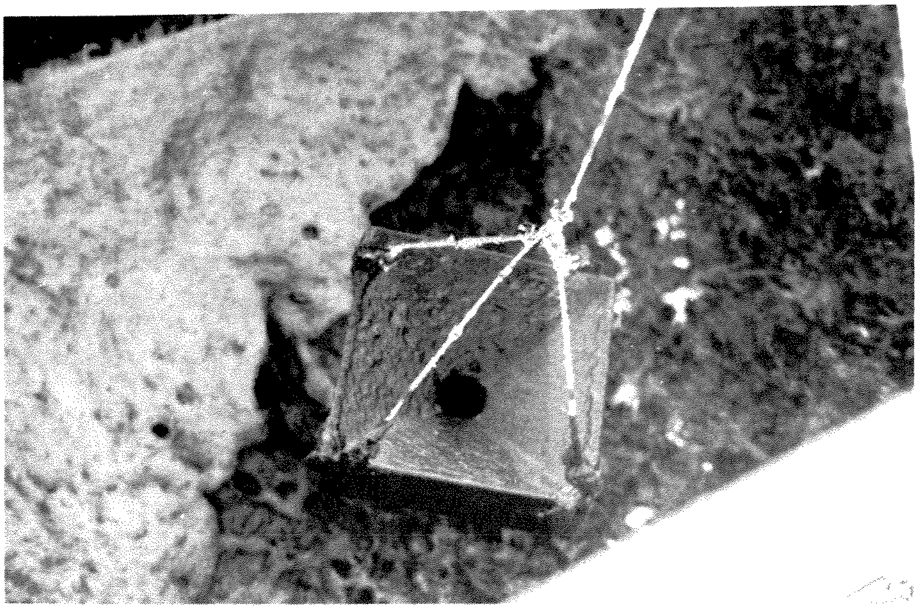


Figure 5. Equipment for Supernatant Withdrawal

ANALYTICAL PROCEDURES

In the following discussion only those methods that differ from the procedures set forth in Standard Methods for the Examination of Water and Waste Water will be discussed.

Hydrogen Ion Concentration

A Radiometer, Type PHM with a combined electrode type GK 2311C, GK 2303C, was used to determine pH. The pH-meter was calibrated against Radiometer buffer solutions pH 6.50 and pH 4.65.

Dissolved Oxygen

Dissolved oxygen (D.O.) was determined with YSI-Oxygen meter, model 54.

Oxygen Uptake Rate

The oxygen uptake rate was measured with YSI-Oxygen meter, model 54, equipped with YSI 5420 A self-stirring BOD bottle probe. A recorder, Leeds and Northrup, Speedomax H was used for plotting change of D.O. in the 200 ml test bottle vs. times. The oxygen uptake rate would then be the slope of the line (mg/1/min). The stirring capacity of the YSI BOD bottle probe is less than desirable for sludges with high solids concentration. For sludges with TSS higher than 10 g/1, the author recommends the use of a magnetic stirrer. The YSI-BOD bottle probe was used throughout this research project (see Figure 6).

Total Suspended Solids

Total suspended solids was determined gravimetrically: a 70 ml volume was centrifuged in a Sorvall Superspeed Centrifuge, type SS-1, KSB-1 for approximately 10 minutes; the clear centrate was withdrawn from the centrifuge tube and the solids put in a aluminum foil dish and dried at 103°C overnight; in the morning, they were placed in a dessicator and weighed. All tests were run in triplicate.

Volatile Suspended Solids

Samples from the total suspended solids test were placed in the muffle furnace at 560°C for one hour. Then they were placed in a dessicator and weighed.

Capillary Suction Time (CST)

A CST apparatus, Model 92 manufactured by Triton Electronics Ltd., was used for this test. The principle of the method is that filtration is achieved by the suction applied to the sludge by the capillary action of an absorbent filter paper of standard grade. A standard-sized circular area in the center of the filter paper is exposed to the sludge, while the rest of the paper area is used to absorb the filtrate drawn out by the capillary suction of the paper. The instrument records the time the filtrate takes to travel between two concentric circles, 3.2 cm and 4.5 cm in diameters. The 1 cm diameter funnel was used for all tests. Since the properties of the filter paper are of fundamental importance in the test result, a large batch of filter papers was ordered from the factory prior to the test period. Only papers from this batch were used during the research period. All tests were run at room temperature ($20-22^{\circ}$C), and no correlation of CST values was made with temperature. Each sample was run three times and the final CST value recorded was the numerical average of the three tests.

Specific Resistance to Filtration

A method applying Carman's theory was used to determine specific resistance. The following applies:

$$r = \frac{2 \cdot P \cdot A^2 \cdot b}{\mu \cdot c}$$

P = filtration pressure (g cm $^{-2}$)

A = effective filtering area (cm^2)

b = inclination of the straight line if t/V is plotted graphically in dependence on V (s cm^{-6})

V = volume of filtrate (cm^3)

t = filtration time (s)

μ = dynamic viscosity of filtrate (g cm^{-1} s^{-1})

c = mass of sludge solids related to the applicable amount of fluid (g cm^{-3})

r = specific **resistance to filtration** (s^2 g^{-1})

An apparatus similar to that used for the Buchner funnel test was used (see Figure 7). The filtration pressure was measured with a pressure gauge. Dynamic viscosity of the filtrate was assumed to be the same as for water at the same temperature. The filtrate was measured with a graduated cylinder vs. time. Whatman filter paper no. 1 was used throughout the test period. A wire screen inside the 9 cm Buchner funnel supported the filter paper. A 200 ml sludge sample and a vacuum of 0.5 kg/cm^2 was used except for compressibility determinations. The general procedure was as follows:

A. The filter paper was seated in the Buchner funnel by using distilled water and then applying vacuum.

B. A 200 ml sample was poured into a 300 ml beaker and the temperature was recorded.

C. The sample was poured into the Buchner funnel and vacuum pressure was applied. The hose clamp for the pressure was opened as soon as a thin layer of sludge had been poured into the funnel, but before all 200 ml had been filled into the funnel. This was to prevent the filter paper from "floating" and then reseating itself.

D. The stopwatch was started and the filtered volume was recorded every 30 seconds for the first 5 minutes and then every minute for the next

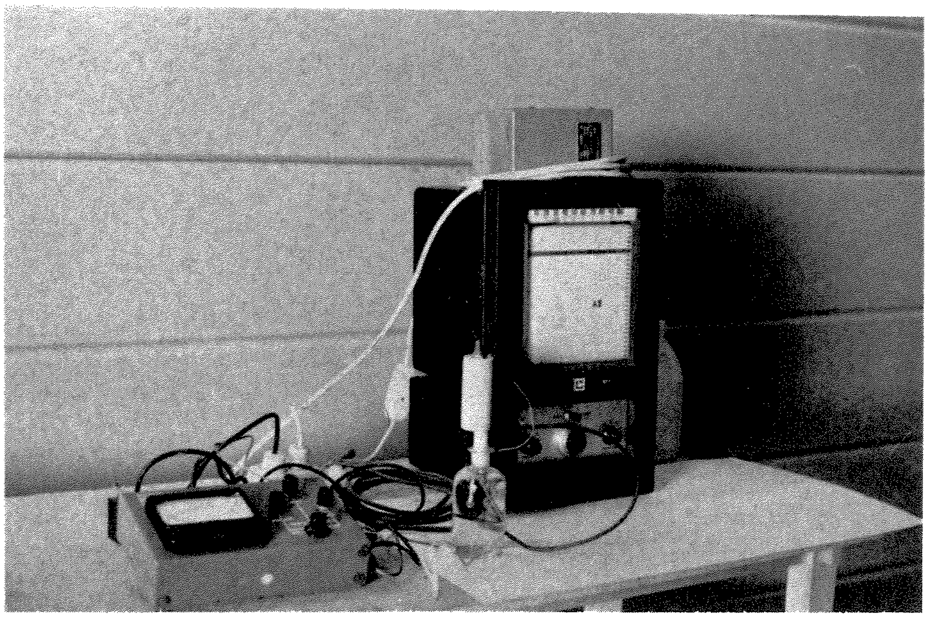


Figure 6. Equipment for Measuring Oxygen Uptake Rate

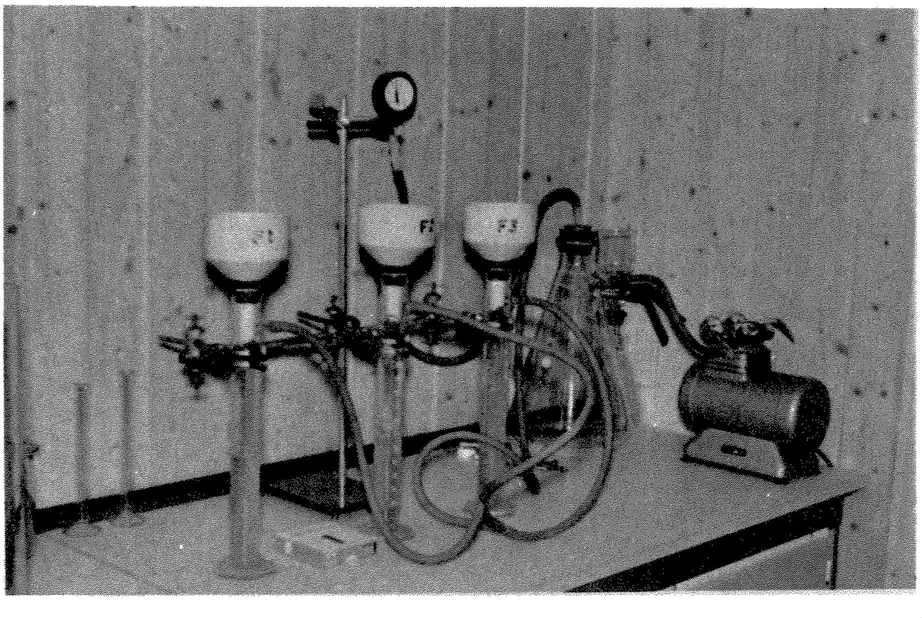


Figure 7. Equipment for Measuring Specific Resistance to Filtration

5 minutes.

The ratio t/V (sec/ml) was then plotted against V and the slope of this line determined the "b" factor. The effective filtering area used was equal to the perforated area in the Buchner funnel.

Drainage Characteristics

Drainage characteristics were measured by using 12 sand-filter units as shown in Figure 9. A Buchner funnel (diam. 7 cm) was placed on top of a 500 ml graduated cylinder. A plastic tube (height 25 cm) fitted inside the funnel. A wire screen was placed inside the funnel to support the 5 cm-thick layer of filtering sand used. The sieve grading of this sand is shown in Figure 8.

Prior to drainage tests the sand was wetted with tap water. The unit was then filled with 10 cm (385 ml) of sludge and the drained volume of water was measured vs. time. The duration of each test was usually 2 weeks. After each test, samples from the drained water volume were taken for further analysis. The sand was replaced after each test.

Rüffer's Lead Acetate Test

Rüffer's Lead Acetate test was used as a measure of degree of stabilization. 100 ml bottles with glass stoppers were filled with 50 ml of sludge. A strip of lead acetate paper was fastened between the bottle and the stopper. The time required for the lead acetate paper to change from white to brown due to evolution of H_2S was recorded (See Figure 10).

ATP-Measurement

The quantitative determination of ATP by bioluminescence is dependent on: (a) firefly luciferace enzyme being absolutely specific for ATP, (b) the rate of the reaction being directly proportional to the concentration of

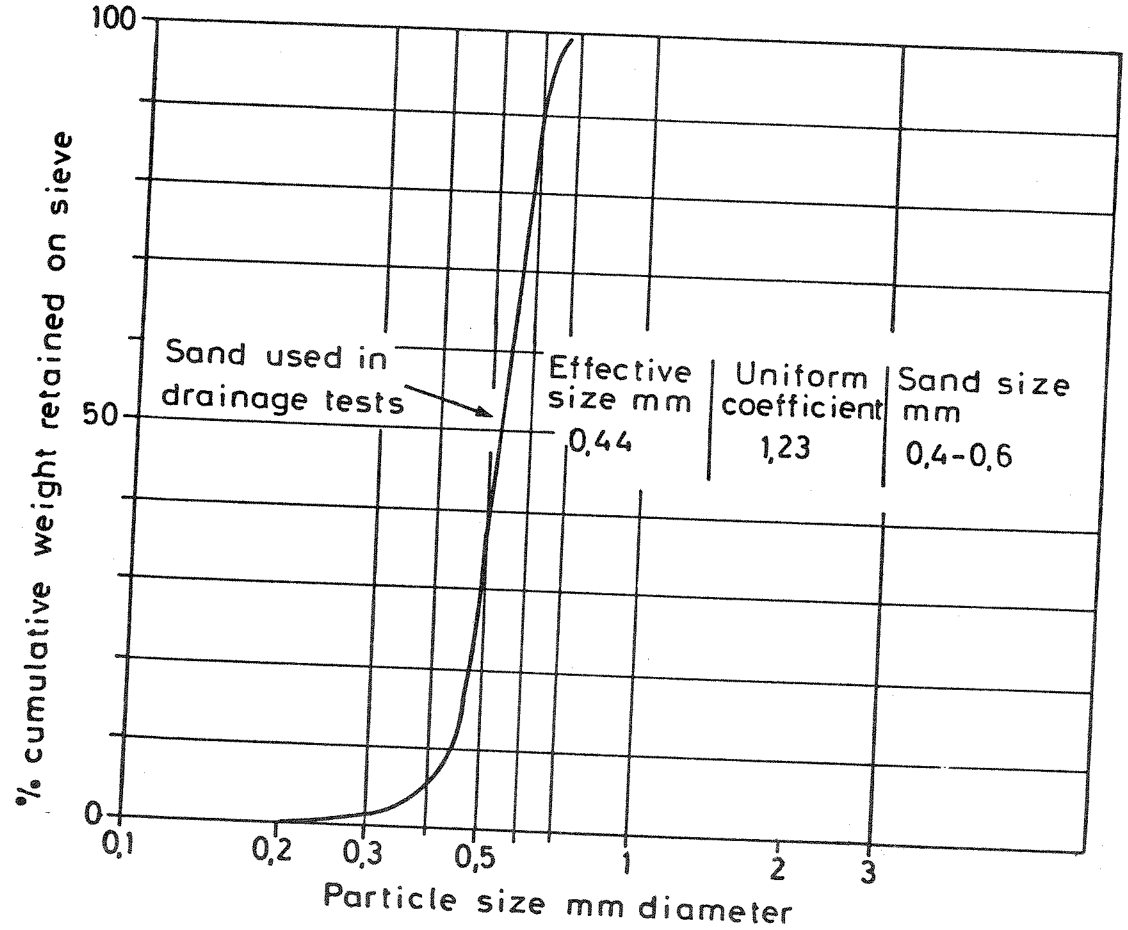


Figure 8. Sieve Grading of Sand Used in Drainage Tests

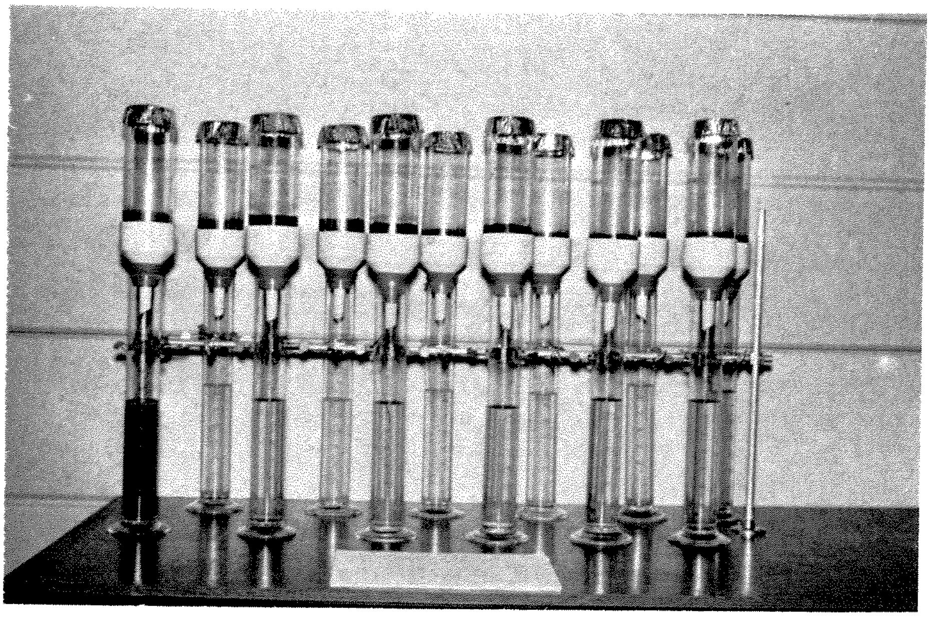


Figure 9. Filter Stands for Measuring Drainage Characteristics

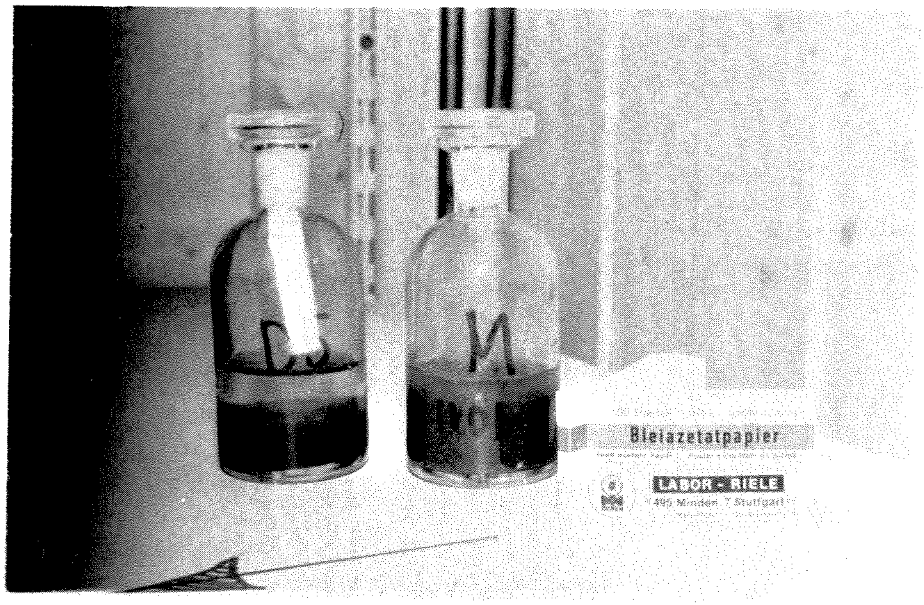


Figure 10. Rüffer's Lead Acetate Test

ATP, assuming that other reactants are in excess, and (c) the emission of one photon of light for each molecule of ATP which is hydrolyzed. The overall reaction is as follows:

$$\text{Luciferin (reduced)} + \text{ATP} + O_2 \xrightarrow[\text{Luciferace}]{Mg^{++}} \text{Luciferin (oxidized)}$$

$$+ PP_i + \text{AMP} + H_2O + hv$$

When a sample containing ATP is injected into the enzyme preparation, there is an immediate burst of light in the range of 560-580 mµ. The intensity of light declines in a semi-exponential fashion. The area under this curve is proportional to the amount of ATP in the sample.

The ATP measurements in this study were made using a JRB-ATP Photometer from JRB Incorporated, San Diego, California, U.S.A. A block diagram of this instrument is shown in Figure 11. According to the JRB-ATP Photometer Instruction Manual (1971), the instrument works in the following manner:

> When a sample is placed in the sample chamber after injection of ATP and the dark slide is pulled out, light strikes the photocathode of the phototube, liberating electrons which cascade through the photomultiplier to produce a current proportional to the light intensity of the sample. This current is converted and amplified to produce a proportional voltage. This voltage is fed into a voltage-frequency converter where a pulse train is produced whose frequency is proportional to the input voltage.
>
> This pulse train is prescaled for increased accuracy and gated by a digital timer. This precision timer allows the pulse train to pass to a counter where it is accumulated for a pre-set interval. At the end of the interval the count displayed represents the integral
>
> $$C \int_{t_1}^{t_2} I_\nu dt = \text{displayed counts}$$
>
> where C is a constant determined by a combination of the high voltage applied to the phototube (gain) and ATTENUATOR setting, phototube sensitivity, and optical geometry.

I_ν is the intensity of the light emitted from the sample, and t_1 and t_2 represent the initial and final times respectively of the integration period.

Reagents:

1. Buffer: Tris-buffer (Tris-(hydroxymethyl)-aminomethane, 0.02 M, pH 7.75) was used. After preparation, the tris-buffer was autoclaved and stored in stoppered bottles in a refrigerator. Once a flask was opened, it was used for one day.
2. Enzyme Preparation: as outlined in the JRB-ATP Photometer Instruction Manual (1971).

Sample preparation:

Approximately one litre of sludge sample was removed from the reactor. This sample was homogenized in a blender and a one-milliliter sample was immersed in 20 ml of boiling (100°C) Tris-buffer. The samples were stored at -20°C.

Microscopic Examinations

Microscopic examinations of the sludges were made to determine the general type of organisms which characterized the different environments during aerobic digestion. A Leitz Wetzlar Dialux microscope and flat glass slides with cover plates were used for making observations.

Sedimentation

Six 1000 ml graduated cylinders were used throughout this project for sedimentation studies.

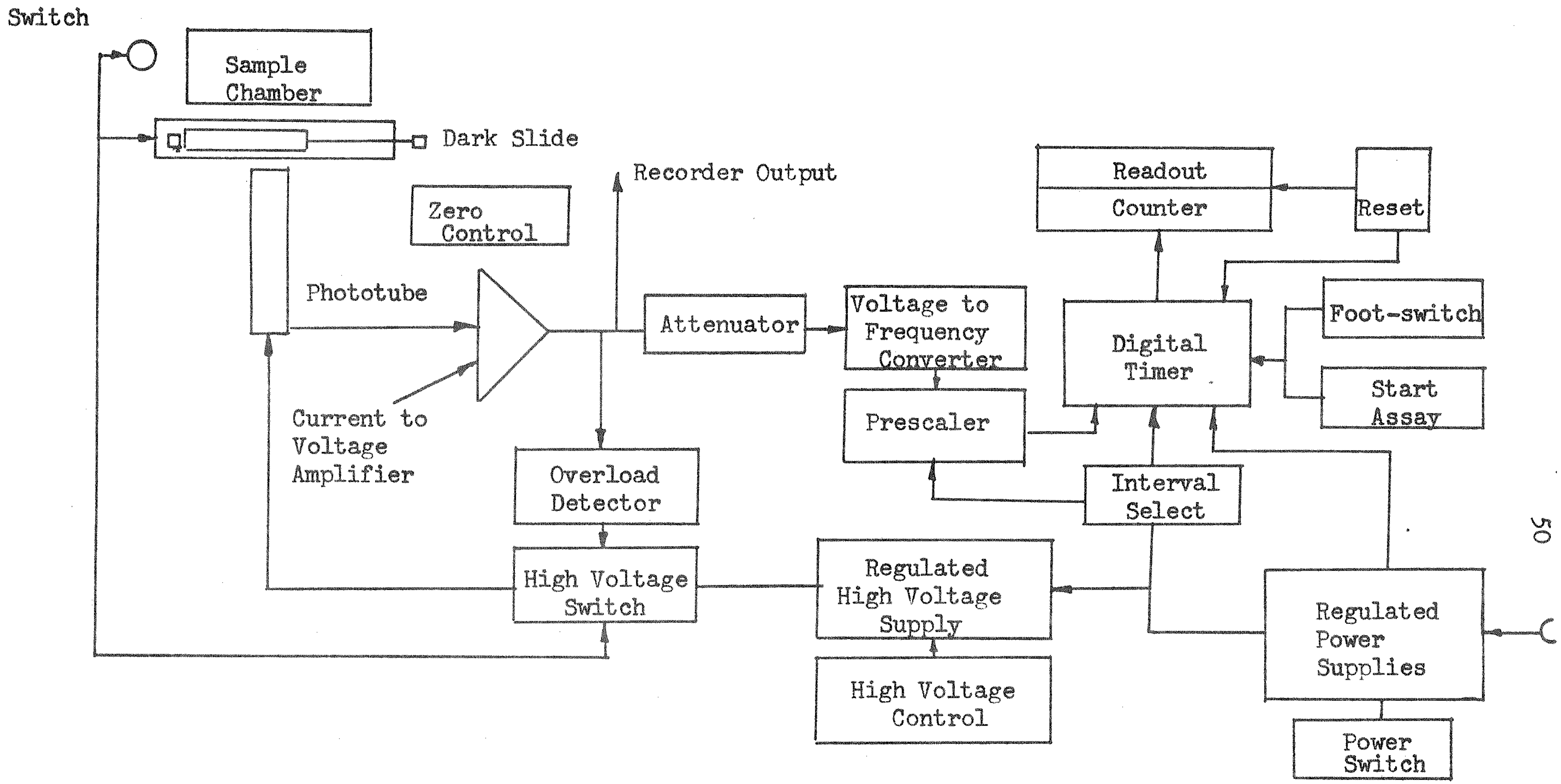


Figure 11. Block diagram of ATP-photometer.

UNTREATED SLUDGE CHARACTERISTICS AND EFFECTS OF STORAGE

The treatment plants at Kjeller Research Station treat domestic waste only. Therefore, the changes in untreated sludge characteristics were what would normally be expected in a treatment plant. To minimize any changes in the raw sludge, the loadings to the primary plant and the chemical plant were kept constant. The dosage to the chemical plant was kept nearly constant at 180 mg/l $Al_2(SO_4)_3$ except the period Nov. 29 to Dec. 7, when the dosage was increased to ca. 240 mg/l $Al_2(SO_4)_3$. The properties of the untreated primary, untreated chemical and mixed primary-chemical are shown in Appendix A. Average values are shown in Table 4 below.

Sludge	pH	TSS mg/l	VSS mg/l	COD mg/l	Tot-P mg/l	PO_4-P mg/l	Alkalinity mg $CaCO_3$/l
Primary	5.35	20607	17957	22970	140	29.6	265
Chemical	-	14366	9113	15060	406	0.48	-
Mixed Prim/Chem	5.60	17508	13235	19255	286	1.18	214

Table 4. UNTREATED SLUDGE PROPERTIES

Each day approximately 13 liters of raw primary sludge and 13 liters of mixed primary-chemical sludge were required to feed the 20 reactors in operation. Since it was impractical to withdraw raw sludge from the treatment plants every day, this was done once a week. The sludge was first put into two 200-liter plastic containers; one was filled with primary sludge and the other with chemical sludge. The total suspended solids (TSS) was determined and then adjusted to 15,000 mg/l for chemical sludge and 20,000 mg/l for primary sludge. If the sludge had to be diluted to reach the proper solids concentration, supernatant from the clarifier from which the sludge was withdrawn was used. After the adjustment had taken place, the TSS concentration was determined again. Equal volumes of primary sludge and chemical sludge were then mixed to make a minimum of 120 liters of sludge. Four 30-liter cans were then filled with primary sludge and four with mixed primary-chemical sludge and stored at 4°C. The same procedure was followed each week.

In spite of the effort to keep the TSS constant, the per cent volatile suspended solids (VSS) varied slightly during the test period. This can be seen from Figure 12. The chemical oxygen demand (COD) also showed higher values during the last part of the test period.

Changes that might take place during storage at 4°C and thus change the character of the raw waste added to the reactors each day were of prime interest. There are two major changes which can take place: decomposition of carbohydrates, cellulose and grease to acids; and deamination of nitrogen compounds. One reaction lowers the pH, and the other raises it. pH measurement will therefore not be a good indicator to find out if one or both of these reactions will take place during storage. Figure 13 shows that essentially no pH change was found during storage. There was a slight increase in the ammonium content of primary sludge during one week's storage (see Figure 14) and the COD also varied slightly. The changes of the latter parameter were probably caused by inaccuracy of the analytical method rather than material activity during storage.

The Adenosine Triphosphate (ATP) was also determined for the two sludges during storage at 4°C. Since ATP can be a measure of biochemical utilization of substrate (raw waste), an increase in ATP would indicate an increase in the biological activity during storage. Figure 16 indicates that primary sludge had the highest initial activity and that a slight increase was indicated until the sludge cooled off to 4°C, and then followed by a sudden decrease in mg/l ATP. The ATP content would then remain fairly constant throughout the week. The mixed primary-chemical sludge showed almost no increase in ATP content

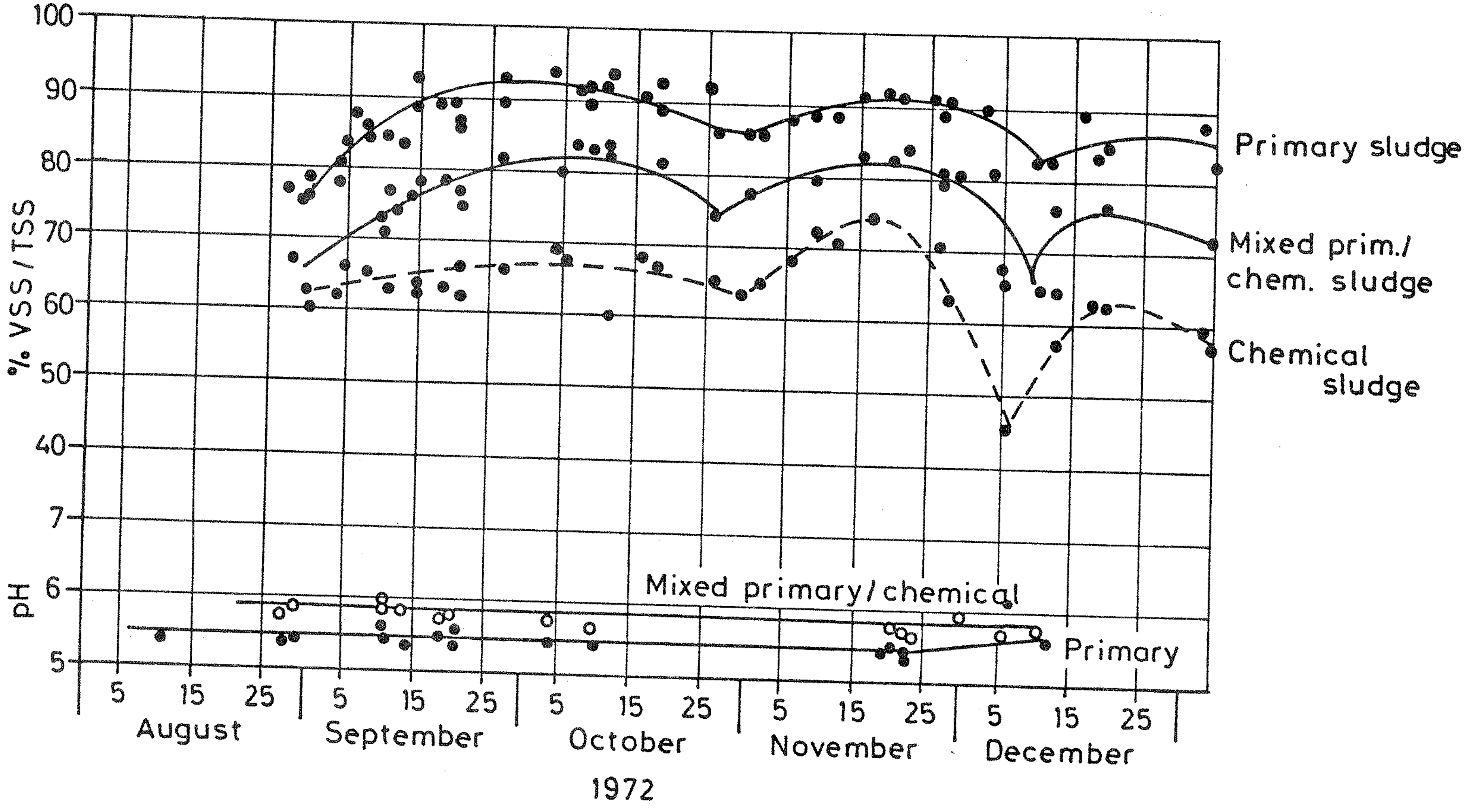


Figure 12. Per cent Volatile Suspended Solids and pH in Raw Sludge.

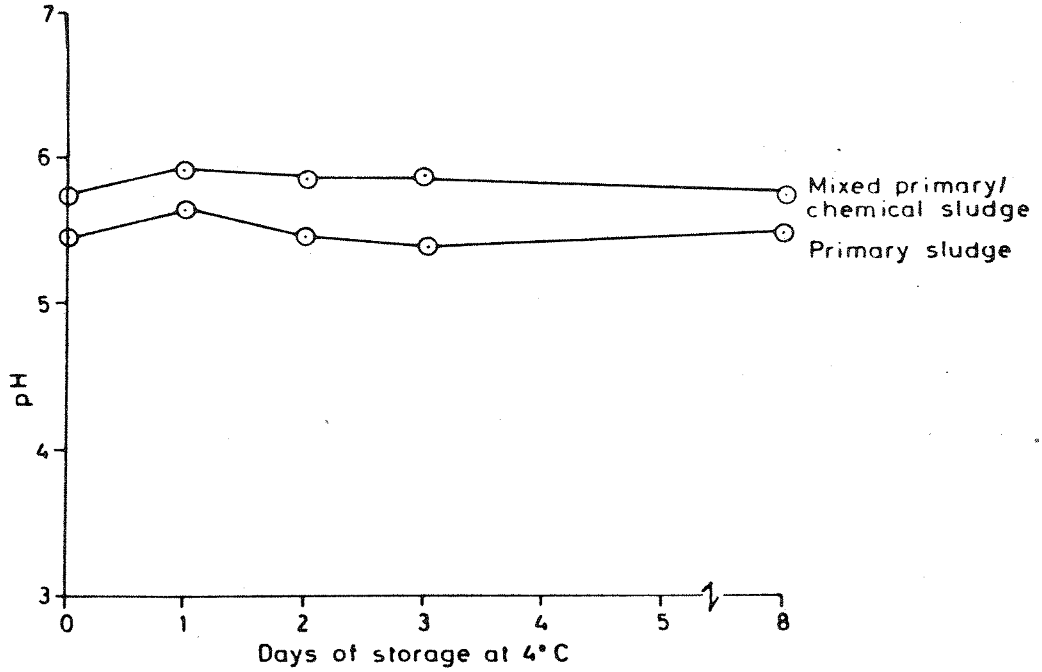


Figure 13. pH vs. Days of Storage at 4°C.

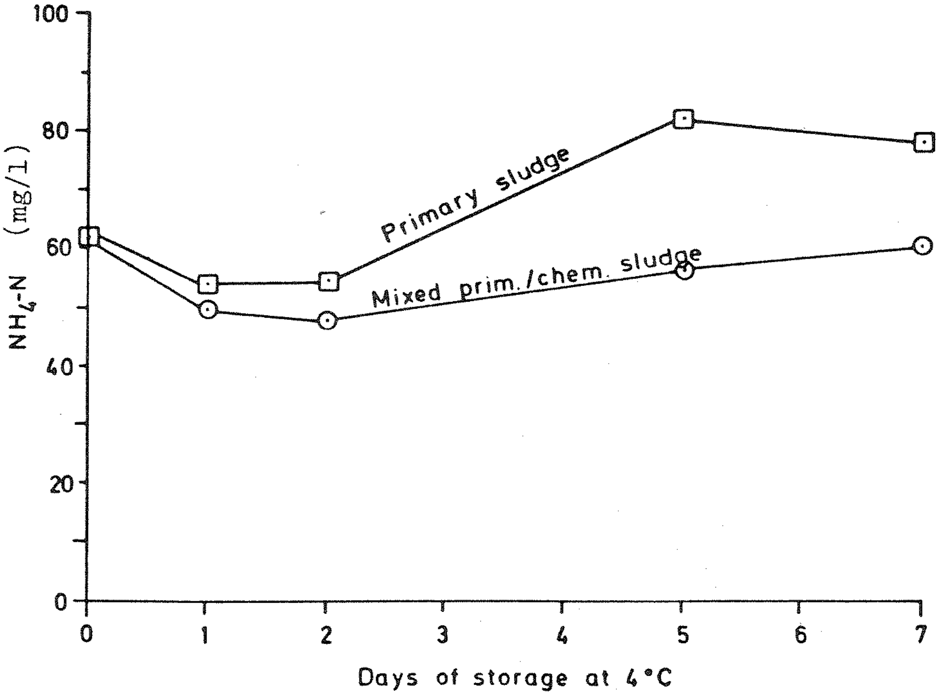


Figure 14. NH_4-N vs. Days of Storage at 4°C.

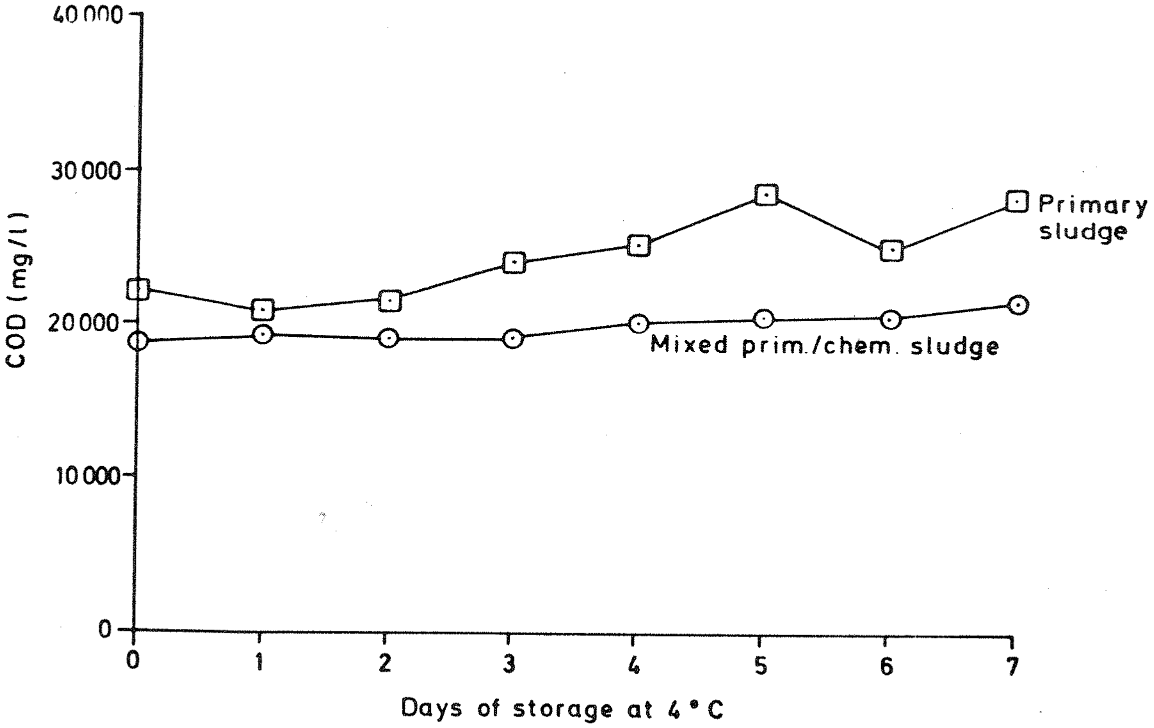


Figure 15. Chemical Oxygen Demand vs. Days of Storage at 4°C.

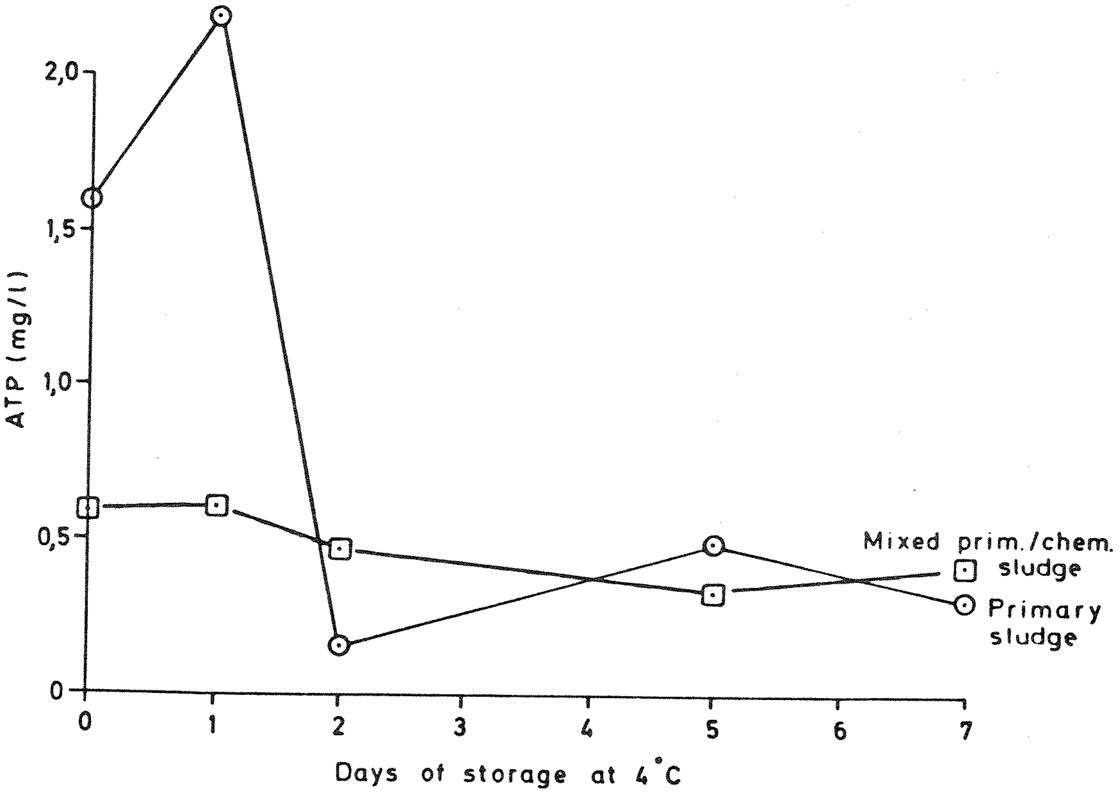


Figure 16. ATP vs. Days of Storage at 4°C.

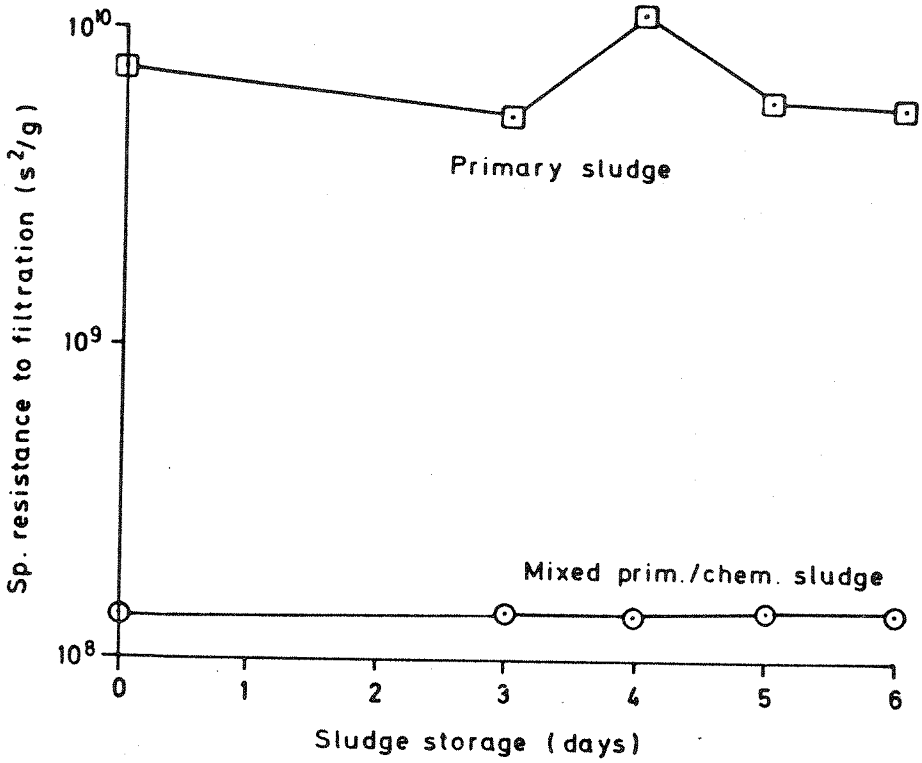


Figure 17. Specific Resistance to Filtration vs. Days of Storage at 4°C.

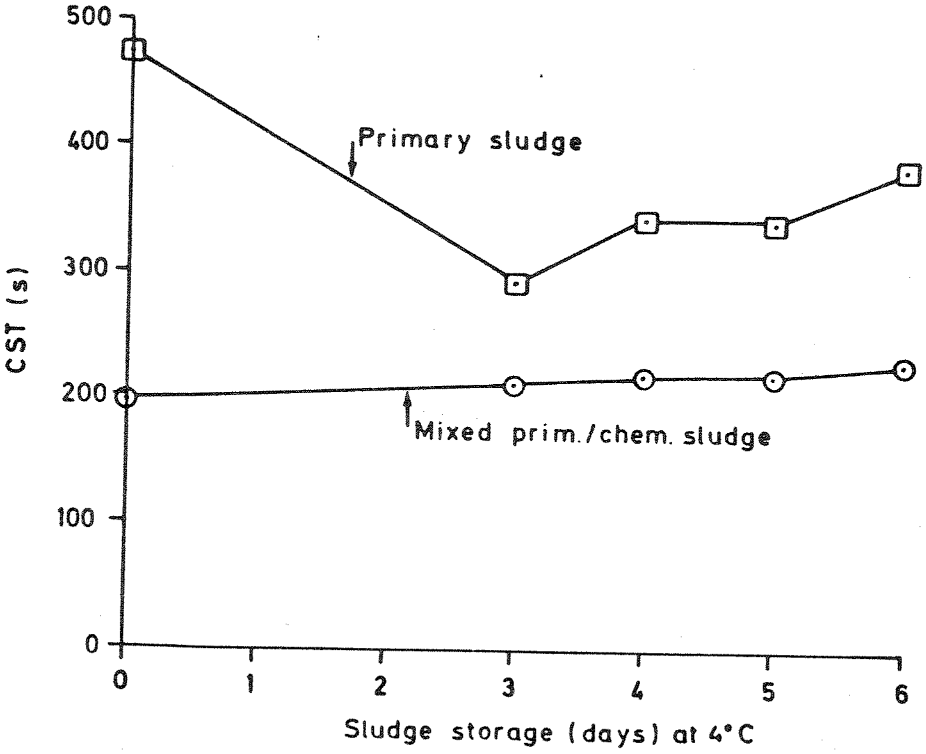


Figure 18. Capillary Suction Time (CST) vs. Days of Storage at 4°C.

during storage.

The change in specific resistance to filtration and capillary suction time (CST) also were measured during storage. Storage at 4°C did not seem to influence these two parameters very much. The variations seen in Figures 17 and 18 for primary sludge are primarily caused by the difficulty in taking representative samples. This is especially true with the CST measurement since only a few ml is needed for each test.

EXPERIMENTAL RESULTS AND DISCUSSION - PILOT UNITS

Reduction of Volatile Suspended Solids, Total Suspended Solids and Chemical Oxygen Demand

The untreated primary sludge had a high percentage of volatile suspended solids; it varied from 75 per cent VSS to as high as 94 per cent. Probably efficient grit removal was the reason for this. The percentage volatile suspended solids in the untreated chemical sludge varied between 45 per cent and 74 per cent. Changes in the primary waste water characteristics would affect the efficiency of the precipitation process and hence the amount of organic material removed from the waste water.

Removal of volatile suspended solids vs. detention time agreed fairly well with a first order biochemical reaction.

$$\frac{VSS_t - VSS_N}{VSS_0 - VSS_N} = e^{-K_T t} \qquad (9)$$

VSS_0 = volatile suspended solids at time zero (mg/l)

VSS_t = volatile suspended solids at time t (mg/l)

VSS_N = nonbiodegradable volatile suspended solids (mg/l)

t = detention time in reactor (days)

K_T = rate of decay constant (days^{-1})

In this study nonbiodegradable volatile suspended solids were considered to be the value of volatile suspended solids approached asymptotically by the 25°C curve. For primary sludge this value was set at 37 per cent of initial volatile suspended solids concentration. For mixed primary-chemical sludge, the nonbiodegradable fraction was 45 per cent of the initial volatile suspended solids concentration.

The rate of decrease of volatile organic solids decreased as the detention time in the reactor increased. This was true for both types of sludges at the four different temperatures investigated (see Figure 19).

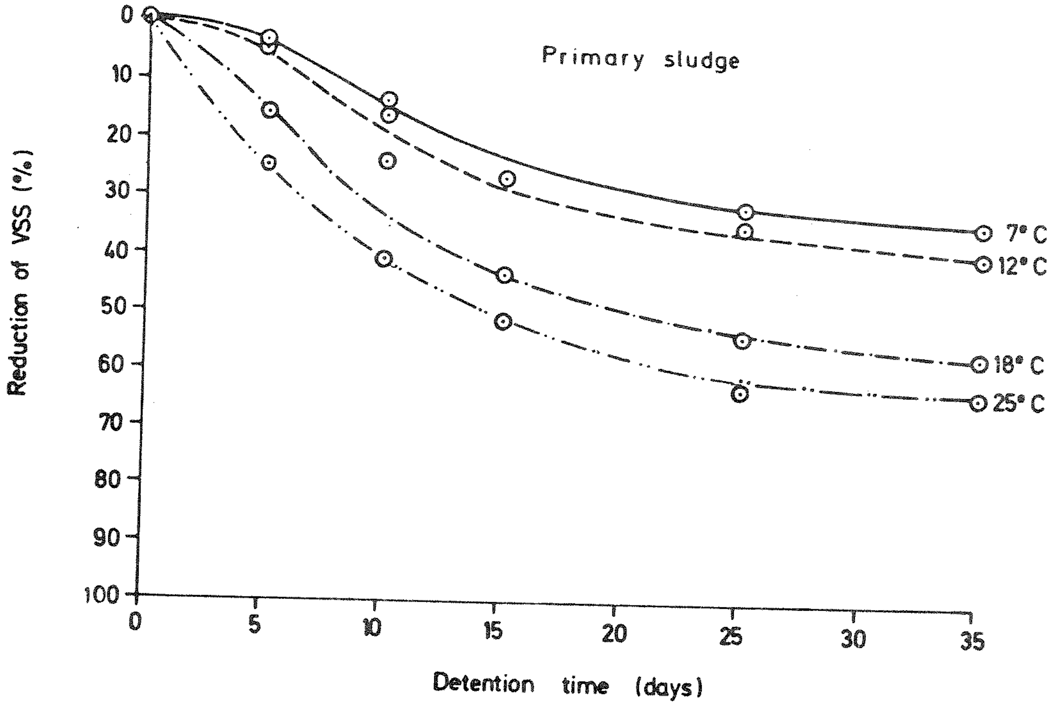
This is expected since in the early stages of digestion the easily available food in solution will be used first. As the process proceeds, the organisms must rely on their ability to liquify organic material. For this, they have to depend on extracellular enzymes. These enzyme reactions are slow and will account for the reduced rate of volatile suspended solids reduction. Reductions of total suspended solids and chemical osygen demand followed the same trend (see Figures 20 and 21). For mixed primary-chemical sludge the reductions of TSS, VSS, and COD had a slight tendency to coalesce as the detention time increased towards 35 days. This was not true with primary sludge. The difference in reductions of TSS, VSS, and COD for the four temperatures investigated were higher at 35 days than at any shorter detention time. This might not have been true if the detention time had exceeded 35 days.

The influence of temperature is evident from Figures 19, 20 and 21. The reduction of TSS, VSS and COD will increase with increasing temperature in the reactor. Based on reduction of VSS, the rate of decay constant K_T was determined by using equation 9. The result is given in Table 5 below:

Sludge	K_{7^oC}	K_{12^oC}	K_{18^oC}	K_{25^oC}	θ_{aver}	Q_{10}
Primary	0.0228	0.0324	0.0668	0.1086	1.114	2.72
Mixed Prim/Chem	0.0293	0.0385	0.0731	0.0960	1.090	2.19

Table 5. K_T AT DIFFERENT TEMPERATURES BASED ON REDUCTION OF VOLATILE SUSPENDED SOLIDS

This is also shown in Figure 22. The influence of temperature is slightly greater on primary sludge than on mixed primary-chemical sludge. Based on the



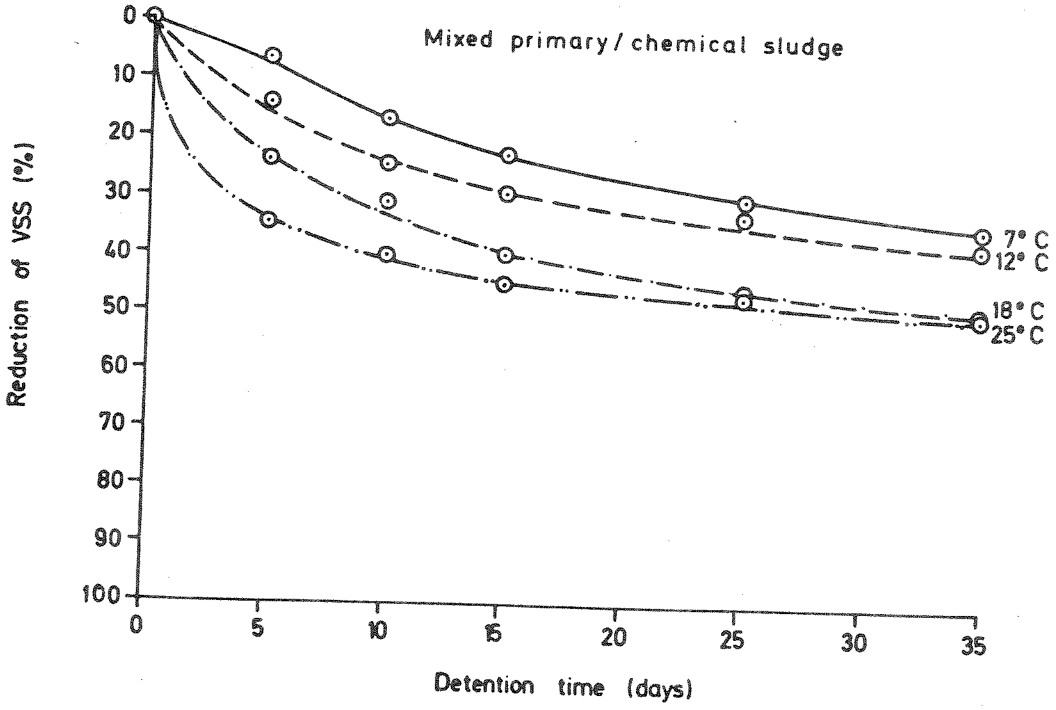


Figure 19. Reduction of Volatile Suspended Solids (VSS) vs. Detention Time.

Q_{10} concept the values were determined to 2.72 and 2.19 for primary and mixed primary-chemical sludge respectively. The temperatures used were 10°C and 20°C. Using Streeter and Phelp's (Jaworski et al., 1963) empirical equation:

$$\frac{K_{T_1}}{K_{T_0}} = \theta^{(T_1 - T_0)} \qquad (10)$$

The average values of θ were calculated (given in Table 5). The θ value for primary sludge was slightly higher than for mixed primary-chemical sludge.

The equations for temperature affects will be as follows:

Primary Sludge:

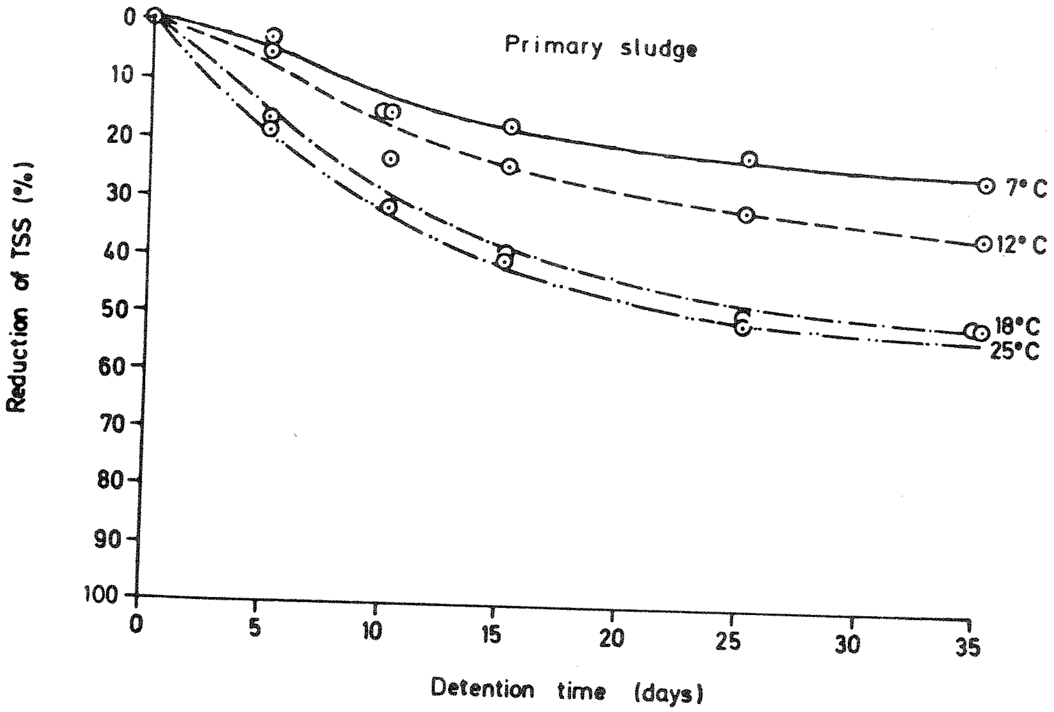
$$K_T = 0.0789\ (1.114)^{(T - 20^{\circ}C)} \qquad (11)$$

Mixed Primary-Chemical Sludge:

$$K_T = 0.0790\ (1.090)^{(T - 20^{\circ}C)} \qquad (12)$$

The temperature will affect the biological system in two ways: first, temperature will affect the enzymatic reactions that are responsible for the reductions of volatile suspended solids; second, the temperature will influence the diffusion of substrate to the organisms. This effect can be determined by calculating the diffusion coefficient at different temperatures. These two major types of temperature influence would possibly account for the different θ and K_T values at different temperatures for the two types of sludges investigated.

Reduction of volatile suspended solids (VSS) vs. temperature for the two types of sludges investigated are shown in Figure 23. It is of interest to note that as the lower temperatures are approached, the rate of reduction of volatile suspended solids will decrease. This seems to be true for both types



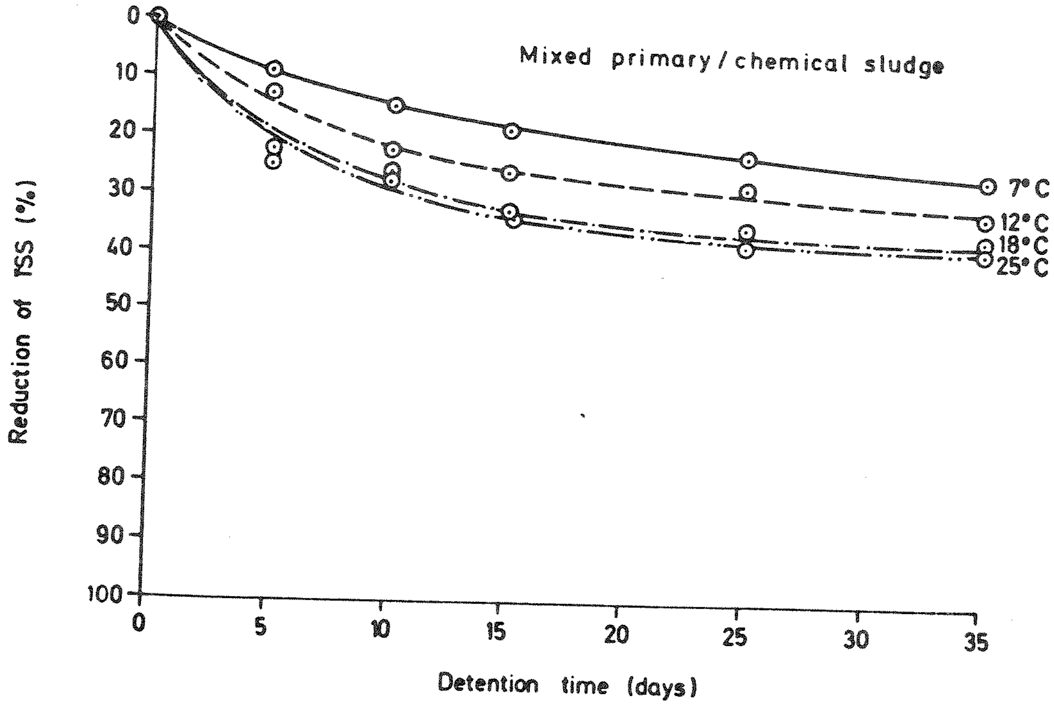
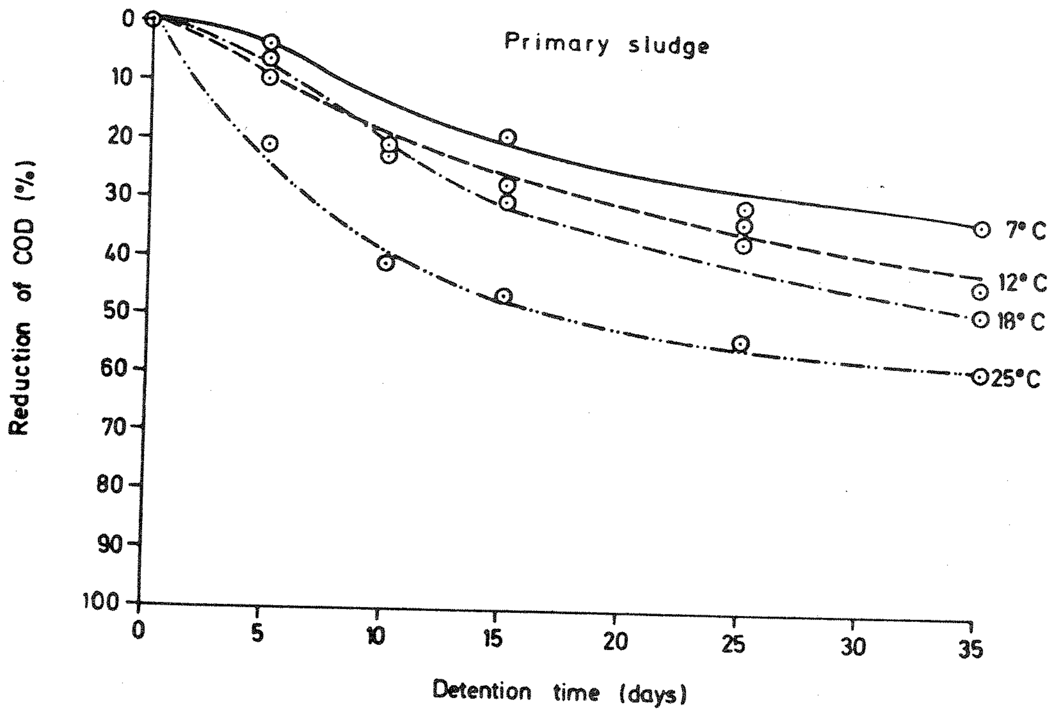


Figure 20. Reduction of Total Suspended Solids (TSS) vs. Detention Time.



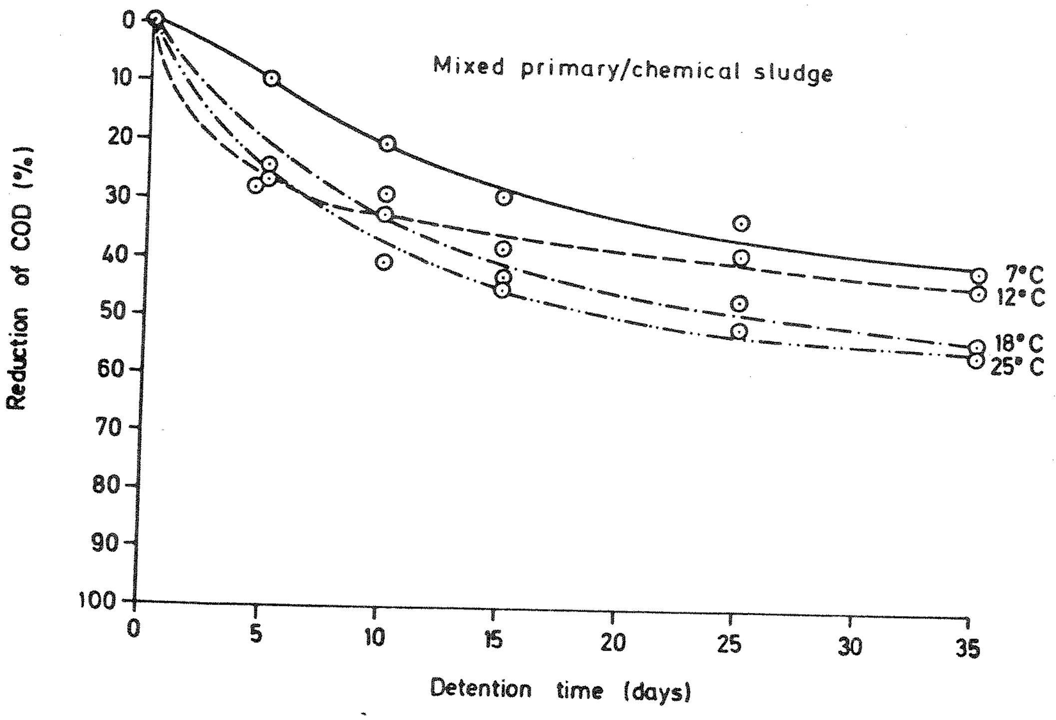


Figure 21. Reduction of Chemical Oxygen Demand vs. Detention Time.

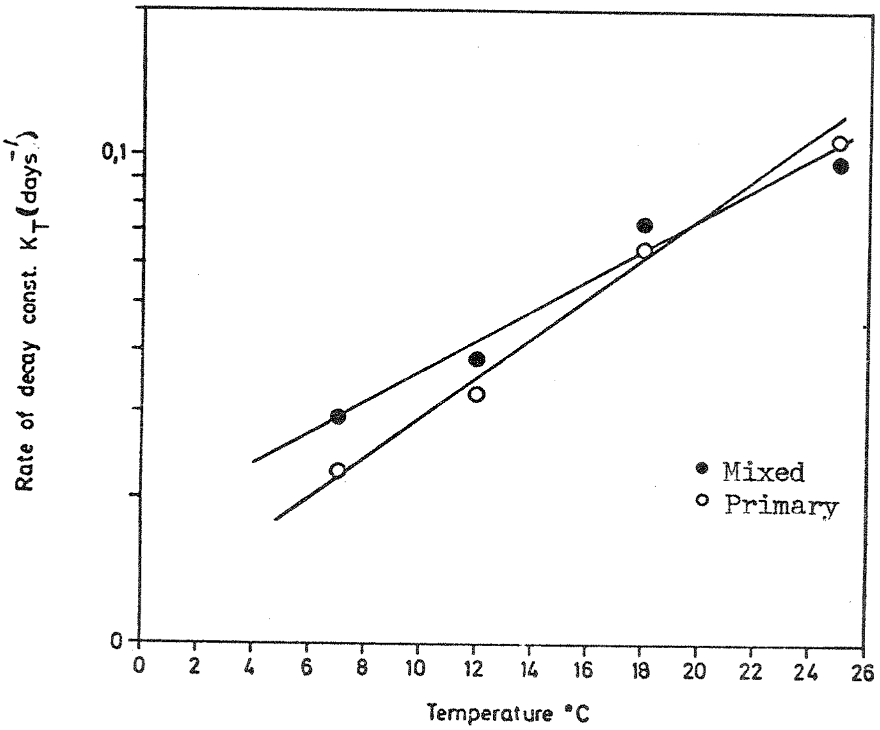
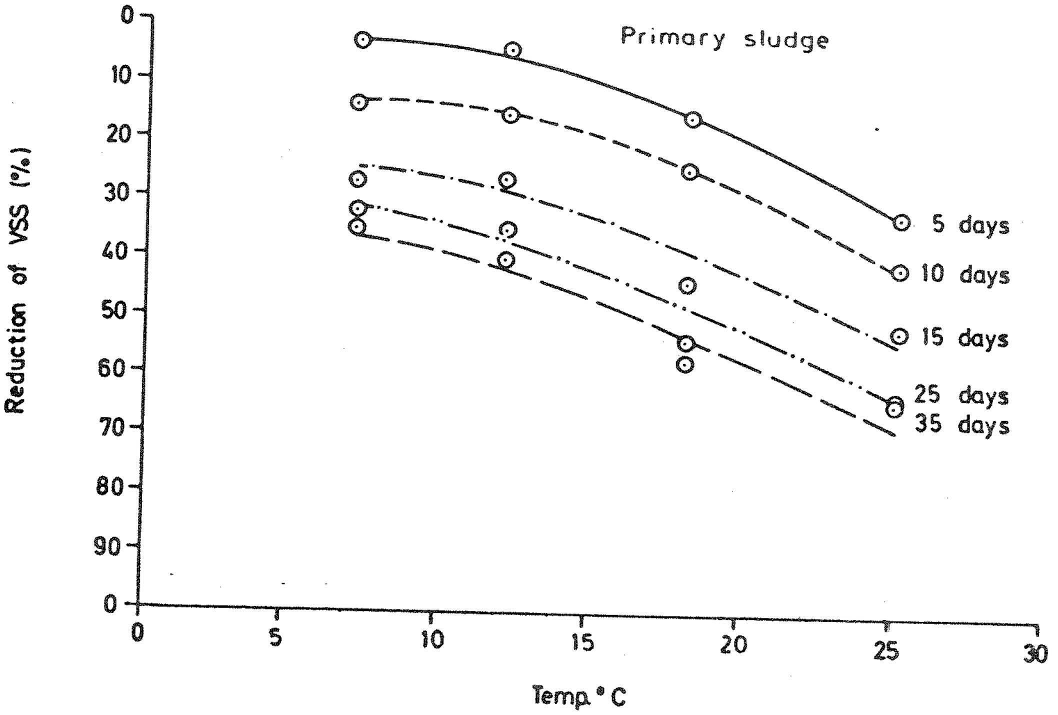


Figure 22. Rate of Decay Constant (K_T) vs. Temperature.



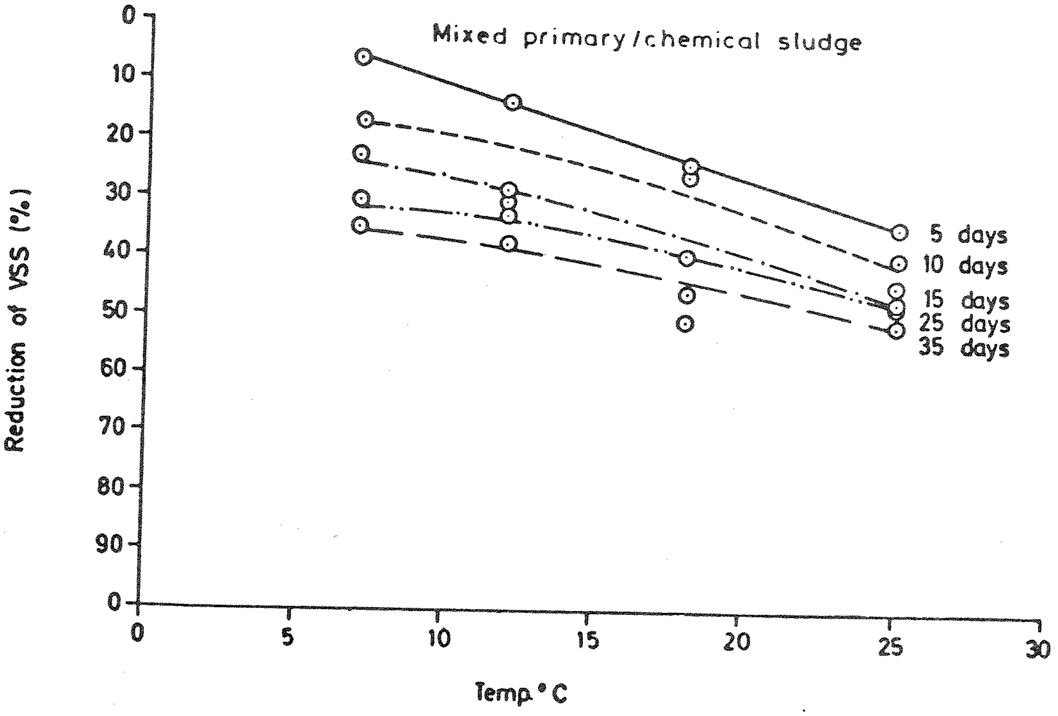


Figure 23. Reduction of Volatile Suspended Solids vs. Temperature at Different Detention Times.

of sludges investigated.

Change of pH and Alkalinity During Aerobic Stabilization

The change of pH during aerobic stabilization is well documented in the literature. The increase of pH during the early stages of the digestion process was experienced for both types of sludges and at all four temperatures investigated. For mixed primary-chemical sludge, this early increase was always followed by a gradual decrease to a low pH value at 35 days' detention time (See Figures 24 and 25). Similar results were obtained with primary sludge except during the 12°C series. During this series, no gradual reduction with increasing detention time was obtained. Also during the 18°C and 25°C series the gradual decrease with increasing detention time was very small. For these three series, the pH increased from pH 5.3 to approximately pH 7.0. Digestion of primary sludge at 7°C showed a more typical pH curve: an increase from pH 5.3 to pH 7.25 and then a gradual decrease to approximately pH 6.3.

Wide fluctuations of the pH values were experienced in most reactors, even though they were at a steady state. This was especially true for primary sludge at the 7°C series and mixed primary-chemical sludge at 7°C and 25°C series. The possible explanation for this is that the always changing alkalinity of the raw waste added to the reactor from one week to the next. Also a gradual change in aeration intensity due to clogging of the diffusers might influence the pH values in the reactors. Changing aeration intensity will change the rate at which CO_2 is stripped from the reactor. The build-up of foam in the reactors, which occurred with no obious pattern, would also possibly influence the stripping of CO_2 from the reactors.

Alkalinity decreased with increasing detention time for both primary sludge and mixed primary-chemical sludge. The reduction of alkalinity was rapid during the first 5 days; then it would gradually decrease or even increase slightly, and then it stayed fairly constant from 15 days' detention time to 35 days' detention time. For primary sludge, the reduction in alkalinity was from approximately 260 mg $CaCO_3$/l in the raw sludge to values between 36 mg $CaCO_3$/l and 107 mg $CaCO_3$/l. These values are average values of four individual measurements. The lowest single measurement of alkalinity for primary sludge was 15.0 mg $CaCO_3$/l (stabilized at 7°C and 35 days). Alkalinity vs. detention time is shown in Figure 26.

The alkalinity of raw mixed primary-chemical sludge was reduced from its initial value at 230 mg $CaCO_3$/l to less than 40 mg $CaCO_3$/l. Values less than 10 mg $CaCO_3$/l were not uncommon. These low values of alkalinity indicate that a complete loss of alkalinity might have happened at times in the reactors treating mixed primary-chemical sludge with 25 to 35 days' detention time. This is probably the reason for the wide fluctuations in the pH values.

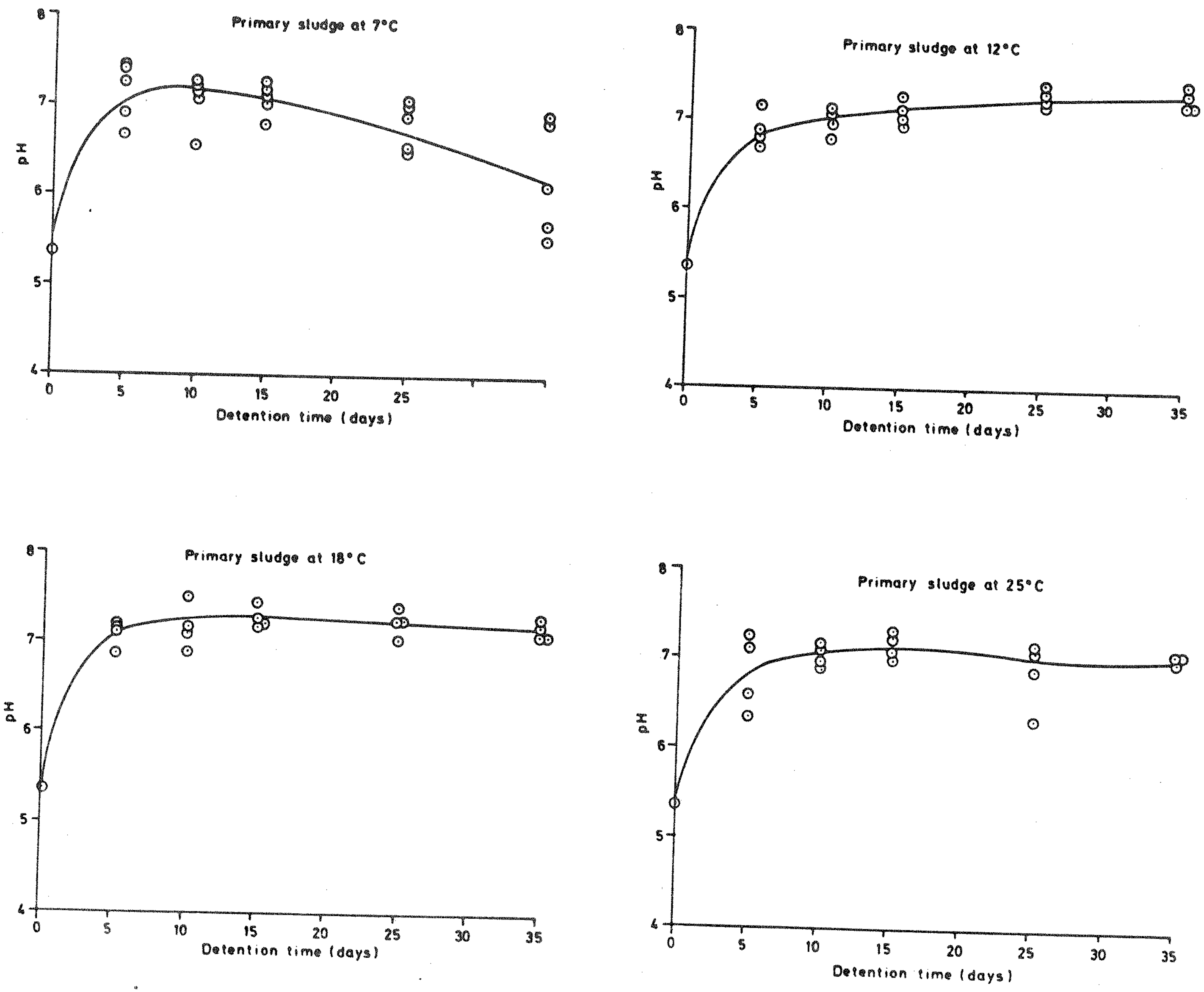


Figure 24. pH vs. Detention Time - Primary Sludge.

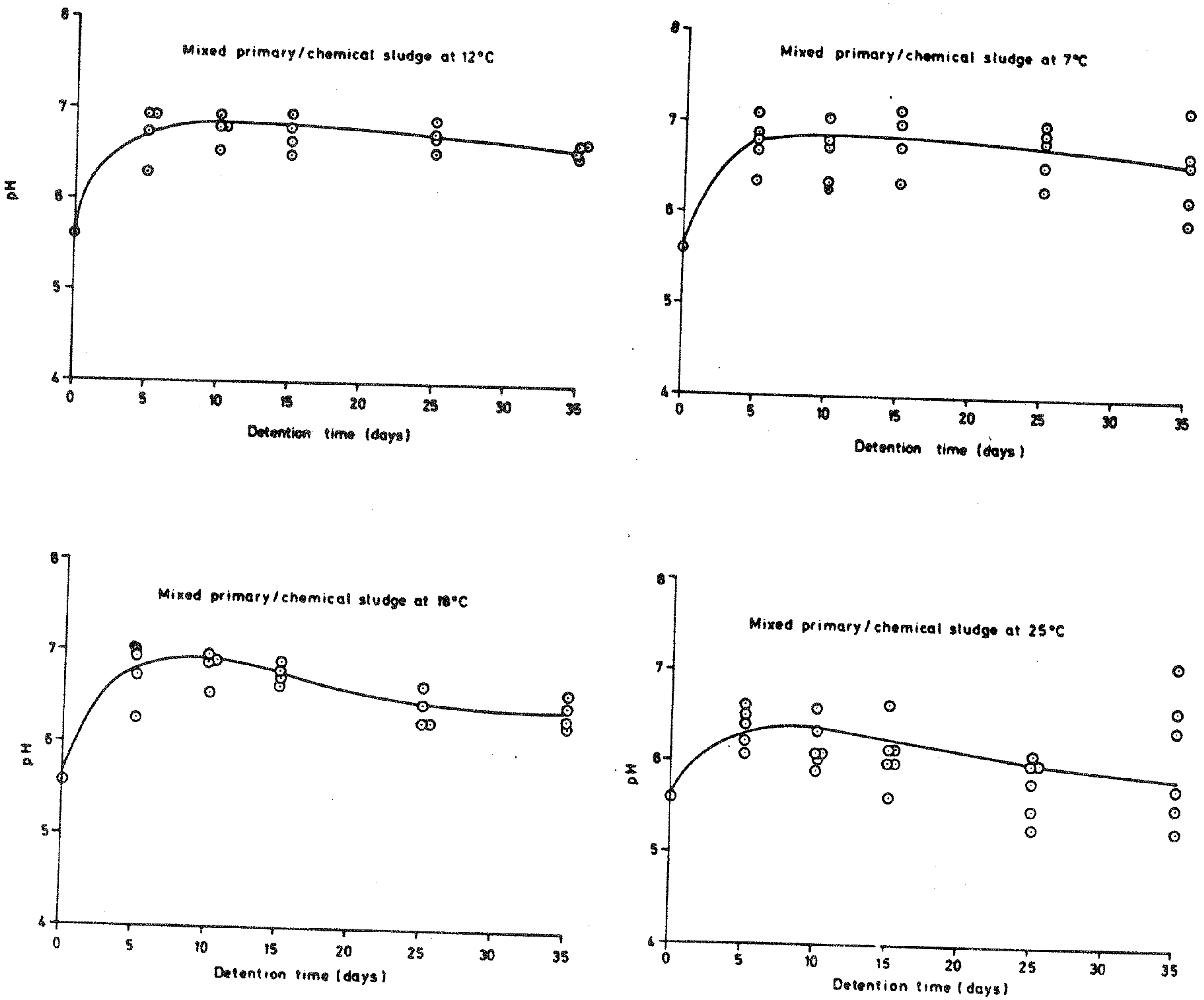


Figure 25. pH vs. Detention Time - Mixed Primary-Chemical Sludge.

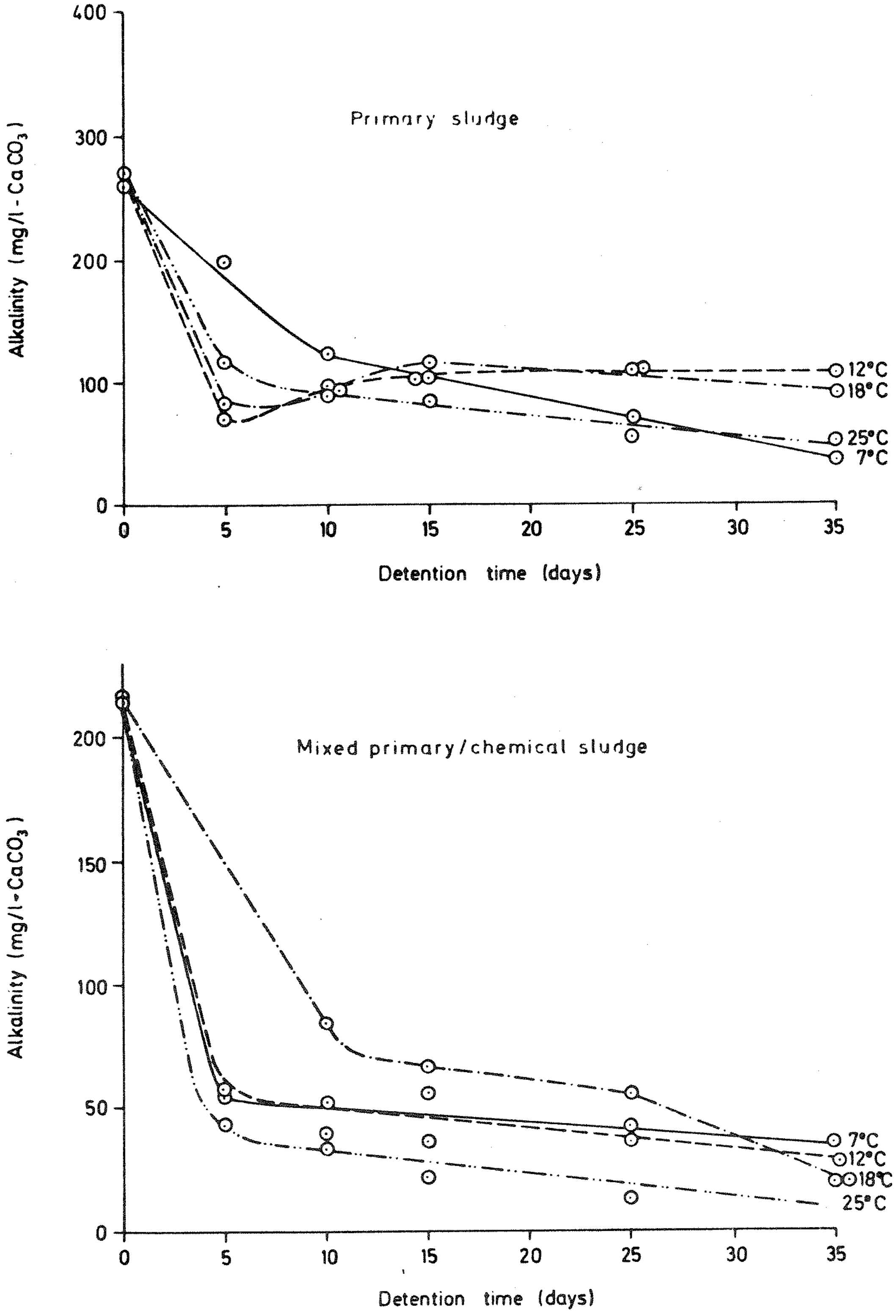


Figure 26. Alkalinity vs. Detention Time.

Change in Forms of Nitrogen During Aerobic Stabilization

The untreated sludge contains nitrogen in the form of ammonium and organic nitrogen. Table 6 gives the average values of the nitrogen forms for the two types of sludges investigated.

	Kjeldahl-N x) mg/l	NH_4-N xx) mg/l	(NO_2+NO_3)-N x) mg/l
Primary sludge	623	64.8	0.02
Mixed Primary-Chemical sludge	533	43.5	0.02

x) Average values of 22 samples

xx) Average values of 6 samples

Table 6. FORMS OF NITROGEN IN RAW SLUDGE.

A large portion of the nitrogen (approximately 90%) entering each reactor is in the form of organic nitrogen and the rest is in the form of ammonium. No nitrite and nitrate were found.

Several biological processes that change the nitrogen forms will take place simultaneously during the aerobic digestion process. First of all, ammonification will liberate ammonia from organic material. Liberated ammonia, which is the most reduced form of nitrogen, then serves as the starting point for nitrification. The pathways for oxidation of ammonia to nitrite (NO_2) and then nitrate (NO_3) have been discussed in the literature review.

Figure 27 shows a reduction in Kjeldahl-nitrogen with increasing detention times. In other words, nitrogen is lost from the system during the process. Table 7 gives the percent reductions in Kjeldahl-N for primary sludge and mixed primary-chemical sludge stabilized at 18°C.

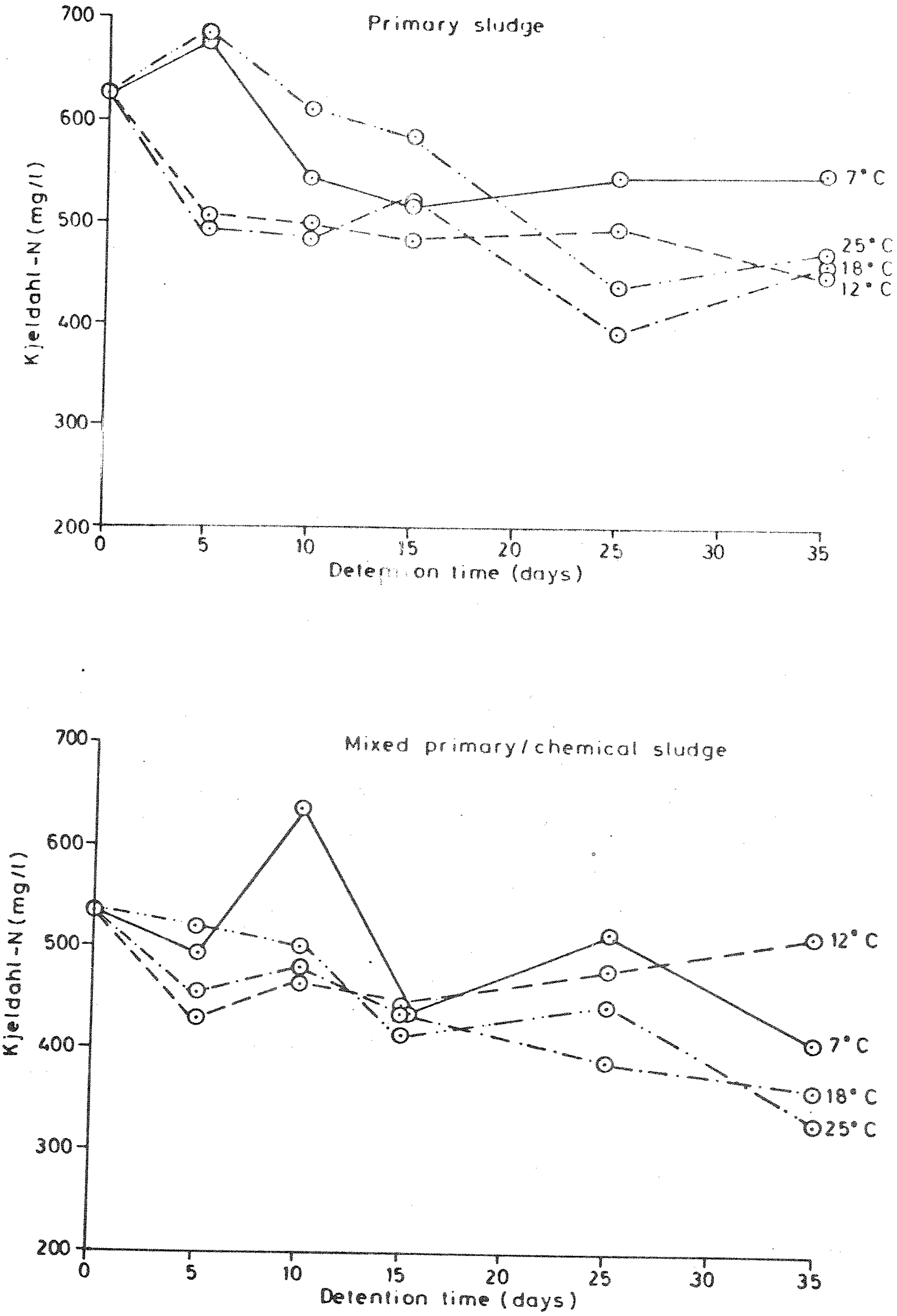
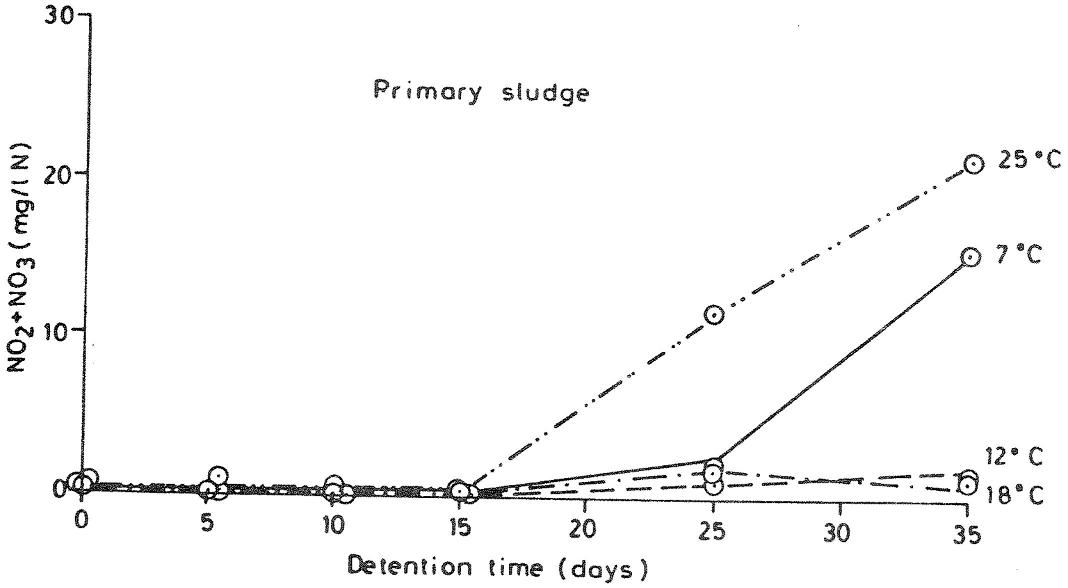


Figure 27. Kjeldahl-Nitrogen vs. Detention Time in Aerobic Digester.



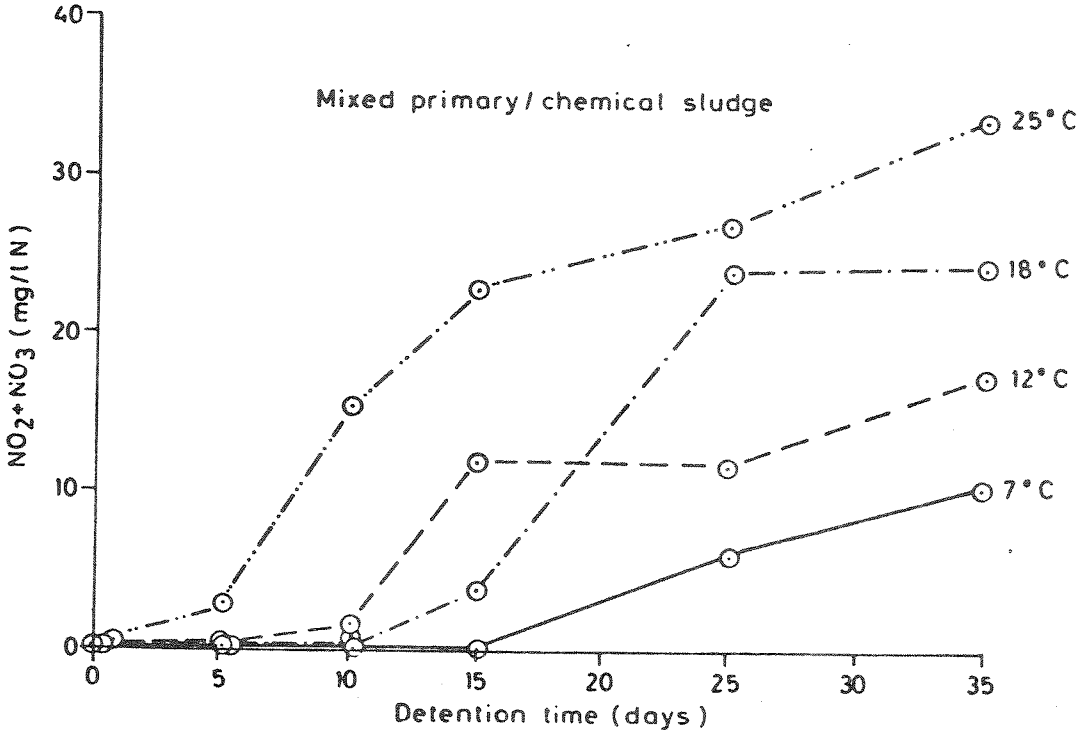


Figure 28. NO_2+NO_3-Nitrogen vs. Detention Time in Aerobic Digester.

Sludge	Detention Time (days)				
	5	10	15	25	35
Primary (%)	20	22	16	37	26
Mixed Prim.-chem.(%)	15	10	19	27	32

Table 7. Reductions of Kjeldahl-N During Aerobic Digestion at 18°C

Similar reductions were found at other temperatures although the affect of temperature on Kjeldahl-N removal is not evident. Experiments with primary sludge indicate a high removal of Kjeldahl-N at 18°C and 25°C for detention times in excess of 15 days. For shorter detention times, primary sludge stabilized at 12°C and 18°C had the highest reduction.

Two possibilities for nitrogen reduction exist: loss of ammonia gas or loss of nitrogen gas. Loss of ammonia gas is most probably negligible at the pH range under which these reactors operate. This is also proven by Irgens et al. (1965). Nitrification with subsequent denitrification is the most logical explanation for the loss of nitrogen. Figure 28 shows the concentration of $(NO_2 + NO_3)$-N at different detention times and temperatures. For primary sludge no $(NO_2 + NO_3)$-N was found at detention times less than 15 days. This was not the case with mixed primary-chemical sludge, although low concentrations of $(NO_2 + NO_3)$-N were associated with low detention times. Nitrification, therefore, was taking place in most of the reactors regardless of the temperature. Nitrogen loss at short detention times, especially for primary sludge, suggested that $(NO_2 + NO_3)$-N was produced even at detention times less than 15 days, but it was reduced to nitrogen gas as soon as it was formed. Anaerobic zones towards the center of the sludge flocs would stimulate denitrification and thus account for the nitrogen loss at short detention times.

These units would normally also have the lowest dissolved oxygen concentration due to their higher organic loadings. As the detention time increases, the production of NO_2 and NO_3 would surpass the loss due to denitrification and thus increase.

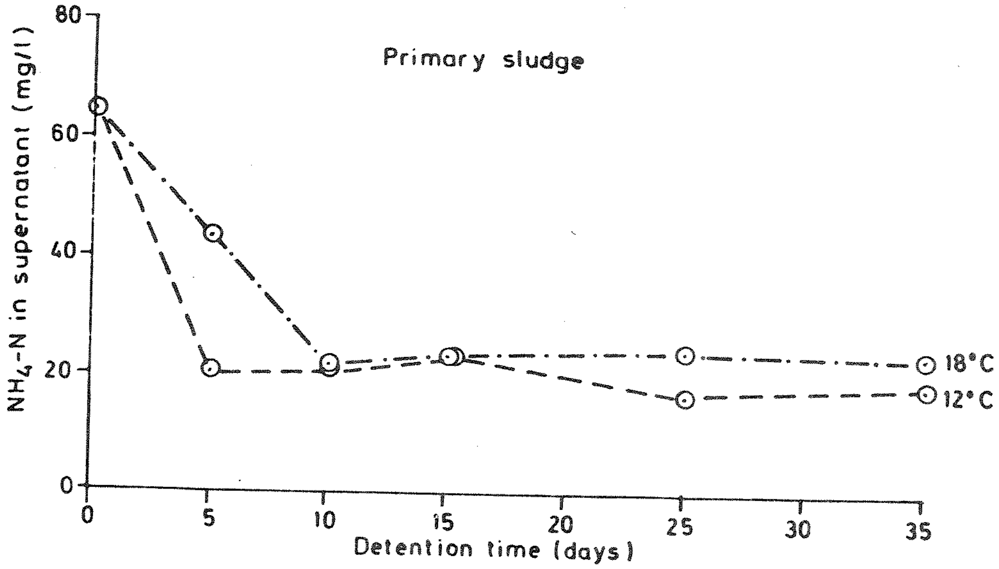
The ammonium concentration would normally decrease rapidly at low detention times and then stay fairly constant at 15 - 25 mg/l NH_4-N. This indicates the rate of ammonification does not limit the nitrification step (See Figure 29).

Figure 30 indicates the nitrogen content as a percentage of volatile suspended solids (gN/gVSS) in the primary sludge will increase with increasing detention time in spite of the fact that the Kjeldahl-N, measured as mg/l-N is reduced. The reason for this is the volatile suspended solids concentration will decrease more than the nitrogen content. The temperature at which the sludge is stabilized, will also influence the nitrogen content of the sludge. At 25°C the nitrogen would increase from 5.1 to 7.2 per cent while at 7°C and 12°C the nitrogen would increase from approximately 3 to 4 per cent.

Mixed primary-chemical sludge stabilized at 12°C and 18°C had an increase in nitrogen content similar to that found for primary sludge. Results obtained at 7°C and 25°C for mixed primary-chemical sludge would tend to fluctuate much more than for the other series. At 25°C there was even a slight decrease in nitrogen content with increasing detention time.

Change in Oxygen-Uptake Rate and ATP During Aerobic Stabilization

The oxygen-uptake rate was measured for both types of sludge at all four temperatures investigated. The result is shown in Figure 31. The oxygen-uptake rate would normally decrease with increasing detention time and decreasing reactor temperature. Primary sludge stabilized at 12°C and 18°C did not indicate a decrease with increasing detention time, but remained fairly constant. At 18°C there was even a slight increase in oxygen-uptake rate with



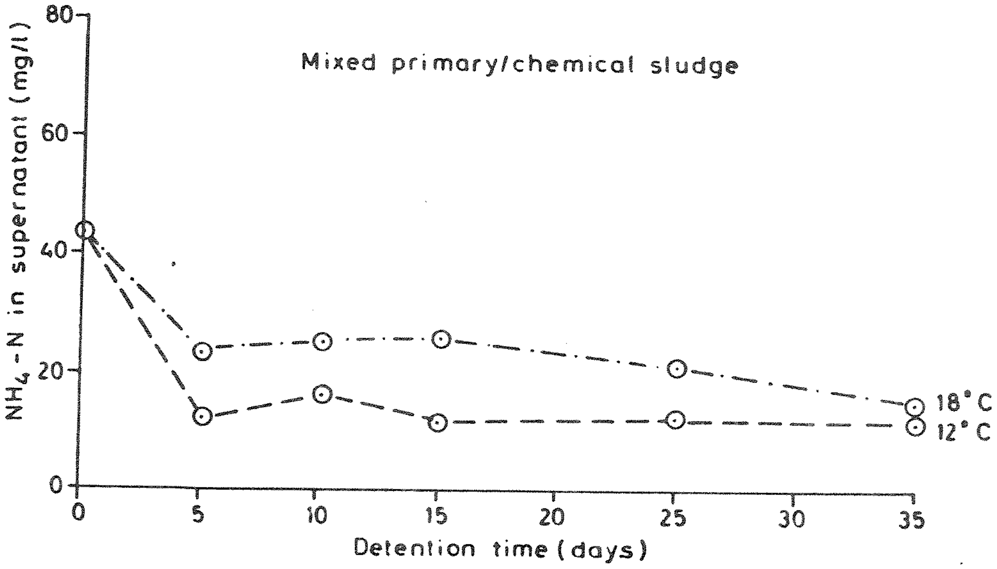


Figure 29. NH$_4$-Nitrogen vs. Detention Time in Aerobic Digester.

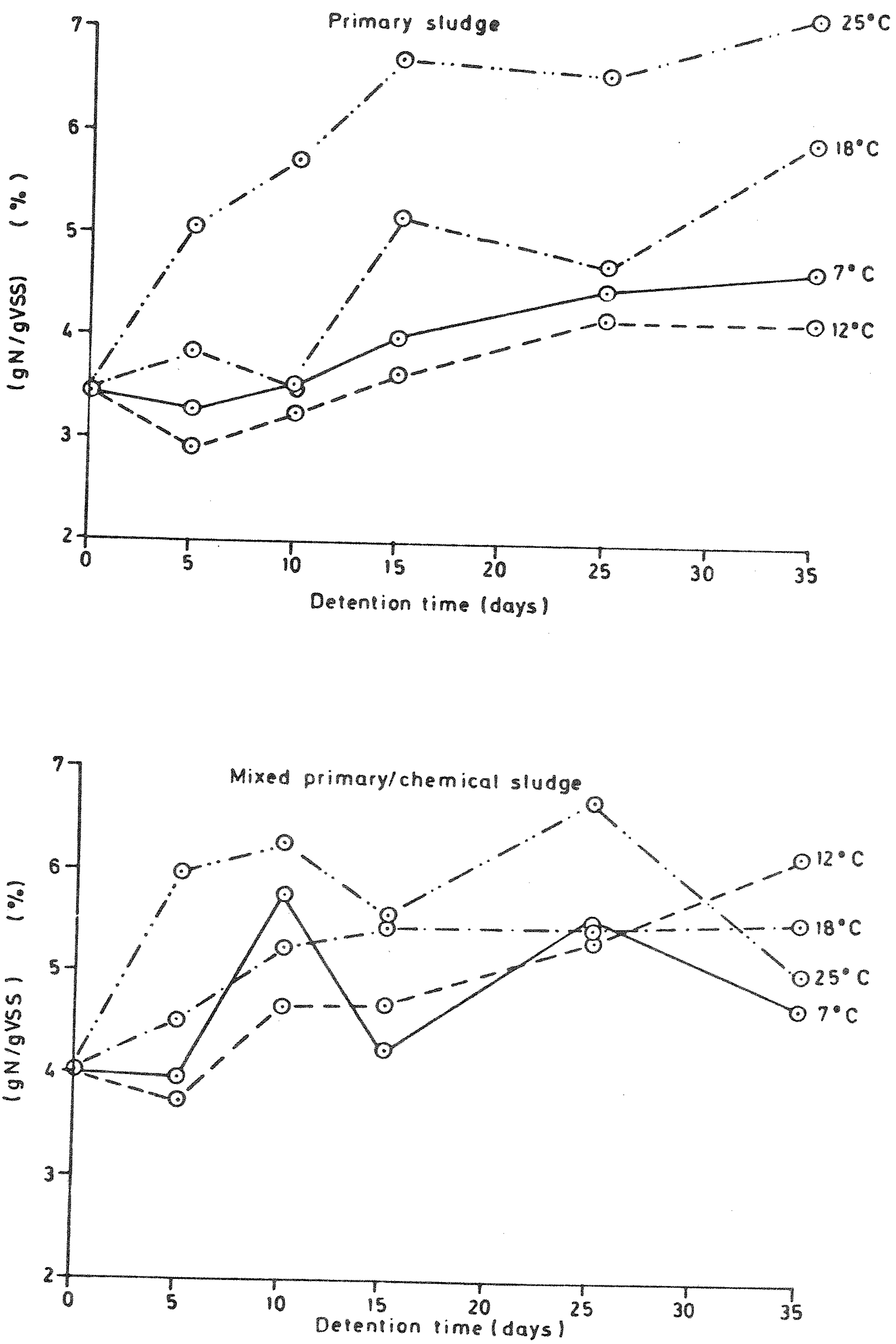
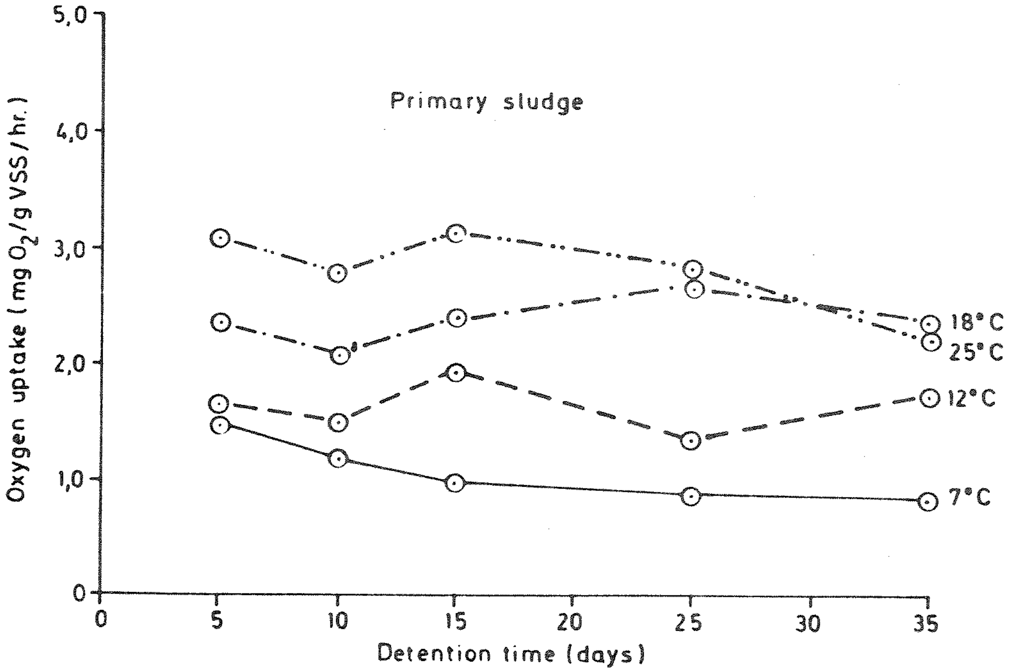


Figure 30. Nitrogen Content in Sludge Solids vs. Detention Time in Aerobic Digester.

increasing detention time. However, the oxygen-uptake rate for primary sludge was more influenced by temperature than the detention time in the reactor. Primary sludge stabilized at 25°C had an oxygen-uptake rate of 3 mg O_2/g VSS•h while the same sludge stabilized at 7°C had an oxygen-uptake rate of approximately 1.0 mg O_2/g VSS•h. This was expected since the rate of reduction of VSS at 7°C is much lower than at 25°C.

The oxygen-uptake rate for mixed primary-chemical sludge stabilized at 25°C and 18°C seemed to vary inversely with detention time in the reactor. The oxygen-uptake rate for the same sludge stabilized at 7°C and 12°C remained fairly constant with increasing detention time. The lowest oxygen-uptake rate was experienced at 7°C. It is of interest to note that for mixed primary-chemical sludge the oxygen-uptake rate at 18°C was higher than at 25°C in spite of the fact that a higher reduction of VSS was found at 25°C. Several factors influencing the oxygen-uptake rate in a culture might account for this. First, the degree of agitation in the testing vessel, in this case a 200 ml BOD bottle, will definitely influence oxygen-uptake by the microorganisms. Since the same testing vessel with the same stirrer was used throughout the test period, this could not account for the difference. Nitrification requires oxygen and therefore it will increase the oxygen consumption in the heterogeneous culture. However, evidence of nitrification was found at both 18°C and 25°C. No higher degree of nitrification at 18°C could be proven.

Another possible explanation for the higher oxygen-uptake rate at 18°C than at 25°C is the difference in the predominance of species in the heterogeneous populations at these two temperatures. Through microscopic examinations, highly mobile protozoa were found in large numbers at 18°C, and although they were observed at 25°C, they were not nearly as abundant as at 18°C. A predator-prey relationship between the bacteria and the protozoa will exist in the reactors and the bacteria will be metabolized by the protozoa.



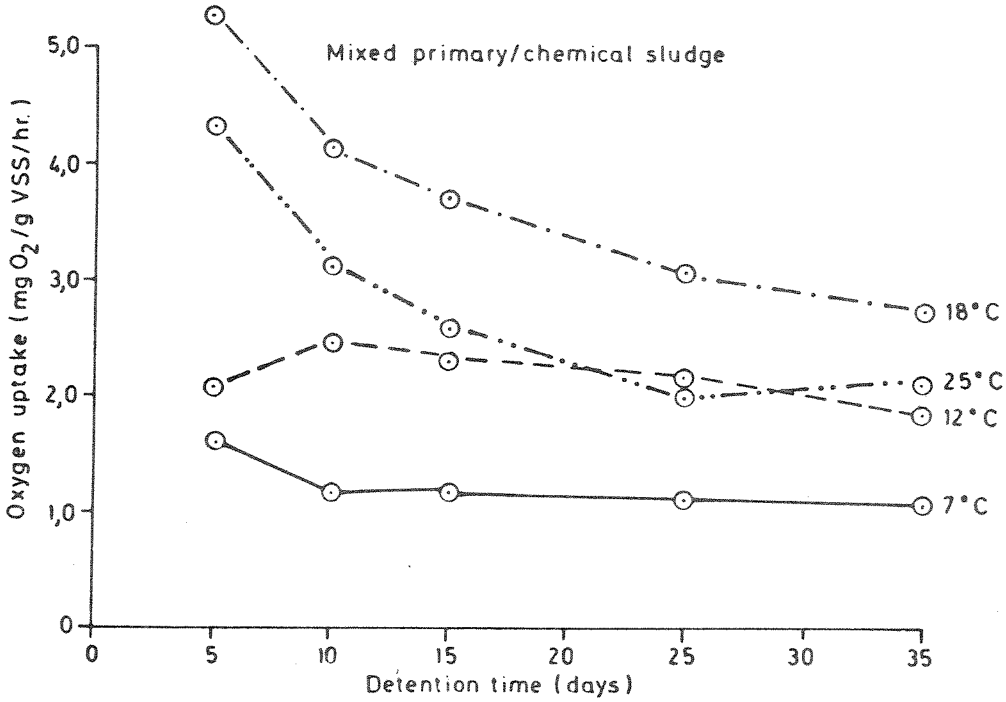


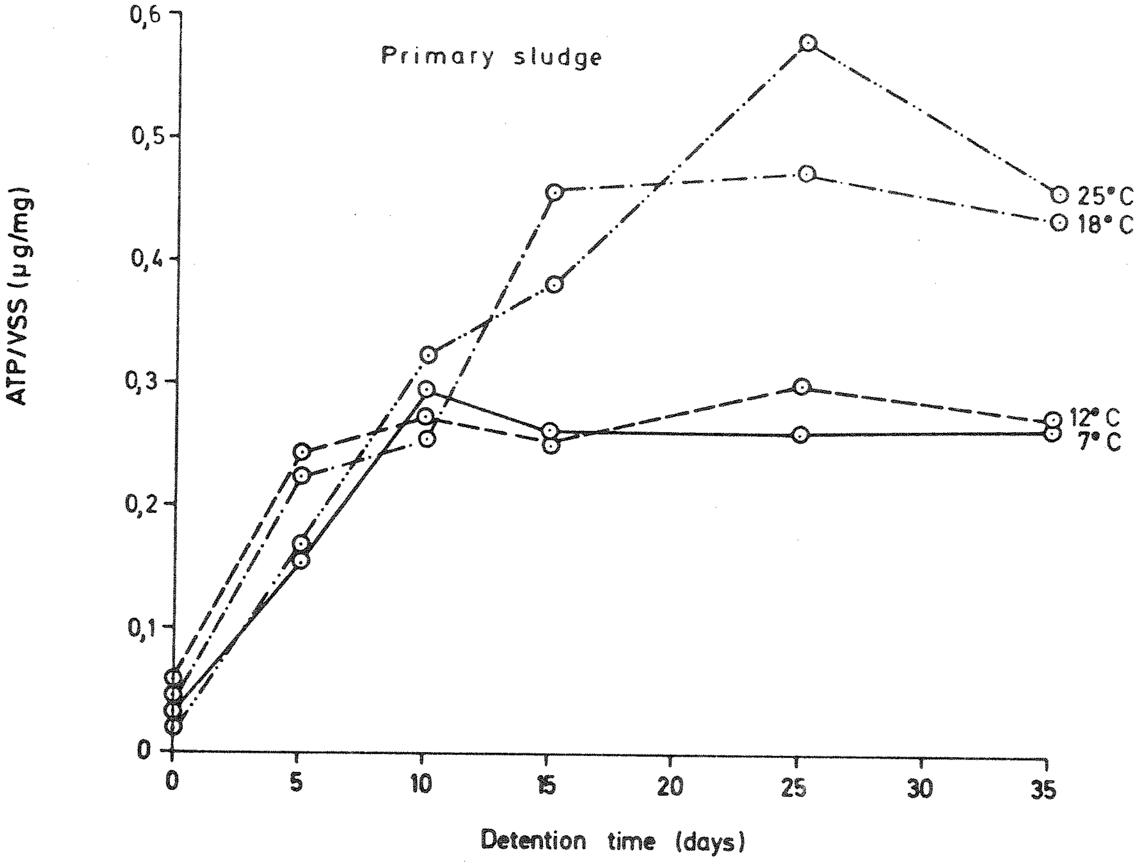
Figure 31. Oxygen-uptake Rate vs. Detention Time.

The increase in the oxygen-uptake rate, then, can be ascribed to either the increased bacterial multiplication stimulated by predator activity or to the respiration of the protozoa feeding on the bacterial population. Work by Bhatla et al. (1965) indicates the latter possibility to be the most likely reason for the high oxygen-uptake rate at 18°C.

The potential of ATP measurements for providing valid approximations of fluctuations in living microbial biomass has been discussed in the literature review. ATP content for both types of sludge and at all four temperatures were measured. However, the values obtained for mixed primary-chemical sludge at 7°C and 25°C were approximately one-tenth of the values obtained at 12°C and 18°C and also for primary sludge at 7°, 12°, 18° and 25°C. No valid explanation for this can be given. The result from these two test series have been discarded.

ATP content in the mixed liquor and ATP per unit of volatile suspended solids for primary sludge are shown in Figures 32 and 33. Since ATP is not found in dead cells nor associated with any nonliving material, Figure 32 indicates that the viable portion of the volatile suspended solids increased from approximately 0.05 µg ATP/mg VSS in the raw primary sludge to a maximum value of 0.27 to 0.57 µg ATP/mg VSS. This maximum value largely depended on the reactor temperature. Higher temperatures yielded higher values of ATP per unit VSS. In other words, a larger portion will be viable biomass. At 25°C and 18°C a reduction in ATP per unit VSS was found for extremely high detention times (35 days), while it stayed fairly constant with detention times in excess of 10 days at 7°C and 12°C.

To relate ATP to microbial biomass, it is necessary to know the approximate ATP concentration per cell of the species present. This determination was outside the scope of this research project, but it is of interest to compare our data with that determined by Patterson et al. (1970). He found ATP values



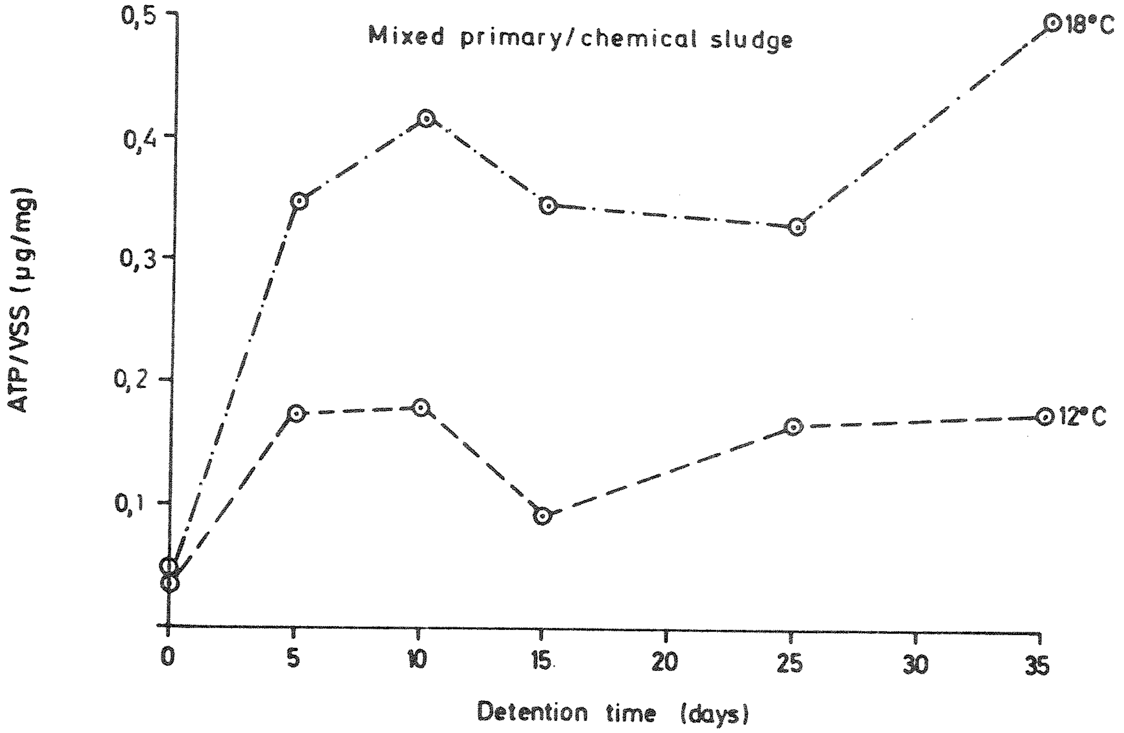
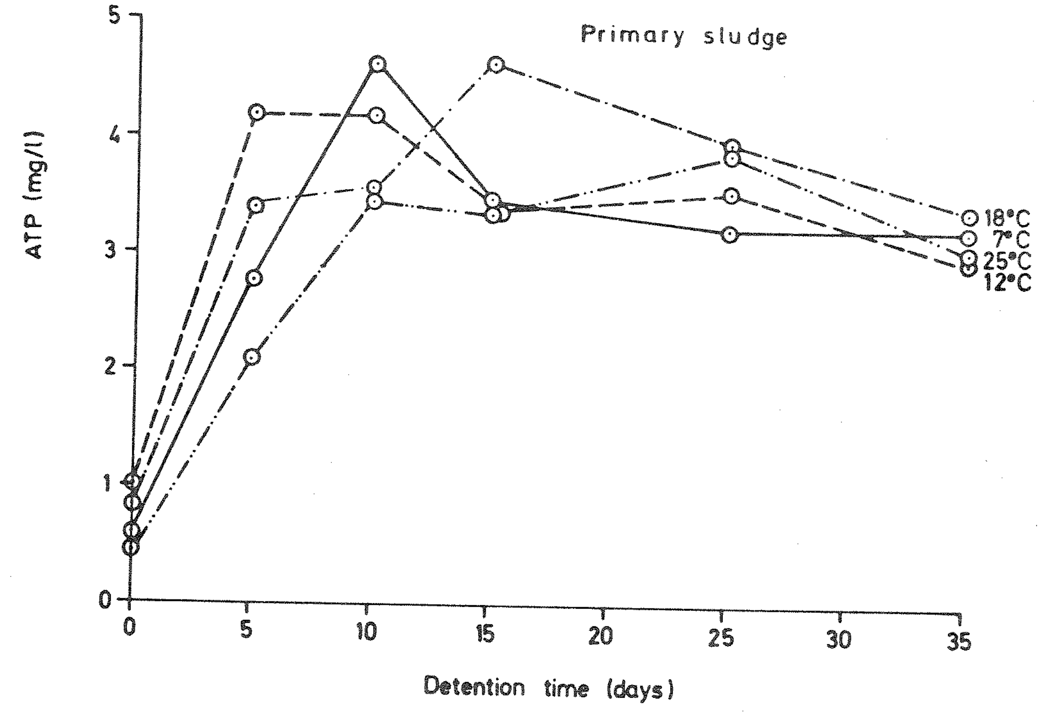


Figure 32. ATP/VSS vs. Detention Time.



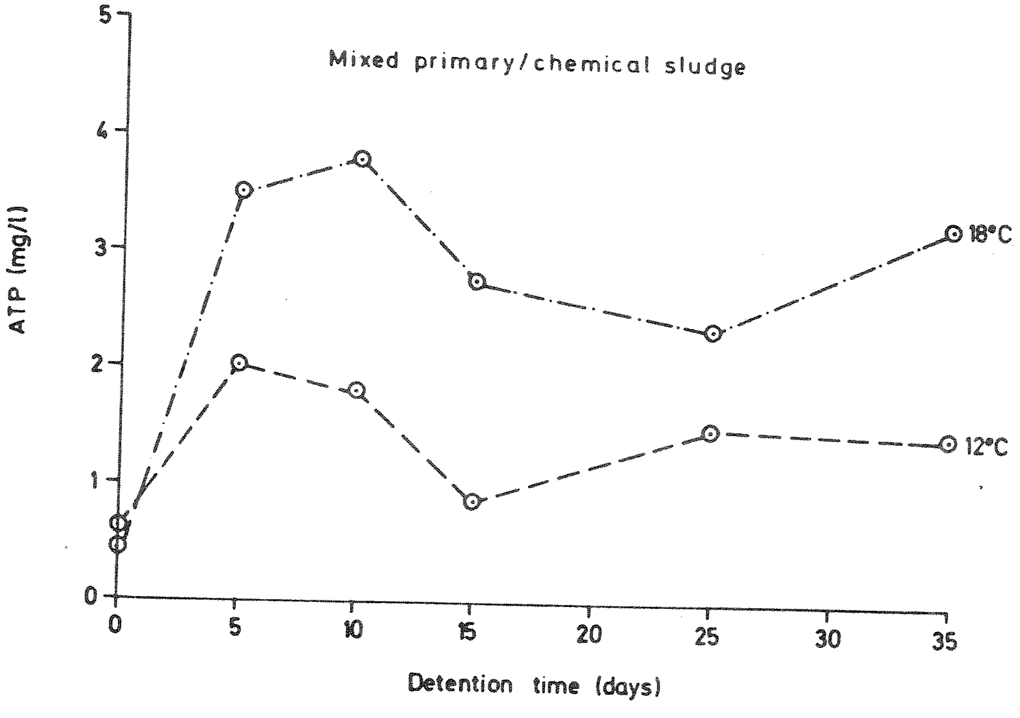


Figure 33. ATP vs. Detention Time.

of 1.4 to 2.0 μg/mg VSS for activated sludge which is 3-10 times that obtained during aerobic stabilization of primary sludge. Again this indicates a very low content of active biomass in the volatile suspended solids during aerobic digestion.

Data obtained for mixed primary-chemical sludge also are shown in Figures 32 and 33. An increase in ATP per unit volatile suspended solids up to a maximum value at 10 days was found at both 12°C and 18°C. The total value of ATP (mg/l) and the ATP/VSS decreased between 10 and 15-25 days. Beyond 25 days a slight increase appeared, especially at 18°C. Further investigations must be conducted in order to learn if this second increase is reproducable or caused by analytical errors.

Sedimentation, Drainage and Filtration Properties of Stabilized Sludge

Sedimentation Properties:

A distinct interface was formed for both types of sludge and at all temperatures and detention times investigated. The position of the sludge-liquid interface was recorded after 30 minutes and then after each hour for a total test period of 6 or 7 hours.

Figures 34 and 35 show the sedimentation curves for primary sludge and mixed primary-chemical sludge respectively at different detention times in the reactor. The velocity of interface vs. detention time in each reactor is shown in Figure 36. This velocity equals the slope of the initial straight line portion of the settling curve. The following conclusions can be made from these tests:

1. An increase in the reactor temperature increased the interface velocity for both types of sludge investigated. However, the difference between the interface velocity at the high temperature (25°C) and the low temperature (7°C) was more severe for primary sludge than for mixed primary-

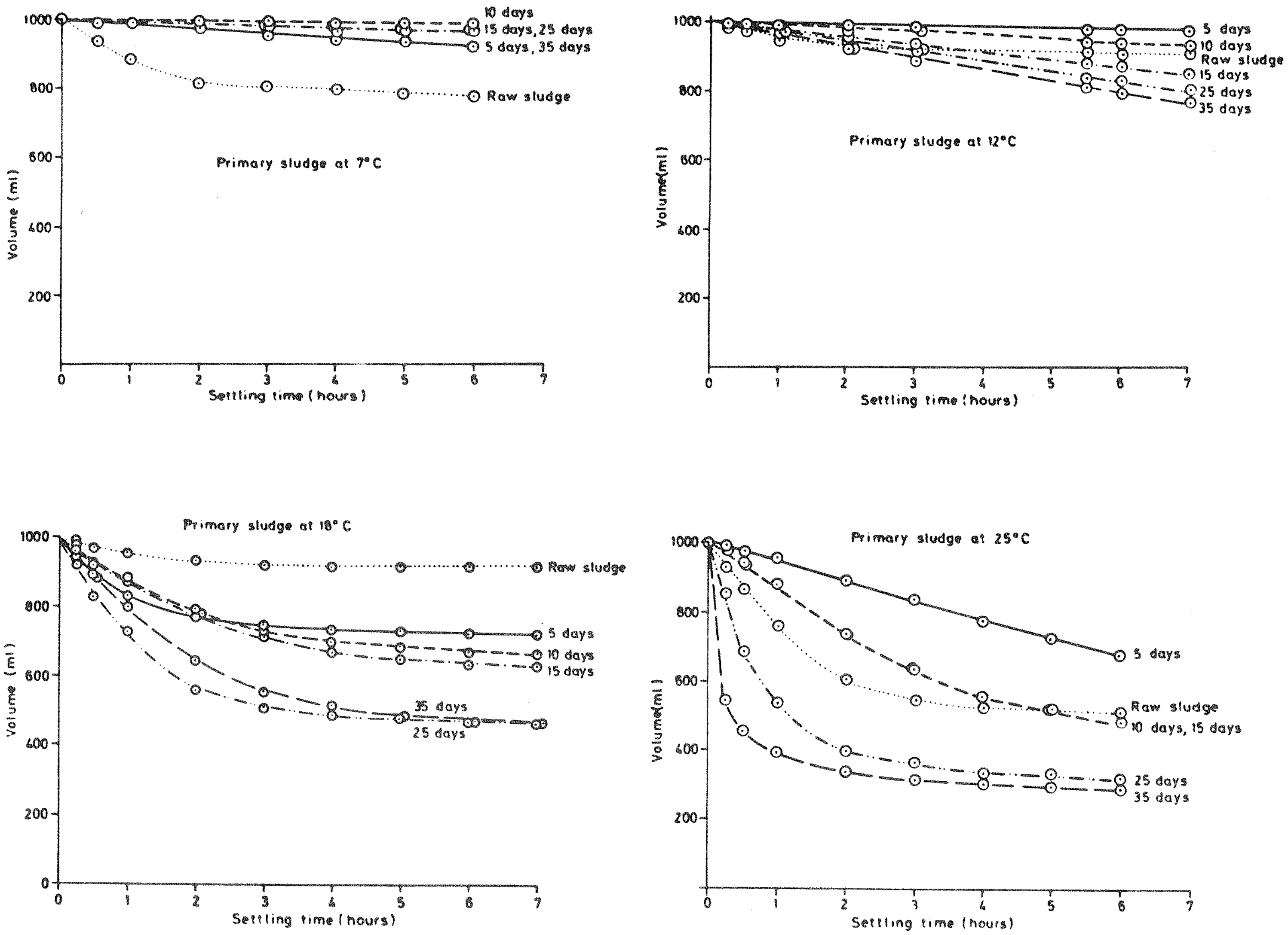


Figure 34. Settling Curves - Primary Sludge.

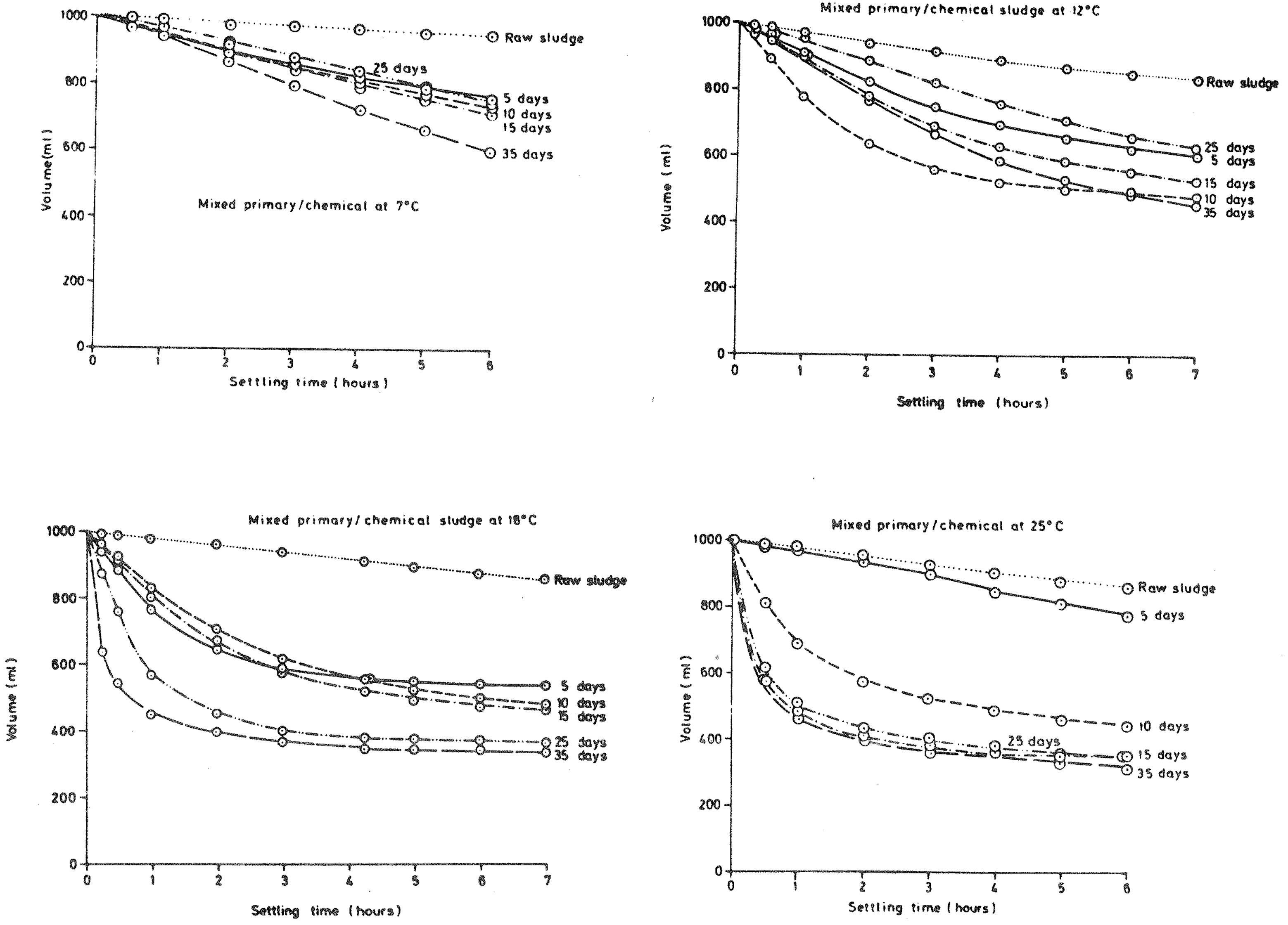


Figure 35. Settling Curves - Mixed Primary-Chemical Sludge.

chemical sludge.

2. If the detention time in the reactor was increased, the interface velocity also increased if the temperature was 18°C or above. At the low temperatures investigated (7°C and 12°C), the primary sludge showed an initial decrease in sedimentation properties up to 5-10 days and then a gradual increase for longer detention times up to 35 days. The same was not true for mixed primary-chemical sludge, although a slight decrease in interface velocity was experienced during the 12°C series between 10 and 25 days detention time.

The sludge volume index (SVI) was calculated (see Figure 37) for both primary sludge and mixed primary-chemical sludge. The author of this dissertation is well aware of the fallacies in using SVI to predict sedimentation properties for sludges. However, several researchers (Bokil et al., 1970, Rüffer, 1966) have applied this parameter for this purpose and it is felt that a brief discussion of this parameter is well within the scope of this research.

The sludge-volume index for primary sludge stabilized at 7°C, 12°C and 18°C increased with increasing detention time. This was also the case with mixed primary-chemical sludge at 7°C and 12°C. This would indicate, then, a reduction in sedimentation properties with an increase in detention time, quite contrary to the conclusion drawn from Figures 34 through 36. The SVI values calculated for primary sludge at 25°C and mixed primary-chemical sludge at 18°C and 25°C seemed to increase to a maximum value and then decrease to a minimum value. Conclusions from these SVI values would also be in disagreement with those conclusions based on the complete sedimentation curves. The author strongly feels that the sludge volume index is not indicative of the sedimentation properties of sludges.

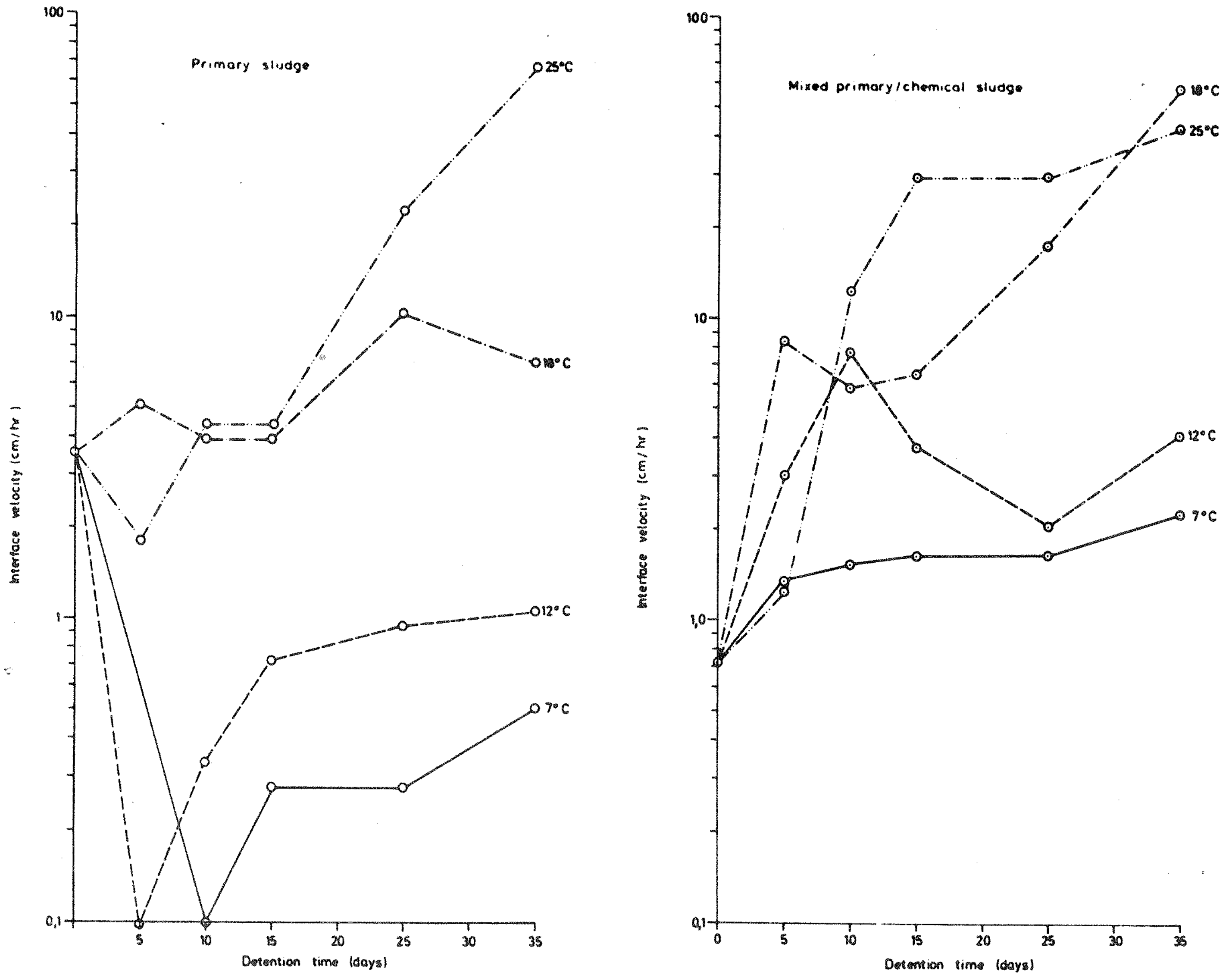


Figure 36. Velocity of Interface vs. Detention Time in Aerobic Digester.

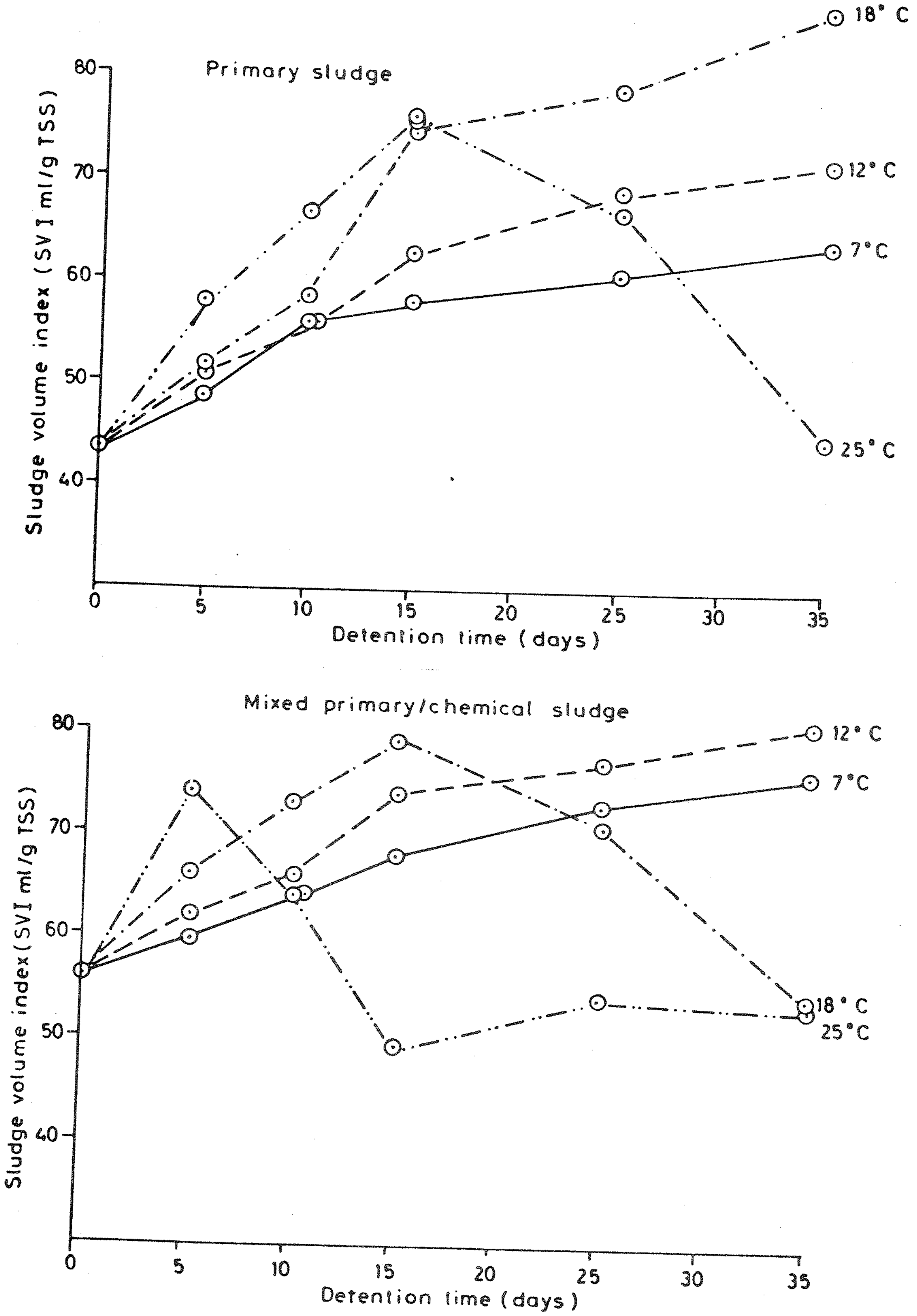


Figure 37. Sludge Volume Index (SVI) vs. Detention Time in Aerobic Digester.

Change in Drainage Properties during Aerobic Stabilization

The changes in the quantity and quality of the water drained from sludges were investigated. The analytical method used is outline in Analytical Procedures. Figure 38 shows that the per cent drained water volume increased with the number of days of aeration. This is the case for both types of sludge investigated. Untreated primary sludge had poorer drainage properties than untreated mixed primary-chemical sludge. This was expected since chemical sludge (Al) will condition the sludge mixture. The total water volume drained from the sludge generally showed an increase with stabilization temperature. This effect was more noticeable for primary sludge than for mixed primary-chemical sludge.

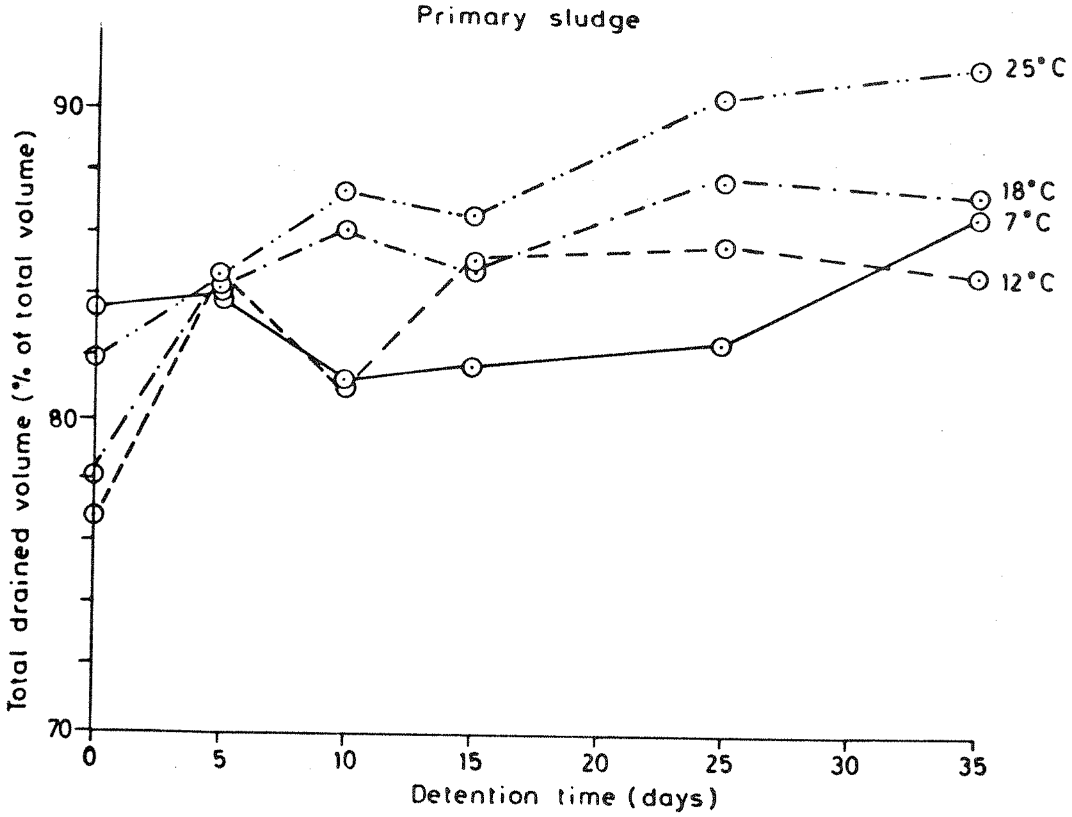
In most cases, between 85 per cent and 90 per cent of the water in the sludge was removed by drainage. Table 8 below lists the calculated total suspended solids concentrations (TSS) obtained in the sludge cake for different reactor temperatures and detention times. Values given for the 7°C and 25°C series are the average values obtained for two individual series. The solids concentration was calculated by using the equation:

$$\%\text{TSS (in sludge cake)} = \frac{100 \cdot A}{(100 - B)} \tag{13}$$

A = TSS(%) in the sludge before drainage

B = Drained water volume in % of total volume

Data given in Table 8 indicate that the final solids concentration in the cake is nearly independent of both the reactor temperature and the degree of stabilization. This might seem a contradiction to the previous statement that the per cent of drained-water volume of the total initial water volume will increase with increasing detention time. However, it must be realized that as the detention time increases in the reactor, the suspended solids concentration



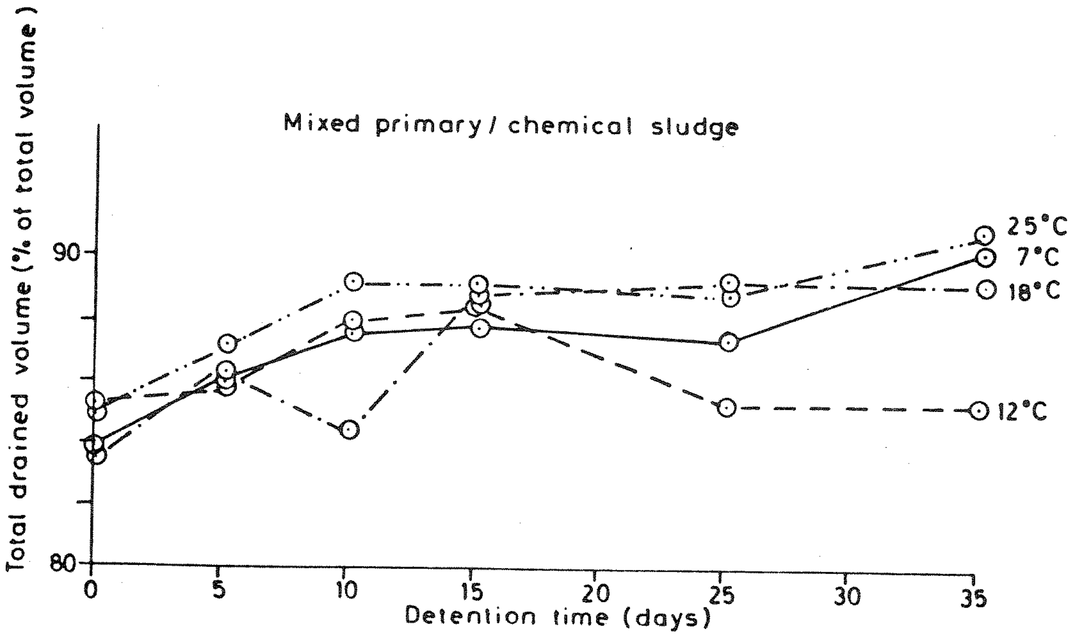


Figure 38. Per cent Drained Water Volume vs. Detention Time.

will decrease. In other words, a larger percentage of water must be removed from a dilute sludge than from a less dilute sludge in order to end up with the same solids concentration in the sludge cake.

Detention Time (days)	Primary Sludge				Mixed Prim/Chem Sludge			
	7°C	12°C	18°C	25°C	7°C	12°C	18°C	25°C
0	12.6	8.9	9.4	10.6	11.0	11.8	10.7	10.4
5	12.6	12.8	10.8	10.1	11.6	10.7	9.8	10.9
10	9.7	9.4	11.5	12.1	12.0	11.1	8.2	14.4
15	9.5	10.6	8.1	8.7	11.7	11.1	10.4	11.1
25	9.7	10.0	8.6	10.3	11.2	8.5	9.8	9.3
35	11.7	8.9	8.0	12.4	13.1	8.0	9.3	12.7

Table 8. PER CENT SOLIDS IN SLUDGE CAKE

The per cent drained-water volume that has been mentioned in this discussion is based on the maximum amount of water that will be released from the sample during the drainage test. The rate at which the water is released will vary with both the process temperature and sludge stability (number of days aerated). As an example, Figure 39 illustrates the drained volume (ml) vs. drainage time (days) for both types of sludges stabilized at 7°C. Sludges stabilized in 15 days and 25 days released their water quite slowly. Sludges with shorter detention times in the reactor released the water at a much faster rate. Sludge aerated for 25 days gave off some water even after 8 days of drainage. Similar curves for 12°C, 18°C and 25°C indicate that the drainage rate will be affected by days of aeration (detention time in reactor), but the influence is insignificant from a practical point of view.

Drained water from a drying bed normally will be returned to the

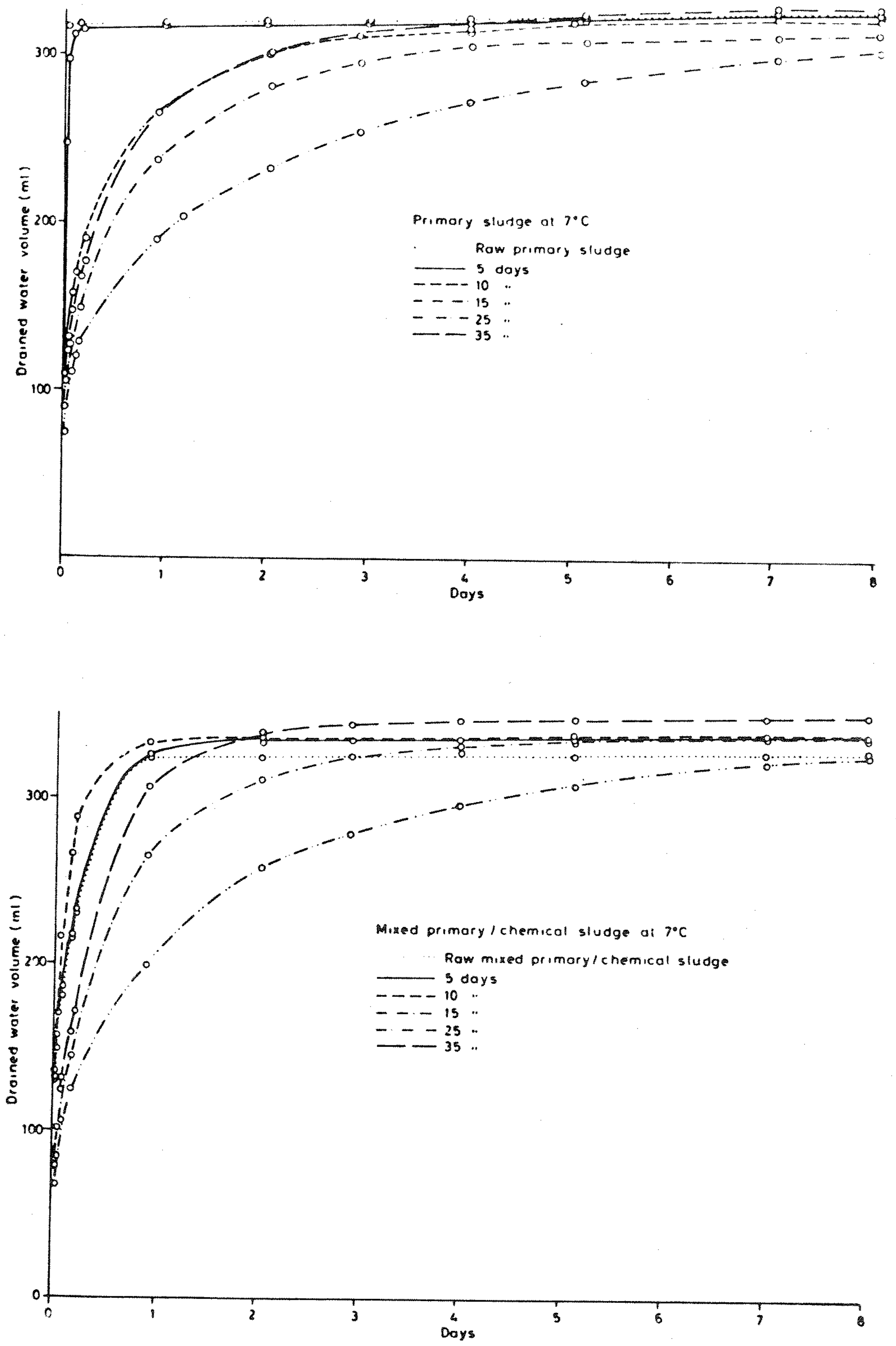


Figure 39. Drained Water Volume vs. Drainage Period.

treatment plant inlet. It is therefore of interest to know not only the quantity of filtrate, but also the quality. Tables 9 and 10 show the COD, BOD_7, orthophosphate, and turbidity values for the filtrate from sludges at different detention times in the reactor. Figure 40 shows a plot of BOD_7 vs. detention time from the first series. It is evident that the quality of filtrate increases with an increase in detention time. Both COD, BOD_7, orthophosphate, and turbidity showed a sharp drop between 0 and 5 days detention time and then a more moderate reduction with detention times in excess of 5 days. Orthophosphate values for mixed primary-chemical sludge at 25°C were exempted from the general conclusion given above.

Det. time (days)	Temp. °C	COD mg/l		BOD_7 mg/l		PO_4-P mg/l		Turbidity JTU	
		1 series	2 series	1 series	2 series	1 series	2 series	1 series	2 series
0	25	1362	1879	470	830	19.00	36.00	324	227
5	25	125	293	10	42	2.10	3.80	15	34
10	25	144	257	13	14	1.30	1.40	14	17
15	25	196	182	9	9	0.18	3.00	16	7
25	25	144	170	0	13	0.07	2.90	7	6
35	25	175	165	12	4	0.30	2.90	9	4
0	7	1735	1800	1365	1350	35.00	32.00	340	460
5	7	430	642	110	135	0.90	11.00	67	88
10	7	304	553	46	220	0.13	0.50	32	33
15	7	290	382	25	155	0.13	0.05	33	37
25	7	309	308	65	54	0.05	0.04	29	22
35	7	310	260	26	24	0.18	1.30	51	34

Table 9. QUALITY OF FILTRATE - PRIMARY SLUDGE.

Det. time(days)	Temp. °C	COD mg/l		BOD$_7$ mg/l		PO$_4$-P mg/l		Turbidity JTU	
		1 series	2 series	1 series	2 series	1 series	2 series	1 series	2 series
0	25	468	693	350	646	0.09	0.18	22	25
5	25	161	132	23	17	0.50	0.33	25	16
10	25	69	94	6	10	0.27	0.09	15	7
15	25	74	106	5	8	0.34	0.14	17	8
25	25	61	54	3	6	0.43	0.12	16	6
35	25	70	47	8	4	0.60	0.04	23	4
0	7	809	817	630	700	2.40	0.25	88	40
5	7	306	347	44	67	2.80	0.70	81	32
10	7	120	189	16	16	0.41	0.33	17	18
15	7	-	72	17	-	0.17	0.04	17	3
25	7	115	49	18	-	0.06	0.09	14	3
35	7	85	39	17	-	0.13	0.04	14	2

Table 10. QUALITY OF FILTRATE - MIXED PRIMARY-CHEMICAL SLUDGE.

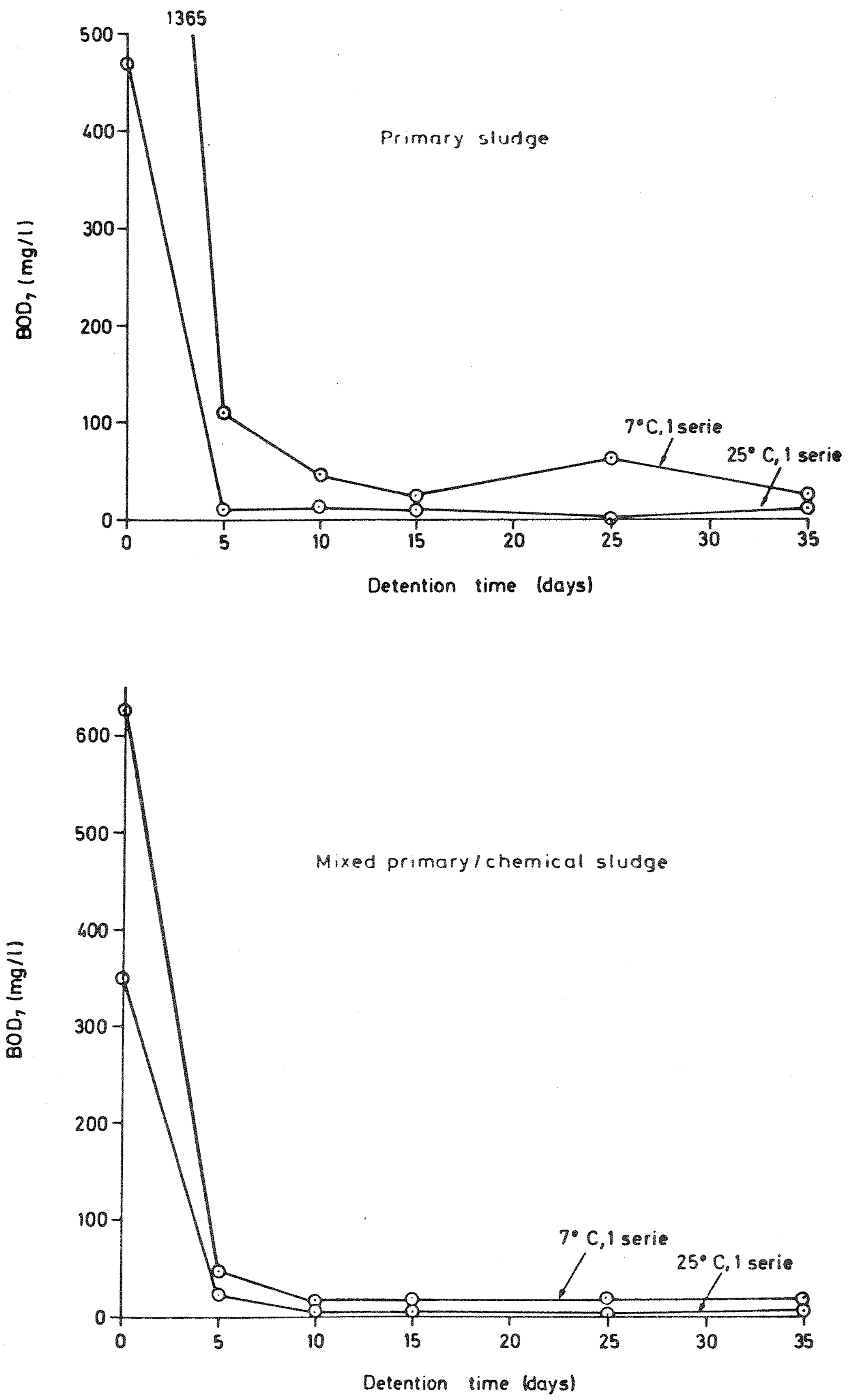


Figure 40. Biochemical Oxygen Demand of Filtrate vs. Detention Time in Aerobic Digester.

It appears from Tables 9 and 10 that the filtrate from sludges stabilized in excess of 5 days was so low in COD, BOD_7 and orthophosphate that it could be piped directly to the receiving water without being recycled to the treatment plant inlet.

Filtration Properties:

Two types of tests were used to measure the change in the filtration properties during aerobic stabilization. The specific resistance to filtration test as outlined under "Analytical Procedures" was used. In addition the capillary suction time (CST) was measured. The major reason for using these methods was to evaluate one method against the other under different conditions. This will be discussed later in this chapter.

The specific resistance to filtration (r) decreased with increasing detention time in the reactor treating primary sludge at 12°C and 18°C. For primary sludge stabilized at 7°C, a slight increase in specific resistance to filtration took place the first 5 days followed by a gradual decrease. The overall change of specific resistance to filtration at 7°C was insignificant. Primary sludge stabilized at 25°C showed a decrease in specific resistance to filtration, and then after 15 days' detention time it increased again. The increase in specific resistance to filtration after 15 days of aeration at 25°C is probably caused by an increase in the amount of "pin flocs" and fines. These have been studied in detail by Laubenberger et al. (1971). The fines have a tendency to clog the filter and hence increase the specific resistance to filtration. Figure 41 shows the specific resistance to filtration vs. detention time. It is also likely that the sludge contained an excess of biological polymers and that these acted as dispersants when present in an excess over the optimum dose.

Specific resistance to filtration for mixed primary-chemical sludge

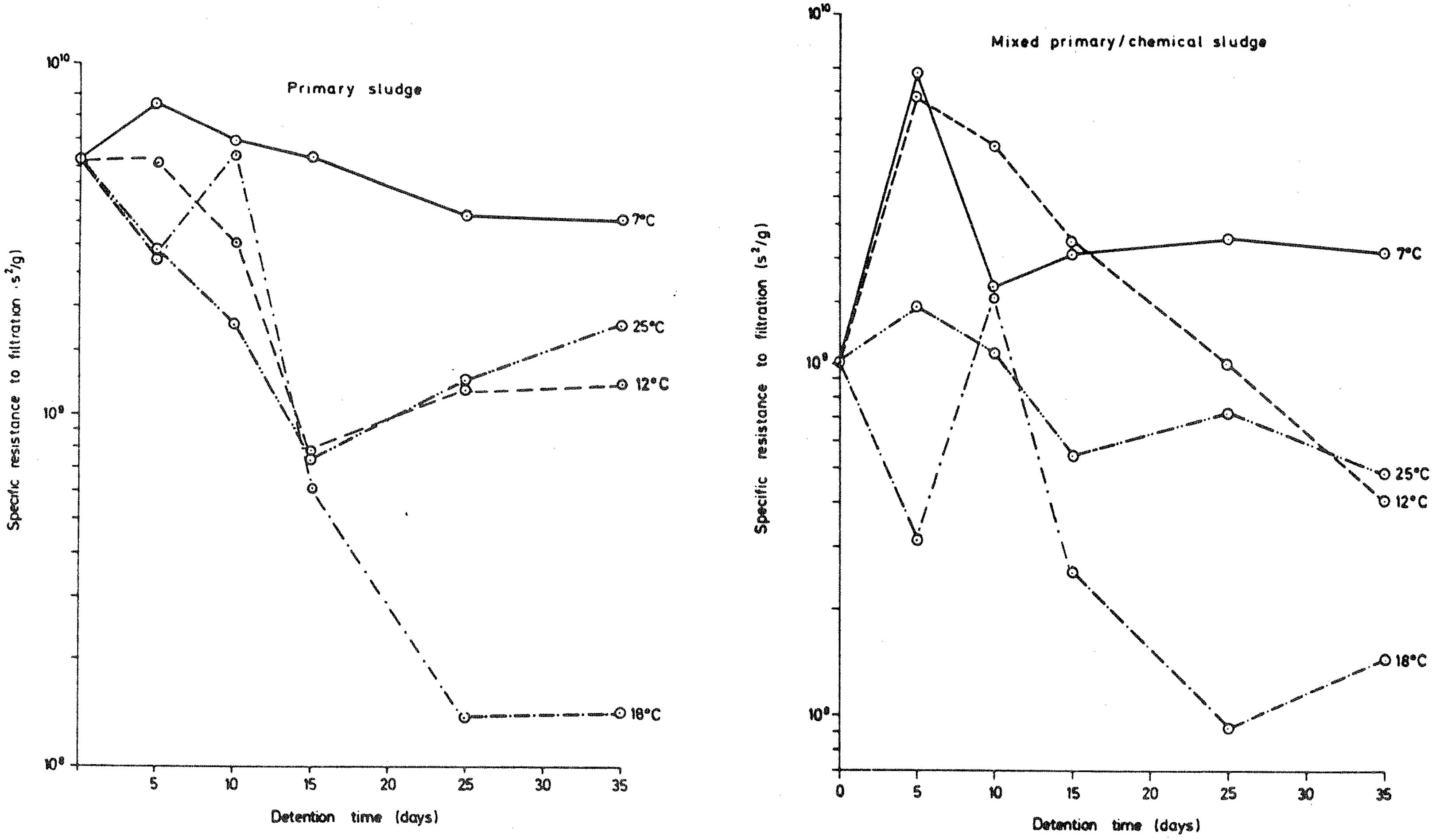


Figure 41. Specific Resistance to Filtration vs. Detention Time in Aerobic Digester.

increased during the first 5 days and then gradually decreased to a minimum value at 35 days' detention time. The initial increase was probably caused by the initial break up of the sludge particles due to the agitation in the reactor.

Since bio-flocculation is a natural part of the material life-cycle, and maximum flocculation will not occur until the endogenous phase, the particles will reflocculate and improve the specific resistance to filtration with an increase in detention time. Again no significant change in specific resistance to filtration was found for mixed primary-chemical sludge stabilized at 7°C except for the slight increase at 5 days' detention time.

If specific resistance to filtration for the two types of sludge is compared, it appears that mixed primary-chemical sludge has the best filtration properties, although its floc seem to be less resistant to agitation at low degrees of stabilization. The better filtration properties for mixed primary-chemical sludge were partly expected since particles in sewage sludge are held in suspension by repulsion between individual particles due to negative charges. When mixing primary and chemical sludge, added Al^{+++} cations would probably overcome these repulsion forces by neutralizing the negative charges and thus allowing the particles to group together and increase the floc size.

For both types of sludge investigated the stabilization at 18°C gave the best filtration properties. No explicit explanation for this can be given. Some types of organisms capable of improving the filtration properties were possibly present in larger numbers at 18°C than at any other temperature. More likely, the bio-flocculation due to naturally produced polyelectrolytes was more prevalent at this temperature.

Figure 42 shows the change of capillary suction time (CST) at different detention times and temperatures. The result obtained with this parameter was so close to the specific resistance to filtration measurements that the

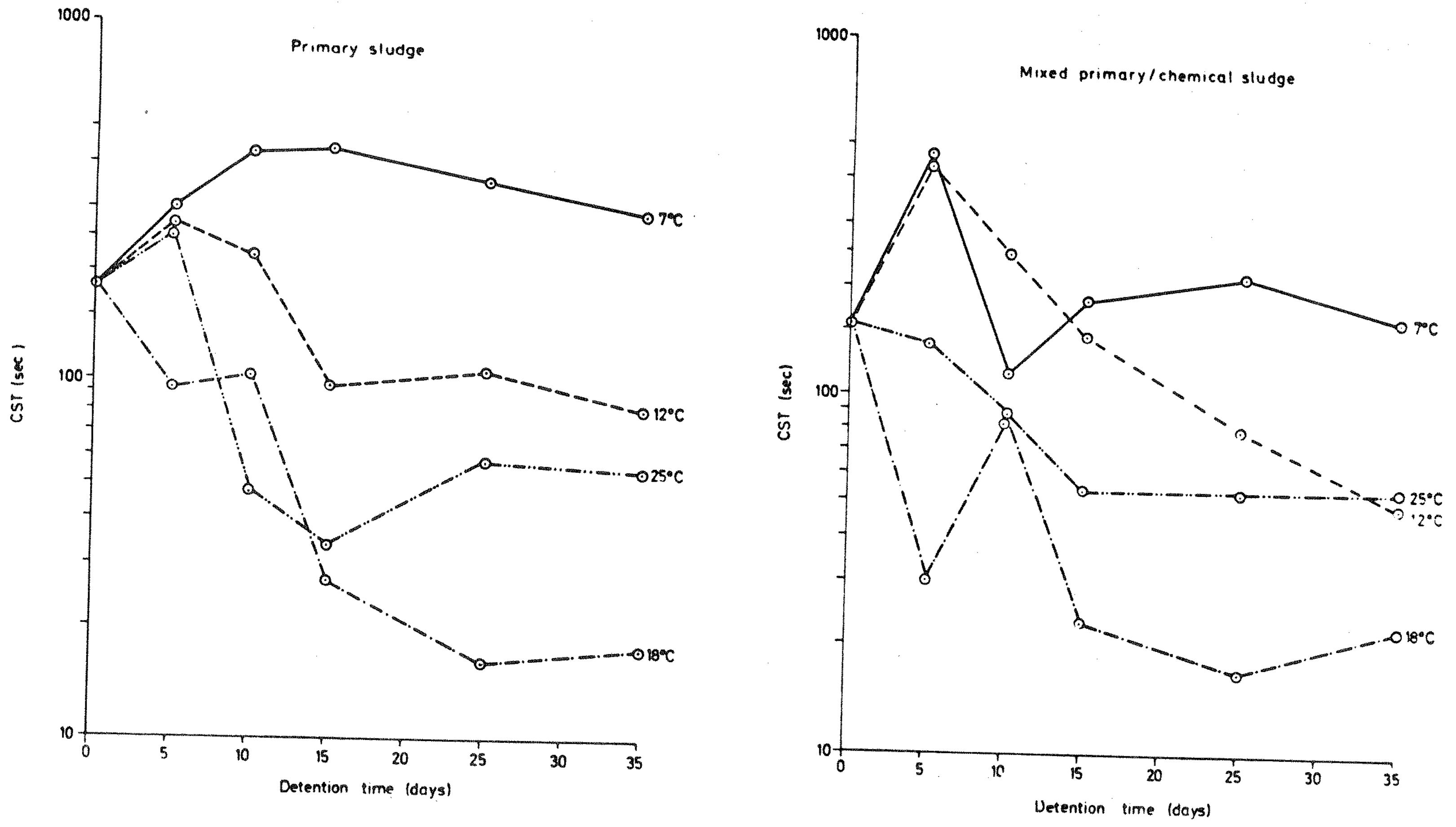


Figure 42. Capillary Suction Time (CST) vs. Detention Time in Aerobic Digester.

discussion above will be valid also for CST measurements. In other words, the CST apparatus was a valuable tool in measuring specific resistance to filtration. Since CST is dependent on the total suspended solids concentration (TSS) in the sample, the CST value divided by TSS (in percent) plotted against the specific resistance to filtration on a logarithmic scale will give a straight line relationship (See Figure 43). An increase in CST/%TSS will normally give an increase in specific resistance to filtration. Since the sample volume used in the CST measurement is very small, difficulties in reproducting the data for untreated primary sludge were experienced. This was expected since the difficulty in taking a representative sample was great. After the sludge had been partly stabilized or mixed with chemical sludge, this difficulty was partly overcome.

A UNIVAC 1108 computer, using the method of least squares, was used to find the best fitting lines for primary sludge, mixed primary-chemical sludge and finally for all the points measured (both primary and mixed primary-chemical sludge). The general form of the equation is:

$$\log \frac{CST}{\%TSS} = A \cdot \log r - B \qquad (14)$$

CST = Capillary suction time (s)

TSS = Total suspended solids (%)

r = Specific resistance to filtration (s^2/g)

A = Constant (slope of the line)

B = Constant

The results of the three runs made are shown in Table 11. It is evident from this table that a much better correlation between CST/%TSS and specific resistance to filtration was found for mixed primary-chemical sludge than for primary sludge alone. The reason for this has been mentioned earlier

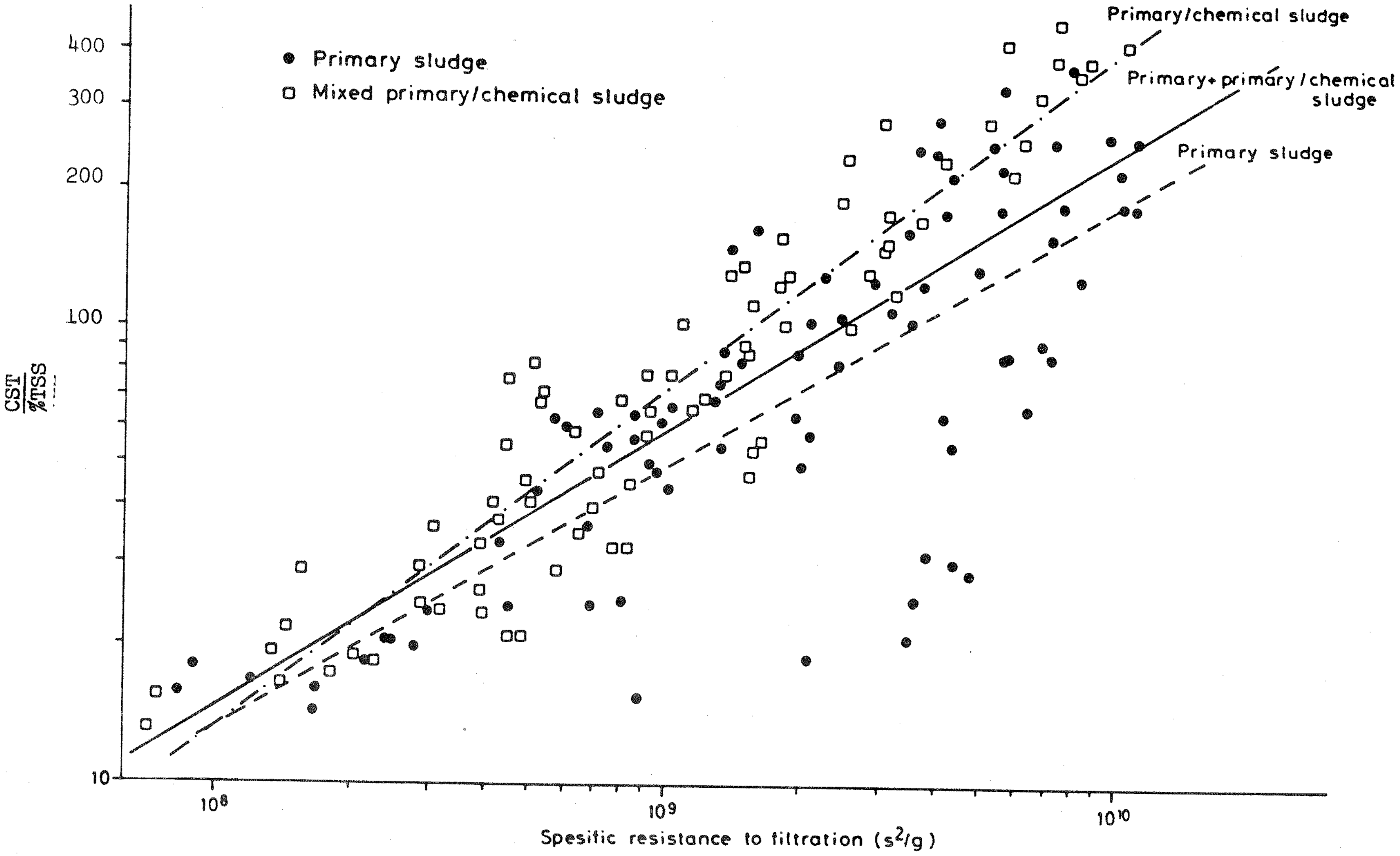


Figure 43. CST/%TSS vs. Specific Resistance to Filtration.

in this chapter.

Sludge	No. of points	Coeff. of correl.	A	B	Equation
Primary	78	0.78	0.57	3.43	log CST/%TSS = 0.57 • log r - 3.43
Mixed prim./ chem.	83	0.93	0.74	4.78	log CST/%TSS = 0.74 • log r - 4.78
Primary + mixed	161	0.82	0.60	3.64	log CST/%TSS = 0.60 • log r - 3.64

Table 11. CST/%TSS vs. SPECIFIC RESISTANCE TO FILTRATION

Change in sludge compressibility with changing degree of stability was investigated for the two types of sludge. Compressibility is defined as:

$$\frac{r_1}{r_2} = \left(\frac{P_1}{P_2}\right)^s \qquad (15)$$

r = Specific resistance to filtration ($s^2\ g^{-1}$)

P = Pressure ($g\ cm^{-2}$)

s = Compressibility

When the specific resistance to filtration is known at one pressure, it can be calculated at other pressures if the compressibility is known. This is important since the operating pressure of a filter press or vacuum filter quite often is different from the vacuum pressure at which the test is run.

Compressibility (s) increased with increasing detention time in the reactor. This was true for both types of sludge at all temperatures investigated.

However, the greatest change occured during stabilization of primary sludge. This type of sludge has a low compressibility (0.15-0.40) prior to stabilization. A rapid increase the first 15 days of aeration was experienced for sludges stabilized at 12°C and 25°C. A more gradual increase was found for sludges stabilized at 7°C and 18°C. The final compressibility of stabilized primary sludge was approximately 0.9-1.1. Mixed primary-chemical sludge in the untreated state had a higher compressibility (0.55-0.70) than raw primary sludge alone. Aerobic stabilization of this type of sludge increased the compressibility to approximately 0.85-1.00 after 5-15 days of aeration and then it stayed relatively constant with increasing detention time. This is shown in Figure 44. Generally a high sludge compressibility is a major disadvantage since it partly rules out those types of sludge-dewatering equipment that apply high pressure (filter press, belt press etc.). Care should be taken, therefore, in selecting dewatering equipment for aerobically digested sludge.

Storage of sludge prior to dewatering is quite often a necessity at small treatment plants. The storage period can vary from a few hours to several days. An effort was made to find out how the storage period would affect the specific resistance to filtration. The sludges used for this test were stabilized from 5 to 35 days at 18°C. The sludges were stored under anoxic conditions at room temperature (10°C ± 1°C).

An increase in specific resistance to filtration with increasing storage time was found for both types of sludge. The specific resistance increased from 4 to 9 times its original value during the 18 days of storage. Primary sludge aerated for 5 or 10 days had the lowest increase during the test period (4 times its original value), while mixed primary-chemical sludge aerated for more than 5 days increased the specific resistance to filtration approximately 8 times. The highest increase always occured during the first four to six days and then the specific resistance to filtration tended to stay fairly constant

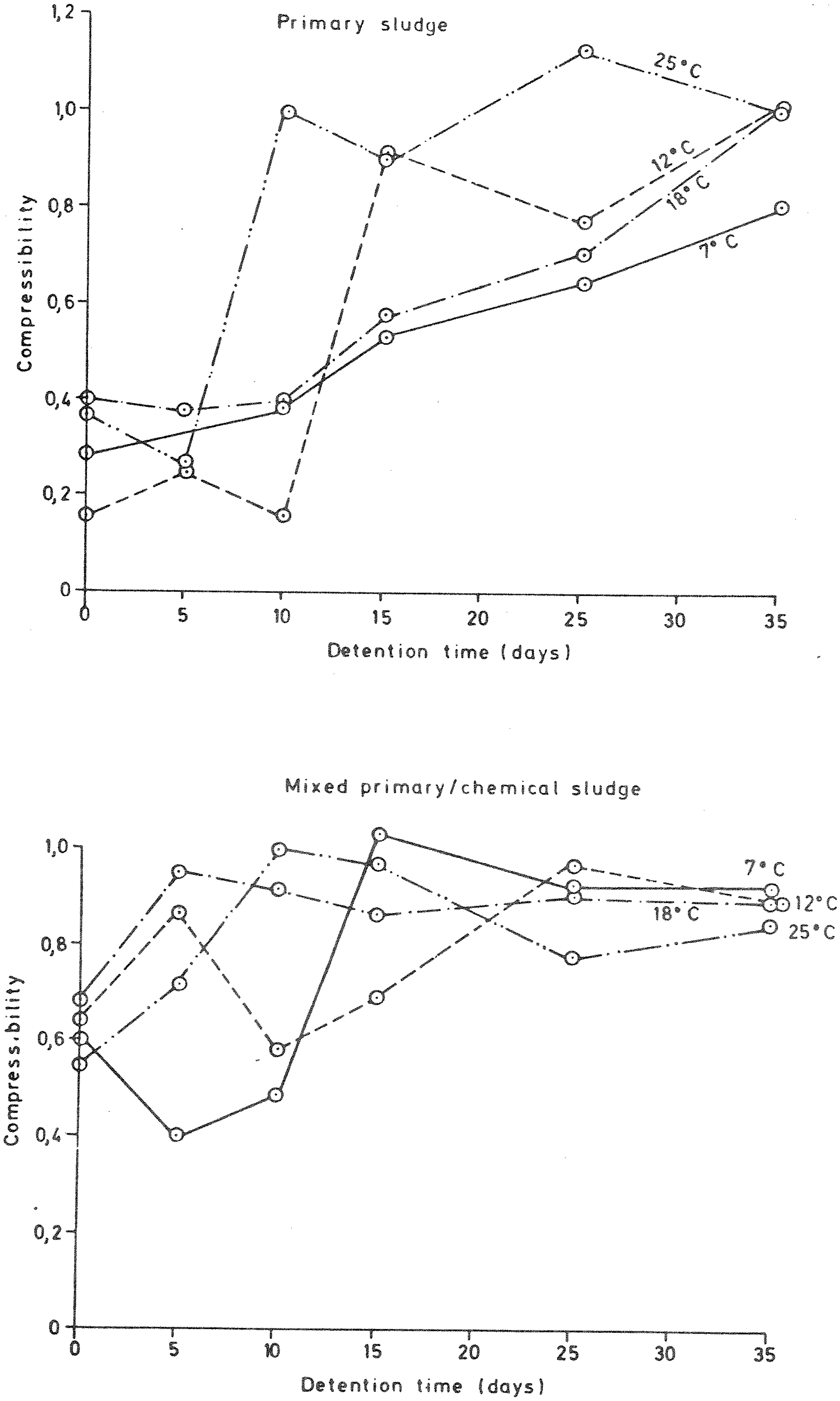


Figure 44. Compressibility vs. Detention Time in Aerobic Digester.

or showed a slight increase afterwards (See Figure 45).

Change in Phosphorus during Aerobic Stabilization and Release of Phosphorus during Storage

Total phosphorus content in the sludge (both solids and liquid) will not change during aerobic digestion. It will depend only on the initial phosphorus content in the raw sludge. This is illustrated in Figure 46. The total phosphorus content of primary and mixed primary-chemical sludge is approximately 120 mg/l-P and 280 mg/l-P respectively. The somewhat higher content of phosphorus in the mixed primary-chemical sludge is due to the addition of chemical sludge from the phosphorus removal step. The average phosphorus content of the chemical sludge alone was 406 mg/l-P.

Phosphorus has a significant role in the cell synthesis. Dissolved inorganic orthophosphate is used within the organism to formulate compounds that are necessary for new cell development. The most important compounds are nucleotides, adenosine triphosphate (ATP) and the nucleic acids, deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). It would be expected, therefore, that dissolved orthophosphate in the raw waste added to each reactor would be used in the biological process. Figure 47 indicates that this is the case for both primary and mixed primary-chemical sludge. For mixed primary-chemical sludge, however, the available orthophosphate in solution is low (less than 2.0 mg/l-P) and hence the change in orthophosphate in solution during the early stage of stabilization is lower than for primary sludge.

Considering the solubility relationships between chemically formed $AlPO_4$ and PO_4 in solution, an explanation can be given for the low PO_4 content of the mixed sludge supernatant compared to primary sludge supernatant.

During endogenous respiration,cell lysis probably will release phosphorus to the liquid phase and thus make this available for cell synthesis.

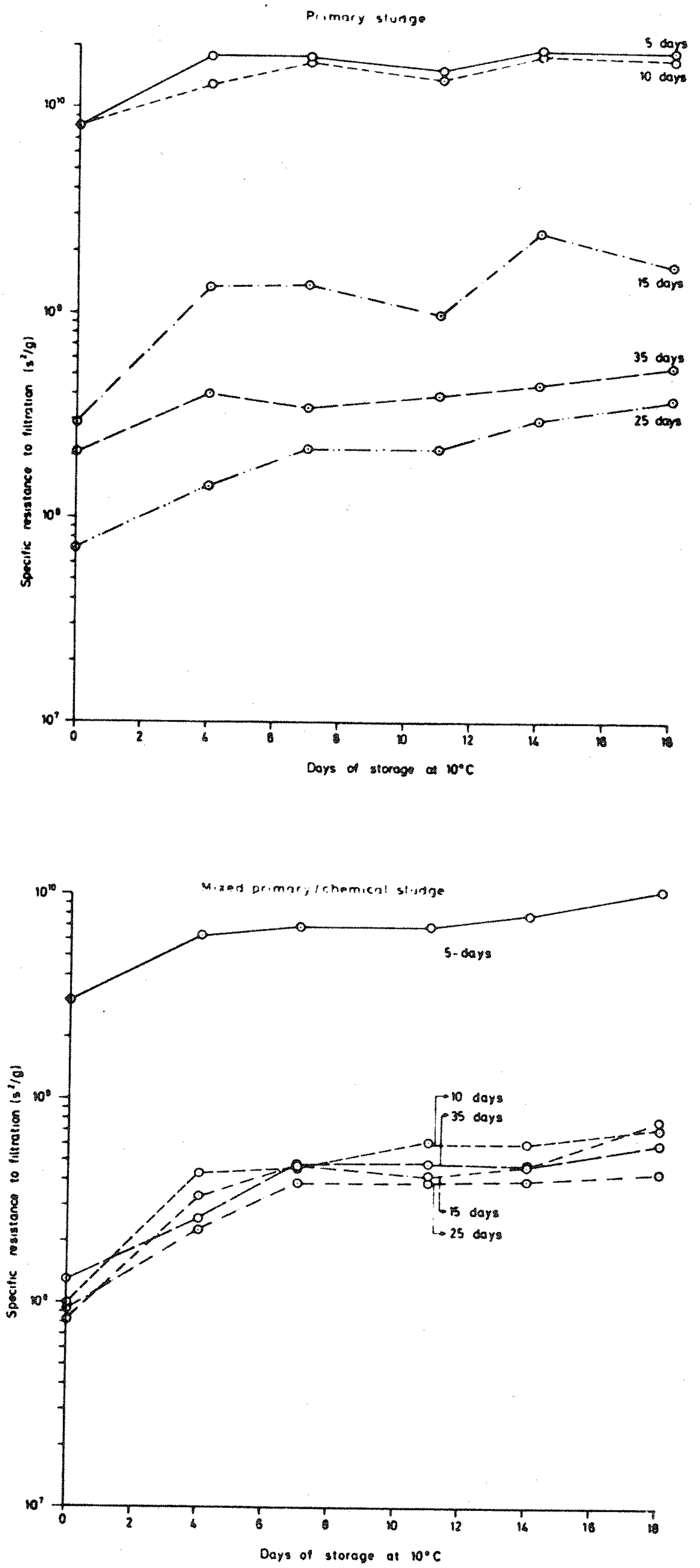


Figure 45. Specific Resistance to Filtration vs. Days of Storage at 10°C.

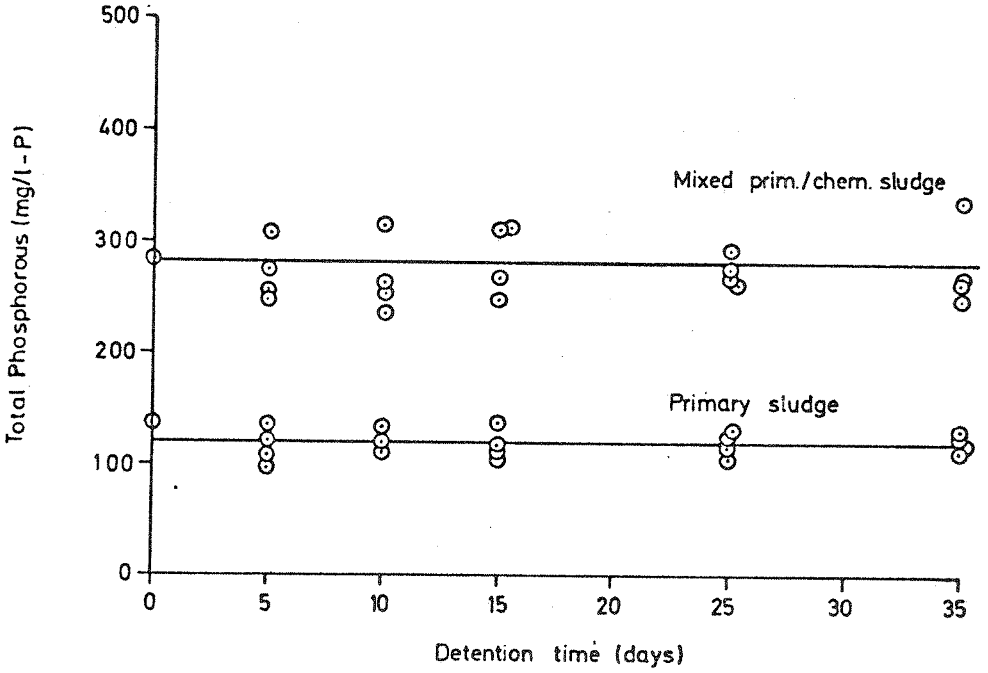
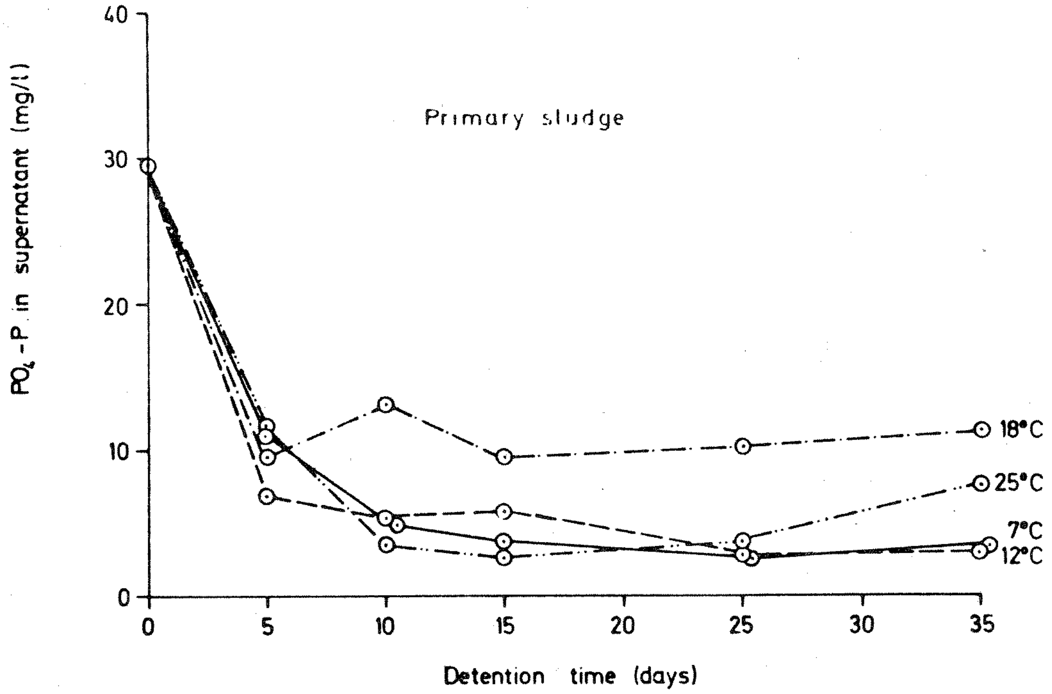


Figure 46. Total Phosphorus Content in Sludge vs. Detention Time.



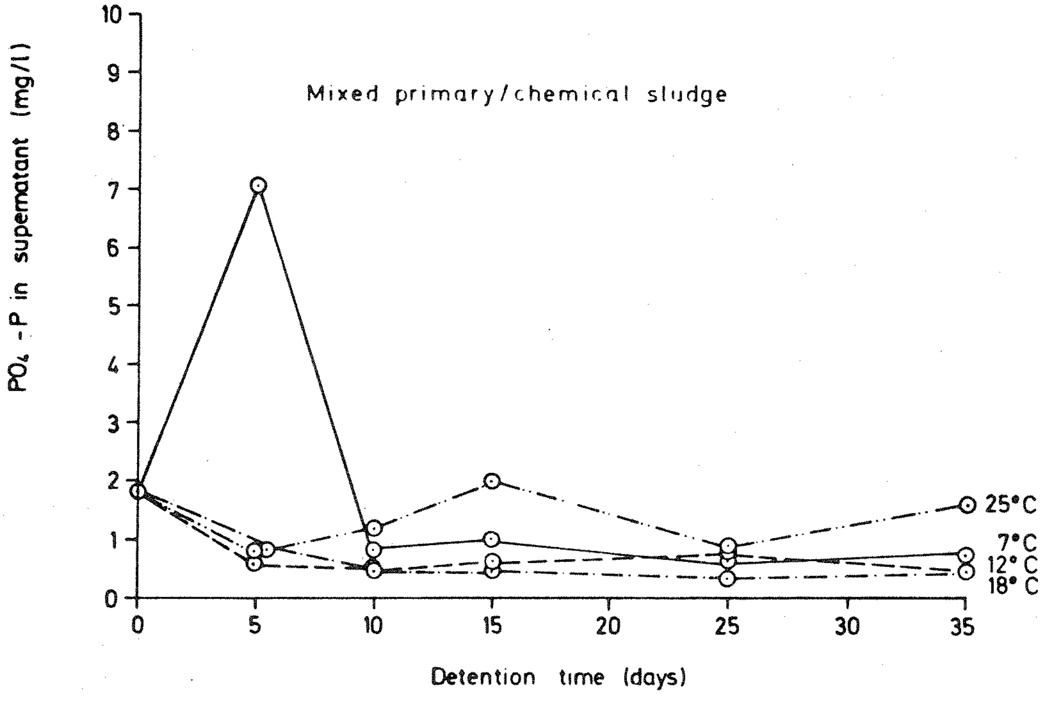


Figure 47. Orthophosphate in Supernatant vs. Detention Time.

With increasing detention time the volatile suspended solids concentration will be reduced, but the amount of bound phosphorus will stay very nearly constant. The per cent bound phosphorus in the sludge would, therefore, increase with increasing detention time. This is shown in Figure 48. Primary sludge increased the per cent phosphorus from 0.6% to approximately 1.6%. Mixed primary-chemical sludge increased from 2.1% phosphorus to 3.2% - 4.0%. For both types of sludge investigated at 25°C the per cent phosphorus in the sludge seemed to reach a maximum value at 25 days detention time and then show a slight decrease with increasing detention time. This indicated an increase in dissolved phosphorus between 25 days and 35 days for the 25°C series.

Leaching of phosphate from the solid phase to the liquid phase during anoxic storage was investigated in detail to determine whether the degree of stabilization and length of storage period would influence the total release. The two types of sludges investigated showed entirely different behavior regarding bleed back of phosphorus to the liquid phase.

During storage of primary sludge at different degrees of stability, phosphorus was always released from the solid phase to the liquid phase. Cell lysis taking place during storage is the most probable explanation. Work by Randall et al. (1970) supports this. The amount of phosphorus in the liquid phase during storage is primarily influenced by the length of storage period and the initial degree of stability of the sludge (number of days aerated prior to anoxic storage). This is clearly shown in Figure 49. The release to the liquid was high during the first 3 to 4 days and then a maximum value was reached after 10 to 12 days of storage. This was taking place regardless of the temperature in the reactor. The orthophosphate concentration increased from 5-10 mg/l-P initially to 25-50 mg/l-P after 10 to 12 days of storage depending on the degree of stability of the sludge. Since the phosphorus release is biological in nature, it should be a function of sludge stability. This is

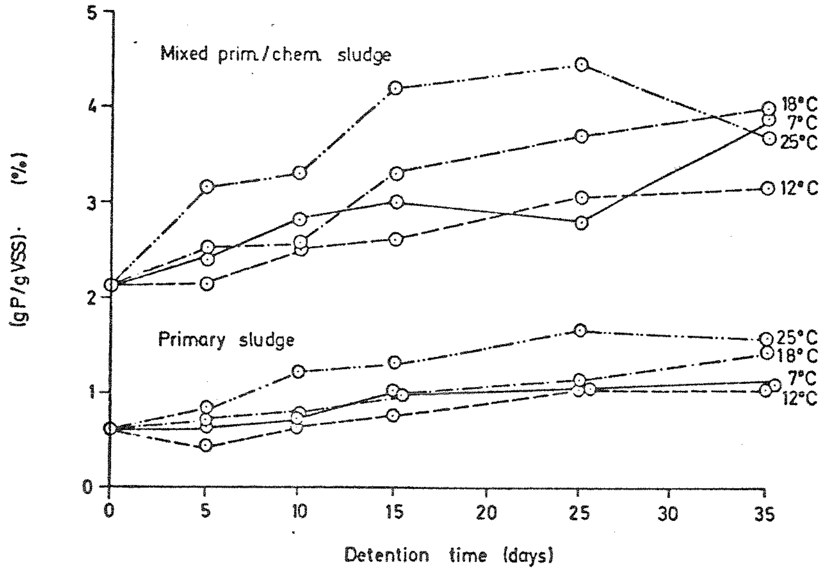


Figure 48. Bound Phosphorus in Sludge vs. Detention Time.

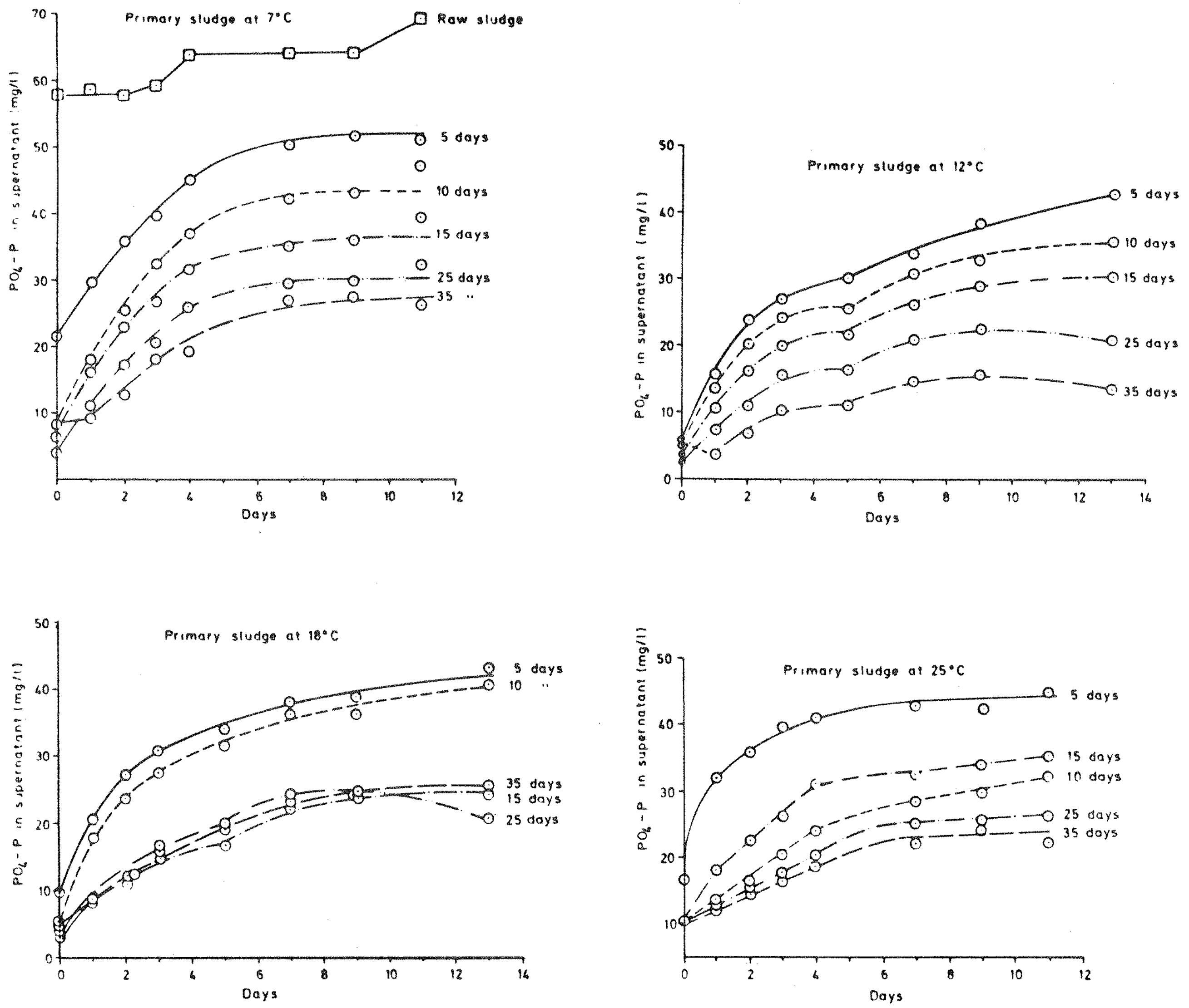


Figure 49. Release of Phosphorus to Supernatant vs. Days of Storage.

because an increase in sludge stability means a lower fraction of viable cells. Figure 50 shows the ultimate orthophosphate release per mgVSS vs. sludge stability (number of days aerated). A linear relationship between ultimate orthophosphate release and detention time (days of aeration) in the reactor prior to storage was found.

Ultimate phosphorus released during anoxic storage was determined as the difference between initial orthophosphate concentration and the maximum orthophosphate concentration reached after 11 to 12 days of storage.

Randall et al. (1970) found that the release of **phosphoros** was a linear function of initial solids concentration. In other words, the release of phosphate per unit solids was constant. Considering that the fraction of nondegradable organic solids will increase during aerobic stabilization, and the number of viable cells will decrease, it can be expected that ultimate orthophosphate release per unit solids will increase with increasing solids concentration. This is shown in Figure 51. In other words, the higher the degree of stability, the less viable cells will be present to release phosphorus during anoxic storage.

Release of orthophosphate during storage of aerobically stabilized mixed primary-chemical sludge proved to be completely different from primary sludge alone. No release of orthphosphate took place during anoxic storage, regardless of the initial degree of **stability and** the reactor temperature during stabilization. The initial concentration of orthophosphate in mixed primary-chemical sludge was also very low compared with primary sludge. In most cases the concentration was less than 1.0 mg/l-P. During storage of sludge aerated in 5 days at 7°C, the concentration of ortho-phosphate was as high as 3.6 mg/l-P and did not change significantly during 11 days of storage. This relatively high concentration was not found in any of the other samples. Release of phosphate by cell lysis might happen during storage of mixed primary-chemical

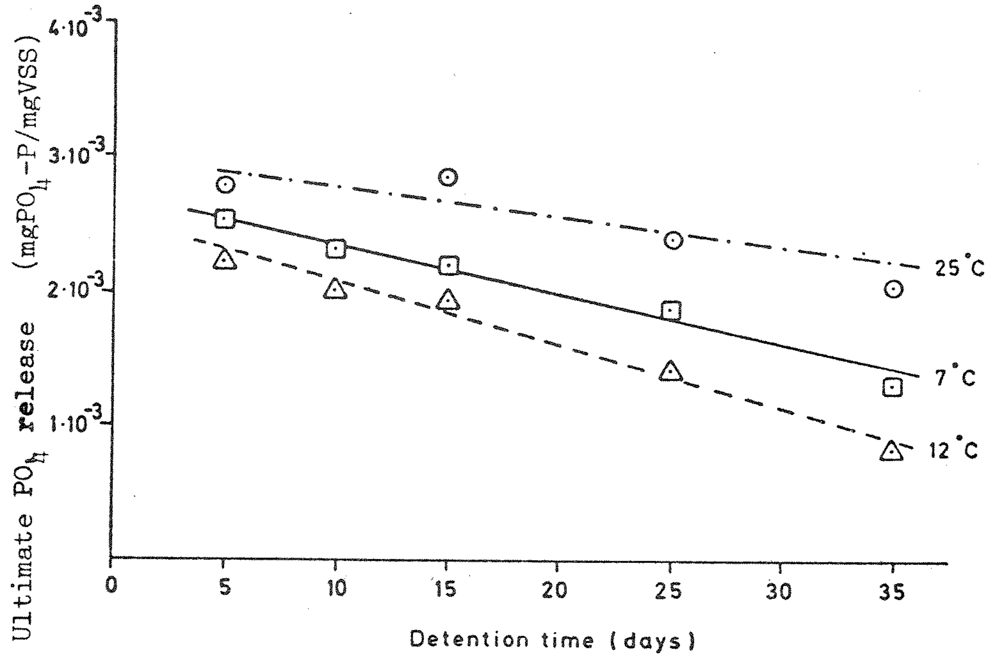


Figure 50. Ultimate Orthophosphate Release vs. Detention Time in Aerobic Digester - Primary Sludge.

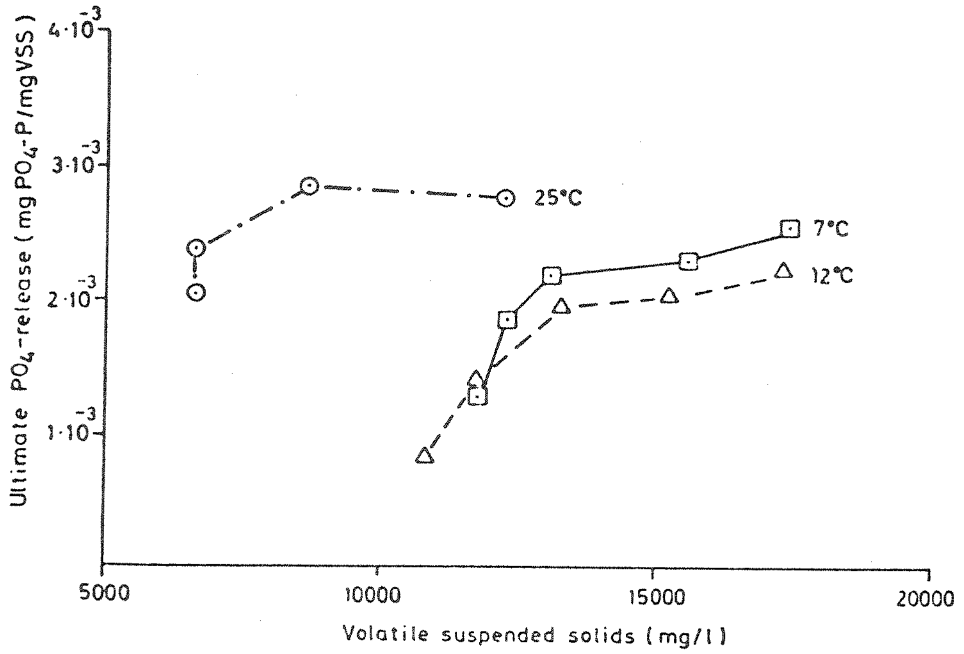


Figure 51. Ultimate Orthophosphate Release vs. Volatile Suspended Solids Concentration - Primary Sludge.

sludge. However, the released phosphorus would be chemically bound as an aluminum phosphate - aluminum hydroxide complex and thus the ortho-phosphate in solution would remain low. Release of ortho-phosphate vs. days of storage is shown in Figure 52.

Microbial Composition during Aerobic Stabilization

Microscopic examinations revealed that changes in the biota took place during the digestion process. This appears from the micrographs, Figure 53 through 56. No effort was made to identify the different organisms present, but a general classification was attempted. The results are shown in Tables 12 and 13. An effort was made to distinguish between biota in reactors treating primary sludge only and those treating mixed primary-chemical sludge.

Higher organisms were present in all the reactors regardless of temperature and type of sludge. Under no circumstances did the high concentration of aluminum in the mixed primary-chemical sludge inhibit the growth of higher organisms. Quite the contrary, the reactors treating mixed primary-chemical sludge at 18°C had very high concentrations of free swimming ciliates, nonpigmented flagellates and rotifiers. The concentrations were higher than in any reactor treating primary sludge. This does not agree with work by Anderson et al. (1973), who found that 26.2 mg-Al/l prevented larger protozoans from functioning.

Stalked ciliates were more abundant at low temperatures (7°C) than at higher temperatures. This is probably due to their lower energy requirement. As temperature increases, the free swimming ciliates seem to take over although stalked ciliates were present in the reactors treating mixed primary-chemical sludge at 25°C. Stalked ciliates were sometimes present in clusters (See Figure 53).

Viable rotifiers were observed in reactors treating primary sludge at 12°C

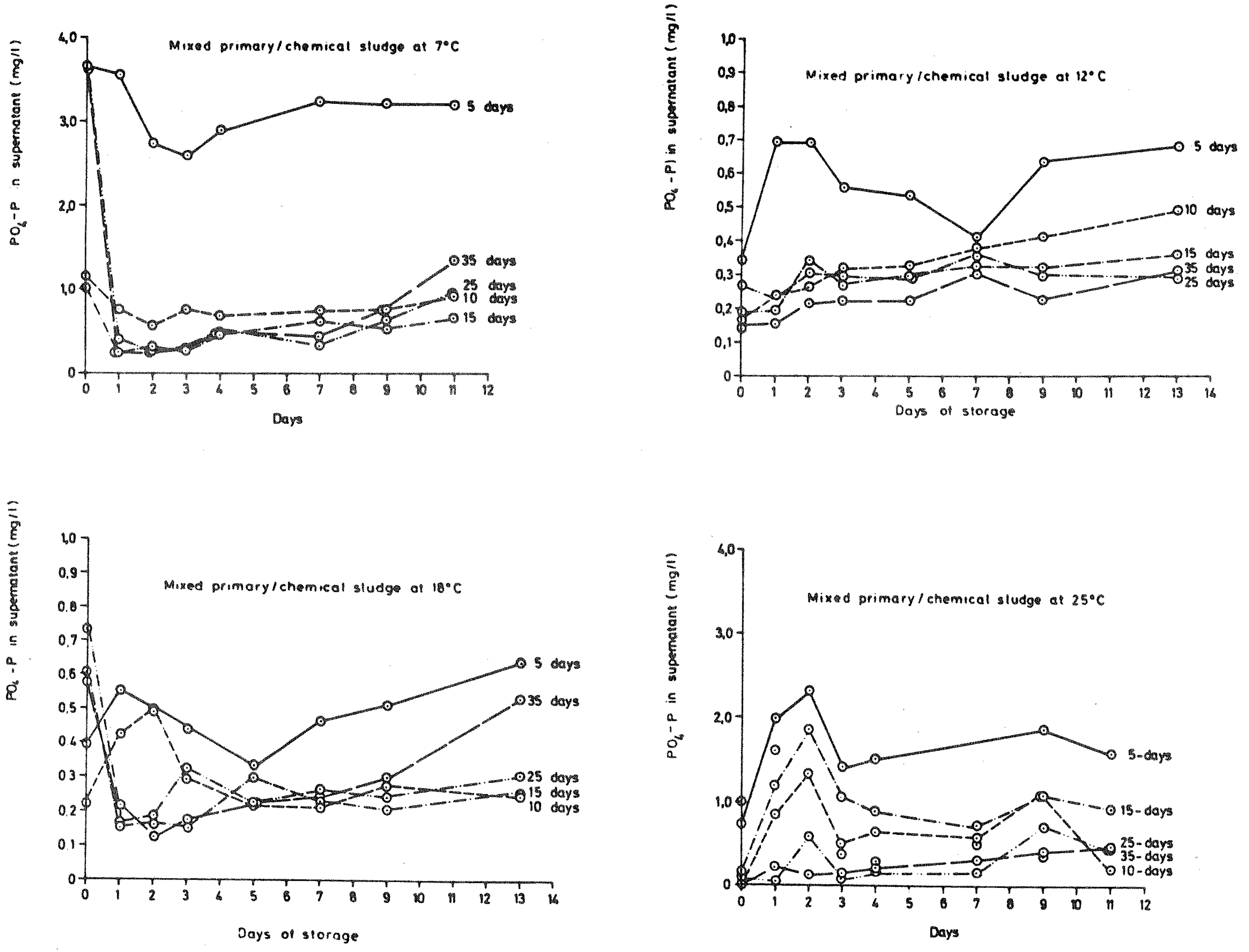
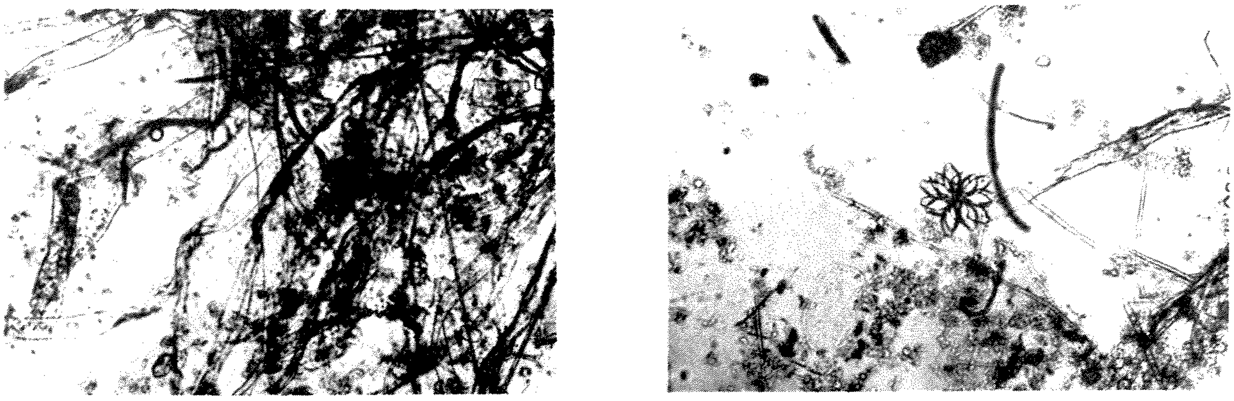
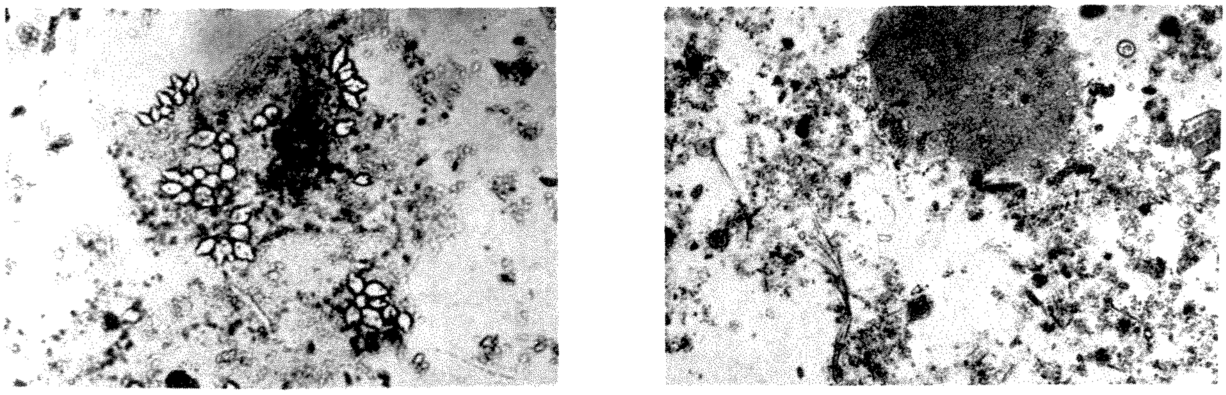


Figure 52. Release of Phosphorus to Supernatant vs. Days of Storage.



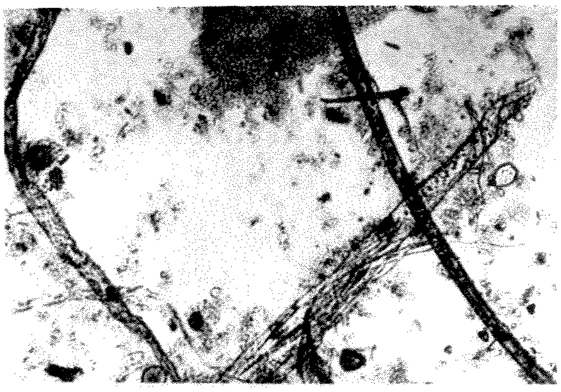
Detention time - 5 days

Detention time - 10 days



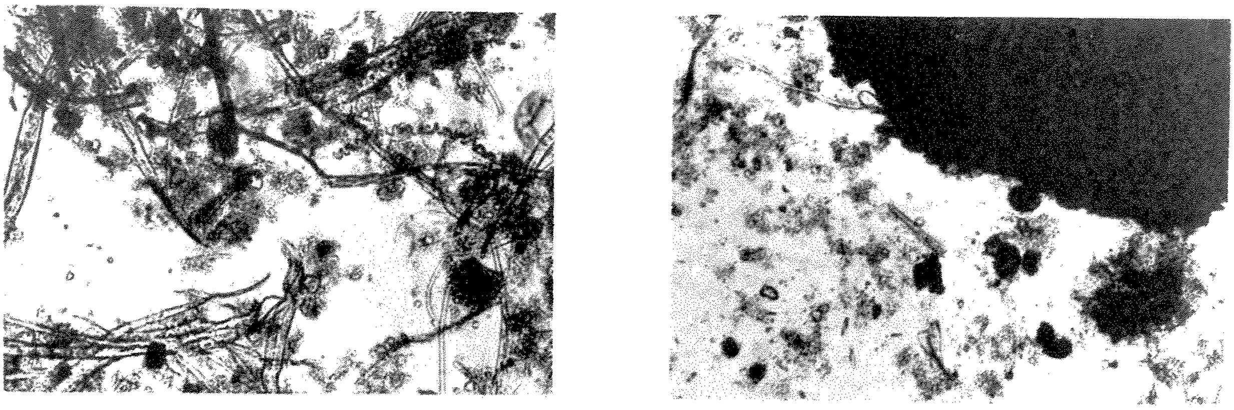
Detention time - 15 days

Detention time - 25 days



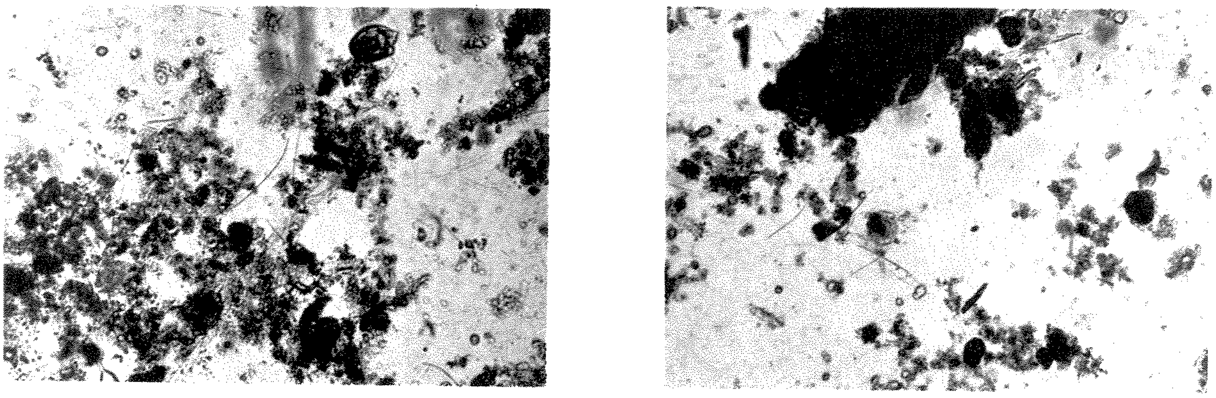
Detention time - 35 days

Figure 53. Primary Sludge Stabilized at 7°C (magnification - 73X)



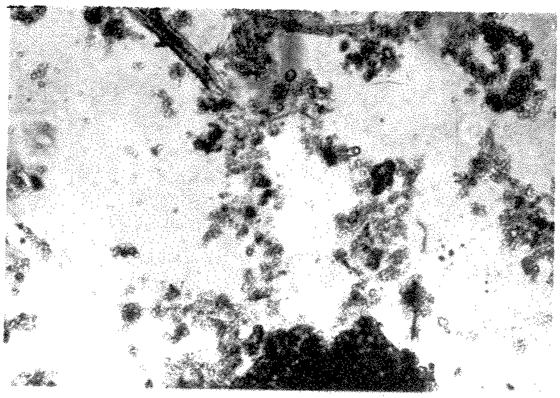
Detention time - 5 days

Detention time - 10 days



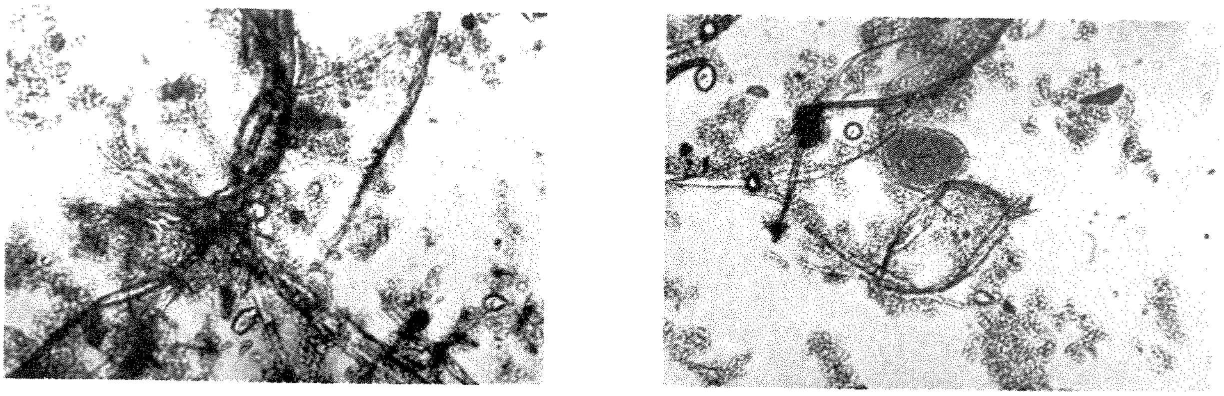
Detention time - 15 days

Detention time - 25 days



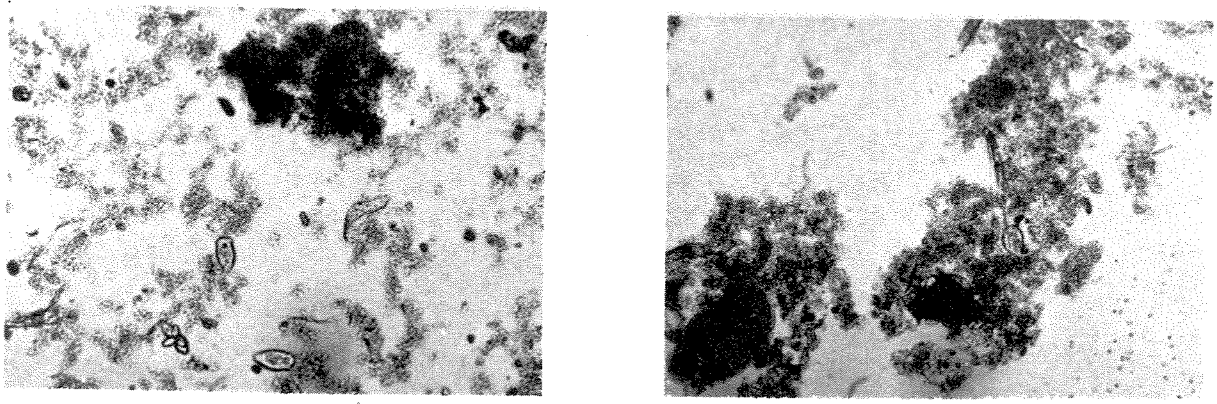
Detention time - 35 days

Figure 54. Primary Sludge Stabilized at 25°C (magnification 73X)



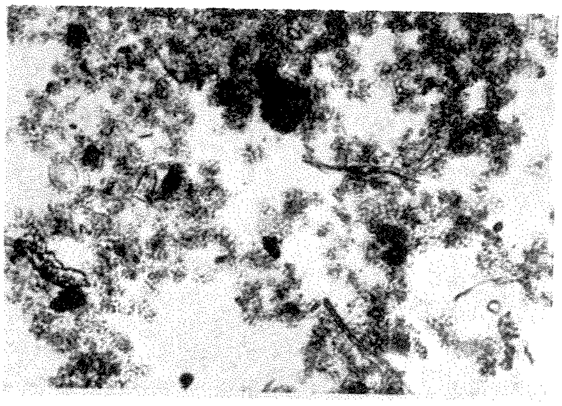
Detention time - 5 days

Detention time - 10 days



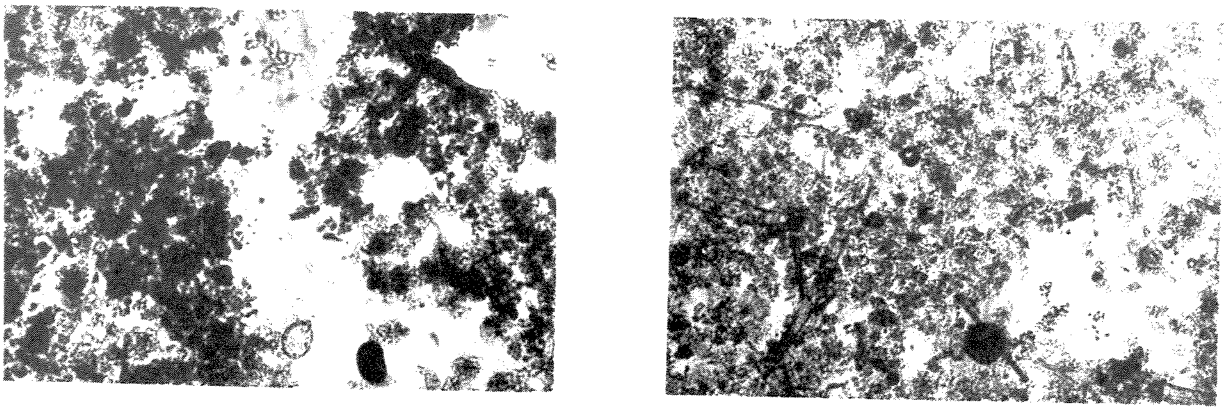
Detention time - 15 days

Detention time - 25 days



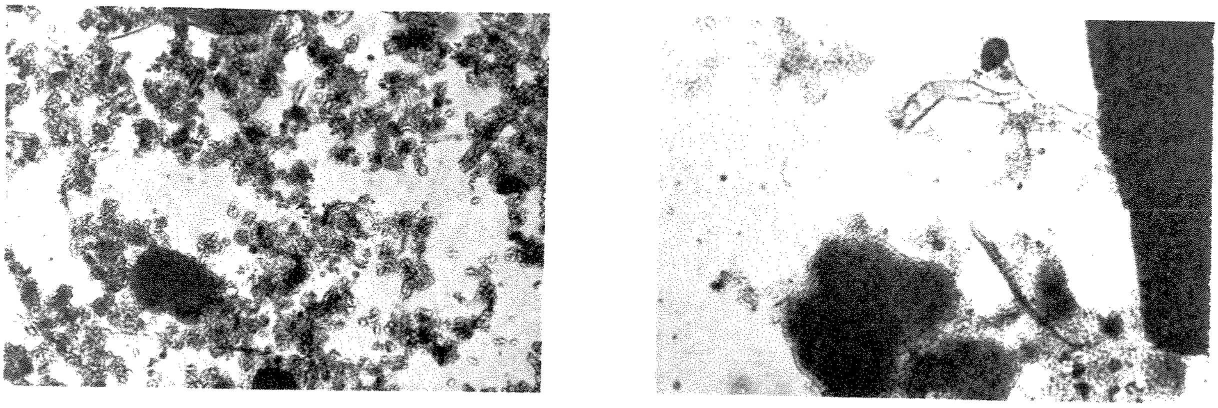
Detention time - 35 days

Figure 55. Mixed Primary/Chemical Sludge Stabilized at 7°C (magnification 73X)



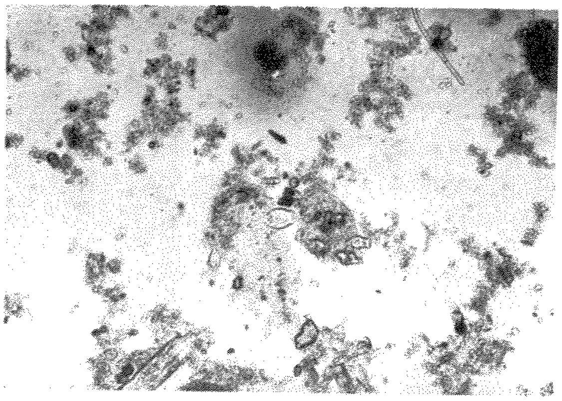
Detention time - 5 days

Detention time - 10 days



Detention time - 15 days

Detention time - 25 days



Detention time - 35 days

Figure 56. Mixed Primary/Chemical Sludge Stabilized at 25°C (magnification 73X)

MICROSCOPIC EXAMINATIONS

Sludge	Det. t days	Temp. ^{o}C	Size flocs	Material dispers.	Ciliates		Nonpigm. flagell.	Rotifiers	Nematodes
					Swim.	Stalked			
Primary	5	7	Small	Some	4	3	1	1	1
"	10	"	"	"	2	3	1	1	1
"	15	"	"	"	2	3	1	1	1
"	25	"	"	Little	1	1	3	1	1
"	35	"	Medium	"	1	1	5	1	1
Primary	5	12	Small	Some	2	2	1	1	1
"	10	"	"	"	1	2	1	3	1
"	15	"	Medium	"	3	2	1	2	1
"	25	"	"	None	3	1	1	3	1
"	35	"	Small	Much	4	1	1	3	1
Primary	5	18	Small	Much	2	1	1	1	1
"	10	"	Medium	Some	1	4	3	1	1
"	15	"	"	"	1	1	3	2	1
"	25	"	"	"	2	1	2	3	1
"	35	"	"	"	3	1	2	2	1
Primary	5	25	Small	Some	2	1	5	1	1
"	10	"	Medium	"	4	1	5	1	1
"	15	"	"	"	4	1	5	1	1
"	25	"	"	"	4	1	4	1	1
"	35	"	Large	"	4	3	4	1	1

1 = None. 2 = Very few. 3 = Some. 4 = Many. 5 = Very high concentration.

Table 12. MICROSCOPIC EXAMINATIONS - MIXED PRIMARY-CHEMICAL SLUDGE.

M I C R O S C O P I C   E X A M I N A T I O N S

Sludge	Det. t days	Temp. °C	Size Flocs	Material dispers.	Ciliates		Nonpigm. flagell.	Rotifiers	Nematodes
					Swim.	Stalked			
Prim/Chem	5	7	Medium	Much	2	5	1	1	1
"	10	"	"	"	1	5	1	1	1
"	15	"	"	None	1	5	1	1	1
"	25	"	Small	"	1	1	2	1	1
"	35	"	"	Some	1	1	1	1	1
Prim/Chem	5	12	Small	Much	4	3	1	1	1
"	10	"	"	"	2	2	1	1	1
"	15	"	Medium	"	2	2	1	1	1
"	25	"	"	"	1	1	1	1	1
"	35	"	Small	"	1	1	1	1	1
Prim/Chem	5	18	Small	None	3	2	1	2	3
"	10	"	Medium	"	4	1	3	2	1
"	15	"	"	"	4	1	3	3	1
"	25	"	Large	"	4	1	4	4	1
"	35	"	"	"	5	1	2	4	1
Prim/Chem	5	25	Large	Some	3	2	5	3	1
"	10	"	"	None	2	1	4	2	1
"	15	"	"	"	3	3	2	2	1
"	25	"	"	"	3	3	3	1	1
"	35	"	Medium	Much	4	3	2	1	1

1 = None. 2 = Very few. 3 = Some. 4 = Many. 5 = Very high concentration.

Table 13. MICROSCOPIC EXAMINATIONS - PRIMARY SLUDGE.

and 18°C, but were completely absent at 7°C and 25°C. Since rotifiers "graze" on the ciliates and bacteria, the lack of food at 7°C and 25°C cannot be the reason for their absence.

In the reactors treating mixed primary-chemical sludge no rotifiers were present at 7°C and 12°C, but at 18°C and 25°C they were observed on almost all the slides. In only one reactor were Nematodes observed.

A complex predator-prey relationship most likely existed between the bacteria, flagellates, ciliates and protozoa. Oscillations in the abundance of the different types of animals would, therefore, be expected. A lack of rotifiers, for example, at a particular temperature does not necessarily mean that these animals cannot exist in that particular environment. More likely it means the animals died out when their food source became exhausted.

Methods for Measuring Degree of Stability

Rüffer's lead-acetate test was used on sludges stabilized at 12°C and 18°C. The method is fully described under "Analytical Procedures." The test flasks were stored at room temperature (20°C ± 2°C). The results obtained are shown in Table 14 and 15 below.

UNIT	Prim.	A1	A2	A3	A4	A5	C1	C2	C3	C4	C5
Detention Time (d)	0	5	10	15	25	35	5	10	15	25	35
Temp. °C	-	18	18	18	18	18	12	12	12	12	12
Days Before Color Appears	10 min	4	4	NC	NC	NC	3	3	4	4	5

NC indicates no color in 20 days.

Table 14. LEAD ACETATE TEST - PRIMARY SLUDGE

UNIT	Prim. Chem.	B1	B2	B3	B4	B5	D1	D2	D3	D4	D5
Detention Time (d)	-	5	10	15	25	35	5	10	15	25	35
Temp. °C	-	18	18	18	18	18	12	12	12	12	12
Days Before Color Appears	3 hrs	NC	NC	NC	NC	NC	2	3	15	NC	NC

Table 15. LEAD ACETATE TEST - MIXED PRIMARY-CHEMICAL SLUDGE

The evolution of hydrogen sulfide gas (H_2S) colors lead-acetate paper strips brown. This has been proposed by Rüffer as a measure of degree of stabilization. During experiments recorded in Table 14, the raw primary sludge colored the paper strip within 10 minutes, while the raw mixed primary-chemical sludge used 3 hours before the paper strip was colored brown. Primary sludge stabilized at 12°C used from 3 to 5 days before color change appeared. The same sludge stabilized at 18°C would, in the case of 5 and 10 days detention time, use 4 days to color the strips. Detention times in excess of 10 days showed no indication of H_2S evolution during the 20 days of testing.

Mixed primary-chemical sludge stabilized at 12°C showed a color change if the detention time was below 25 days. The same sludge stabilized at 18°C gave no indication of H_2S evolution during the test period regardless of the detention time.

The lead acetate test is not a precise method for measuring the degree of stabilization, but it is a practical method that can be performed at a treatment plant using aerobic digestion as a sludge treatment process. The test is actually meant to be an indication of the odor problem that will be encountered when a particular sludge is put on a drying bed. It is questionable whether or not a sludge that colors the lead acetate paper strip after a certain incubation period will also create a nuisance problem when dewatered on a drying bed.

The water drained out of the sludge stored on the drying bed and the air movement above the bed are both factors that tend to reduce the odor problem. These factors are obviously not taken into account in the lead acetate test. Therefore, there is a need for a closer correlation between the incubation temperature and period and the sludge behavior on the drying bed.

The content of volatile suspended solids as a percentage of total suspended solids also has been proposed as a measure of the degree of stability. In this author's opinion, it is not a good parameter. First of all, the change in percentage volatile suspended solids with increasing detention time is very small (See Figures 57 and 58); therefore, analytical inaccuracy would easily influence the result. Second, the content of volatile suspended solids in the raw sludge varies with time. A "grab-sample," therefore, would not be very

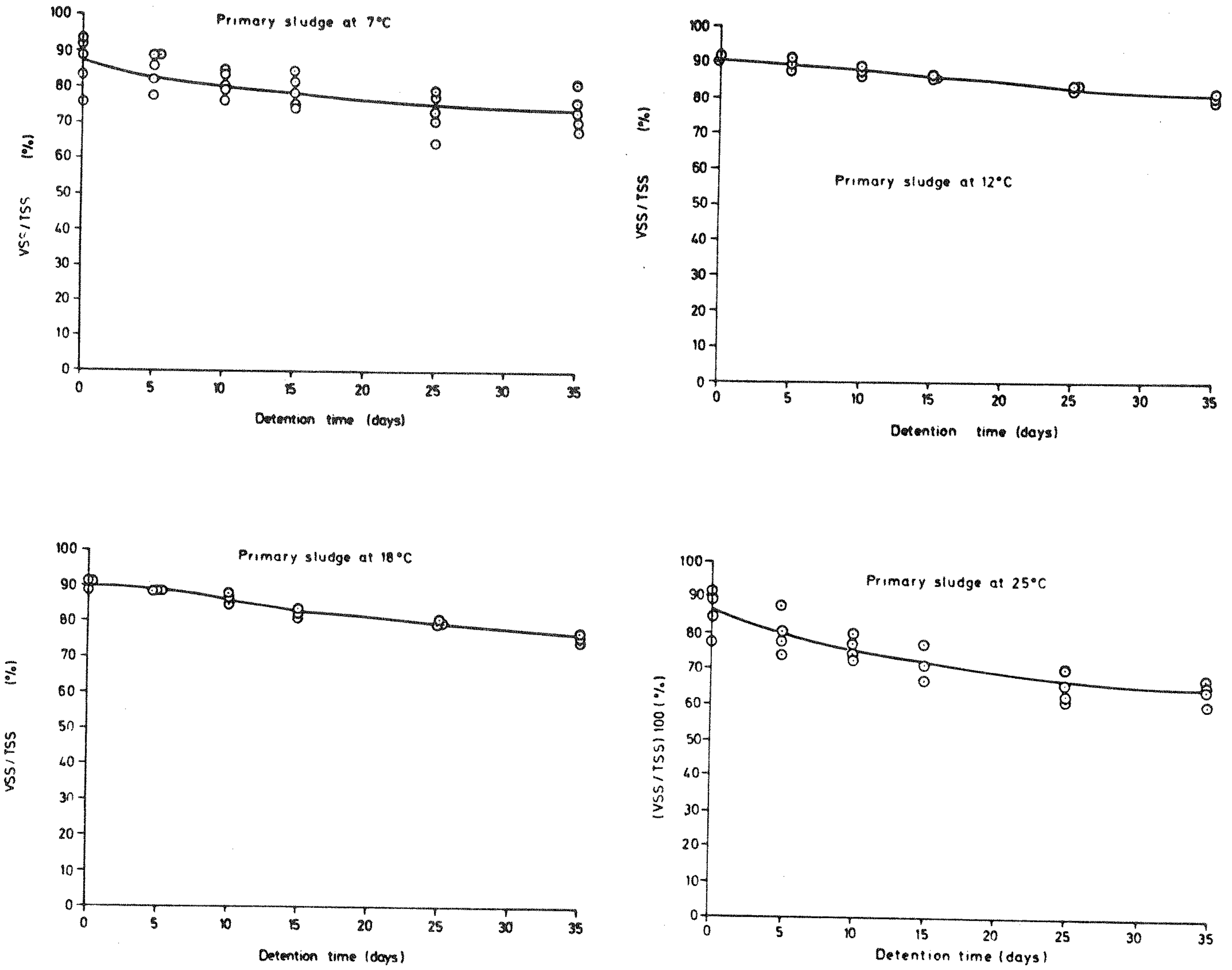


Figure 57. Per cent Volatile Suspended Solids vs. Detention Time - Primary Sludge.

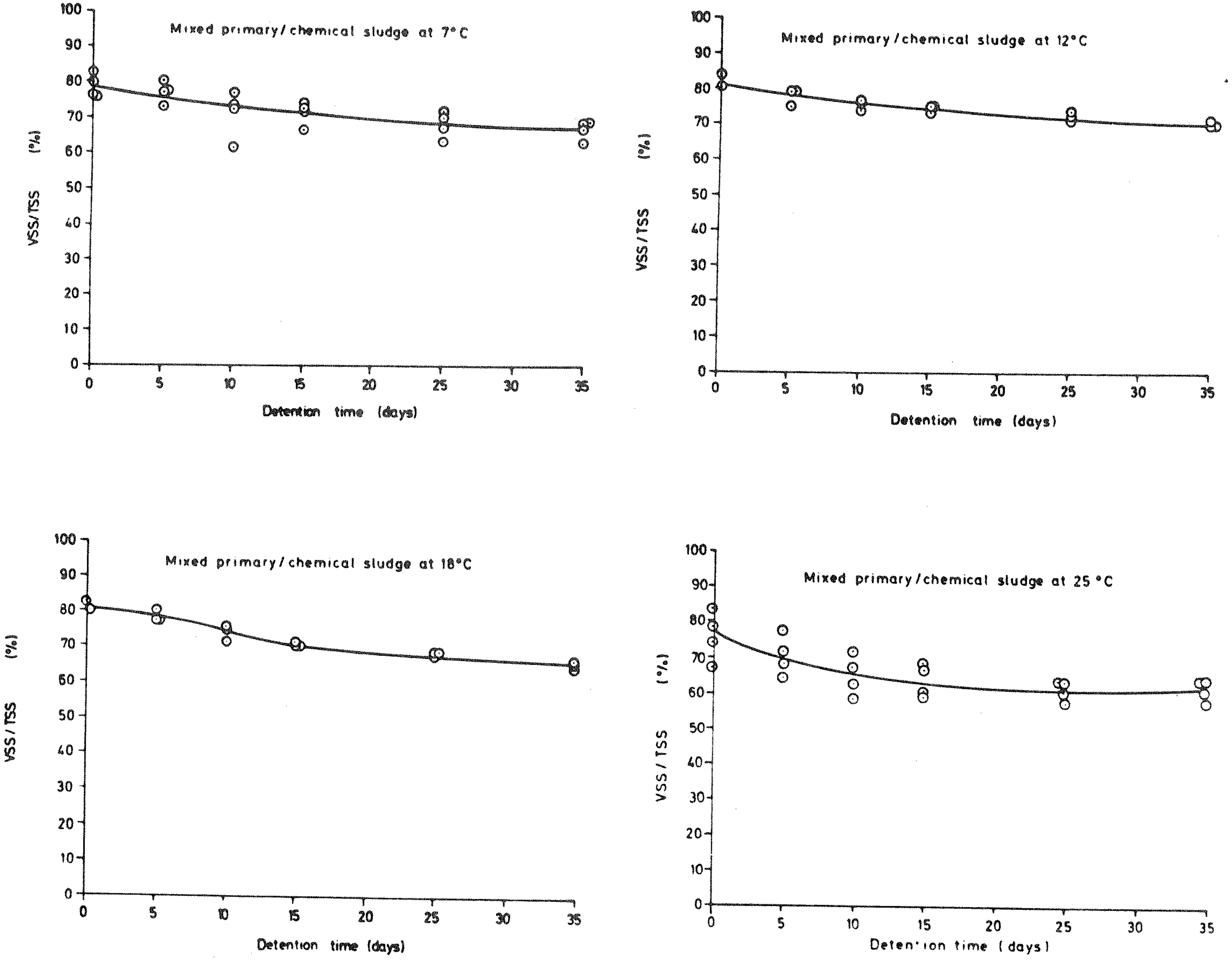


Figure 58. Per cent Volatile Suspended Solids vs. Detention Time - Mixed Primary-Chemical Sludge.

reliable in determining the degree of stability.

A modified version of the expression developed by Rawn and Bant (Kempa, 1967) discussed in the literature review was used to measure the degree of stability. The author of this dissertation introduced a constant K in the equation given by Kempa in order to establish a 100 per cent stability level. To do this the assumption was made that a sludge aerated for 35 days at 25°C had reached 100 per cent stability. The equation used and the calculated constants are shown below.

$$M = 100\left(1 - \frac{V_1\, m_o}{V_o\, m_1}\right) \cdot K \qquad (16)$$

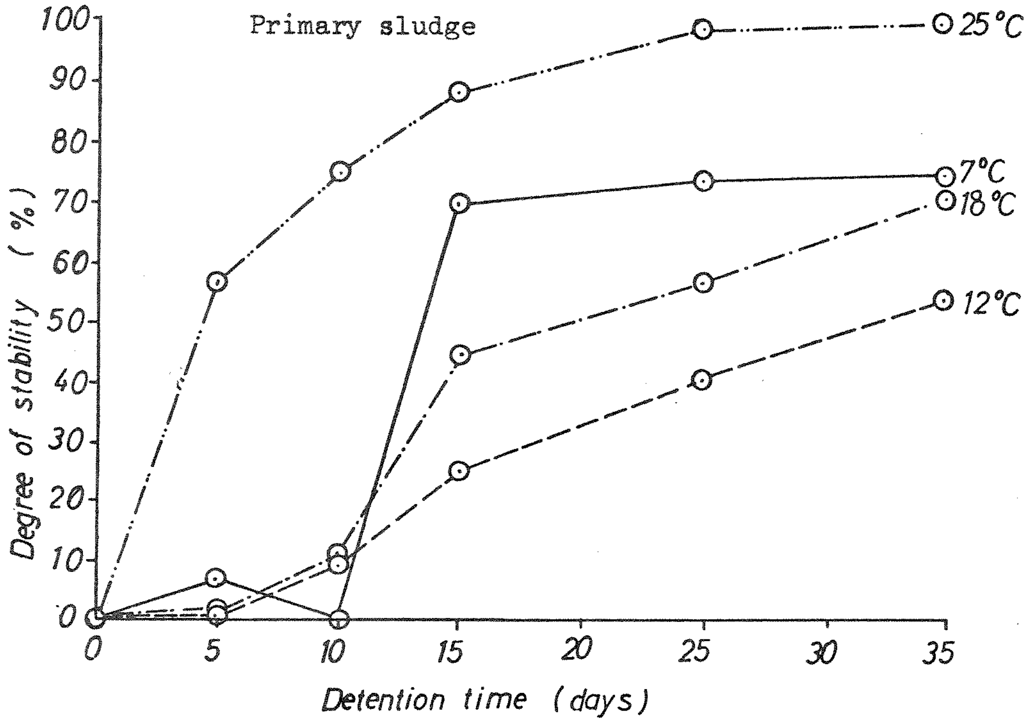
M = degree of stability

v_o, v_1 = organic solids content as per cent of total solids in raw and treated sludge respectively

m_o, m_1 = inorganic solids content as per cent of total solids in raw and treated sludge respectively

K = stability constant ($K_{prim} = 1{,}361$; $K_{prim/chem} = 2{,}028$)

Figure 59 shows the degree of stability (M) vs. detention time (days). At 25°C the sludge seems to reach a relatively high degree of stability fairly soon and then the curve flattens out. At the other temperatures investigated there seems to be a more moderate change of degree of stability with detention time. Both primary and mixed primary-chemical sludge stabilized at 7°C showed a higher degree of stability than expected. The reason for this is that probably the characteristics of the raw sludge (m_o and v_o) varied somewhat with time. If the four temperature series (7°C, 12°C, 18°C and 25°C) had been run at the same time,the result might have shown a better correlation. The author feels that this method can be used to measure degree of stability of sludge.



Primary sludge

Mixed primary/chemical sludge

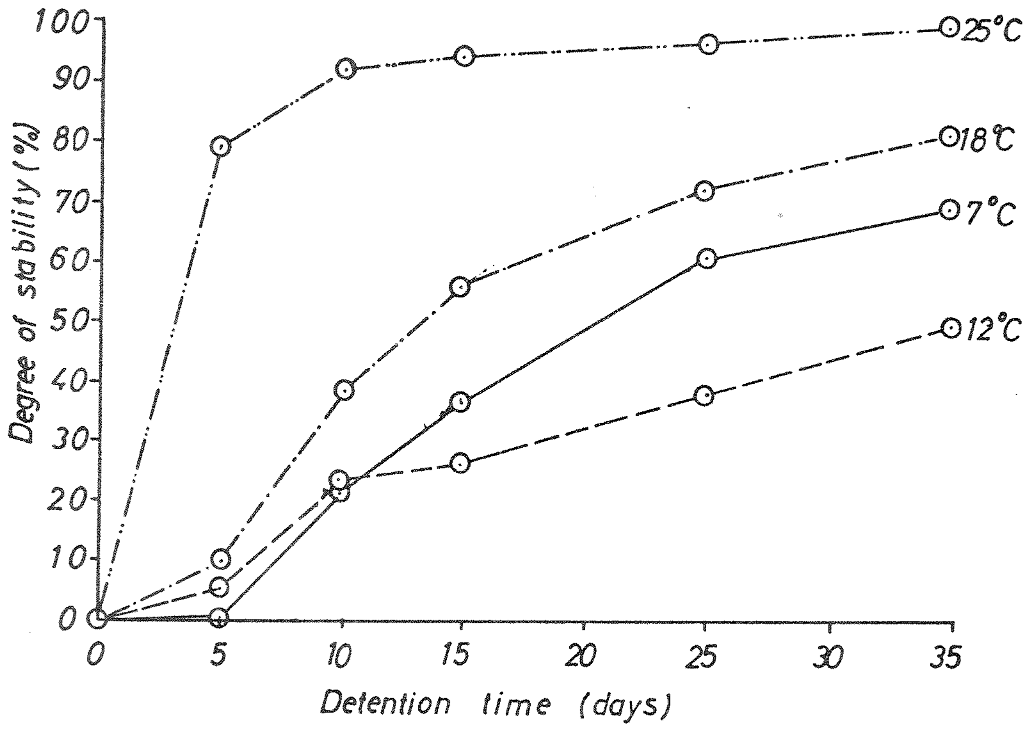


Figure 59. Degree of Stability vs. Detention Time.

However, the stability constant (K) must be determined through laboratory experiments and the values used for organic and inorganic content in the sludge (m_o, v_o) should be average values of a series of tests from different times.

EXPERIMENTAL RESULTS AND DISCUSSION - FULL-SCALE UNITS

General

The test program for the full-scale aerobic digesters was carried out according to the program although the length of the test period was reduced. The reason for this was that it became evident that no additional knowledge would be gained by carrying the test program past December 5, 1972. Several factors influenced the author of this dissertation in making this decision. First of all, it became evident that the digesters at Kjeller Research Station were larger than desirable: not enough sludge was produced in the treatment plants to load the digesters at a reasonable rate. Figure 60 indicates this quite clearly. This diagram shows the weekly average volume (m^3/week) of sludge added and the average detention times based on this weekly load. Only in the early part of the program did the detention time stay below one hundred days. These full scale digesters both had detention times far in excess of any of the pilot reactors. However, in spite of this, some information was gained from these experiments.

The outside aerobic digesters were by no means free from operational problems. The aerators originally had a skirt to prevent splashing on the walls and walkways. However, materials such as rags had a tendency to accumulate under this skirt and thus "ride" on the aerator-vanes. This would cause the motor to become overloaded and the overload switch would turn off the power. This problem was solved by removing the skirts from around the aerators.

Another problem which was not solved during this test period was the leakage of water through the walls and into the ground. This would happen when sludge was removed from the third digester, which was not used for the experiments. The problem was minimized by removing small volumes more frequently from the third digester and refilling it with new sludge or tap water as soon as possible. Construction of lagoons within 10 meters of the digesters and a change in the watertable might also have been part of the problem.

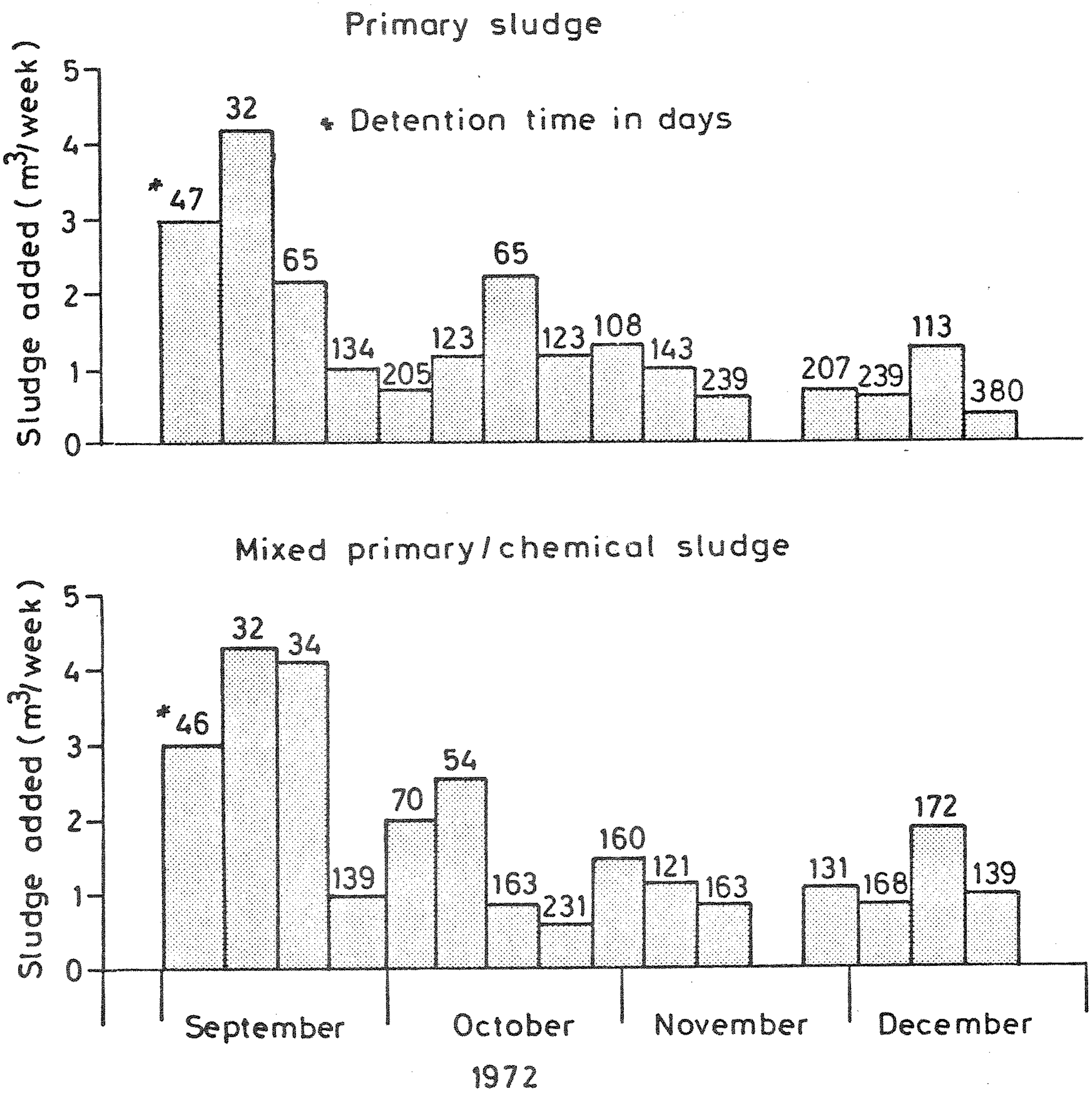


Figure 60. Sludge Added to Full-Scale Digesters.

One of the digesters treated primary sludge only. The second digester treated an equal volume of primary and chemical sludge to simulate the same conditions as in our pilot reactors. The quality of the raw sludge varied from day to day. This is shown in Figure 61. The variations in total suspended solids and volatile suspended solids were larger than what would be expected in a larger treatment plant. On the other hand, the per cent volatile suspended solids did not show abnormal fluctuations.

Variations in Temperature, pH and Organic Solids Reduction during the Test Period

During the last part of August and early part of September 1973, the temperature was above 10°C. However, early in the fall the temperature fell below 10°C and from the middle of October no temperature above 6.7°C was measured. In November the average temperature in the digester treating primary sludge was 3.4°C, well below any temperature investigated in our pilot study. The lowest temperature measured was 1°C on November 13.

This low temperature would, of course, influence the reduction of volatile suspended solids. For primary sludge the percentage of the volatile suspended solids was reduced from approximately 87% to 67%. Considering the long detention time in this aerobic digester, the reduction in volatile suspended solids is far less than what was found in the pilot studies at 7°C and 35 days detention time. Evidently low temperature and also wide fluctuations in temperature will reduce digester efficiency. Percent volatile suspended solids in the digested sludge had a tendency to increase if the temperature decreased and vice versa (See Figure 62).

Volatile suspended solids content of mixed primary-chemical sludge was reduced from the initial 76% to 64%. Again this is well below what was found during our pilot studies at 7°C. However, the per cent volatile suspended

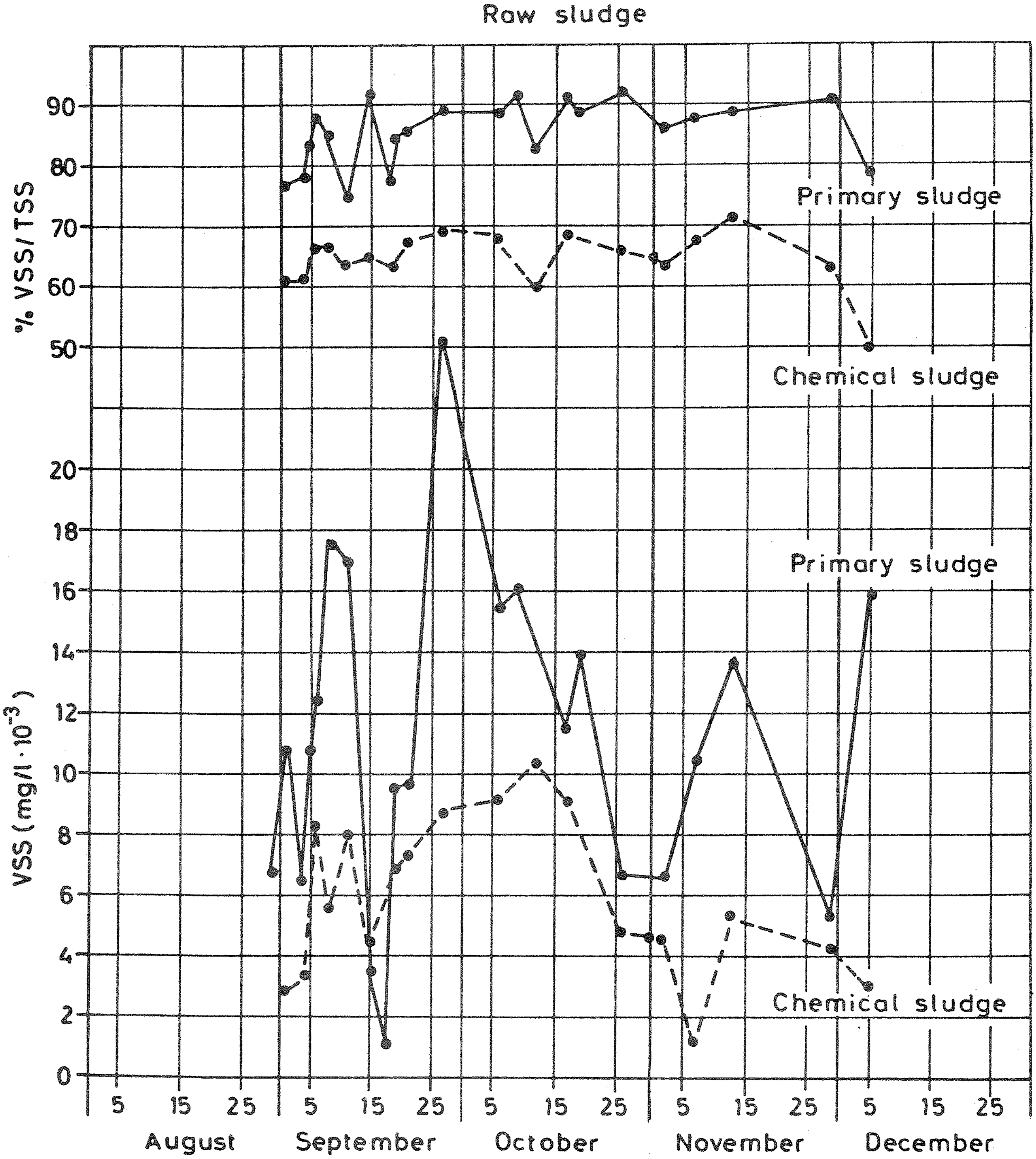


Figure 61. Total and Per cent Volatile Suspended Solids in Raw Sludge.

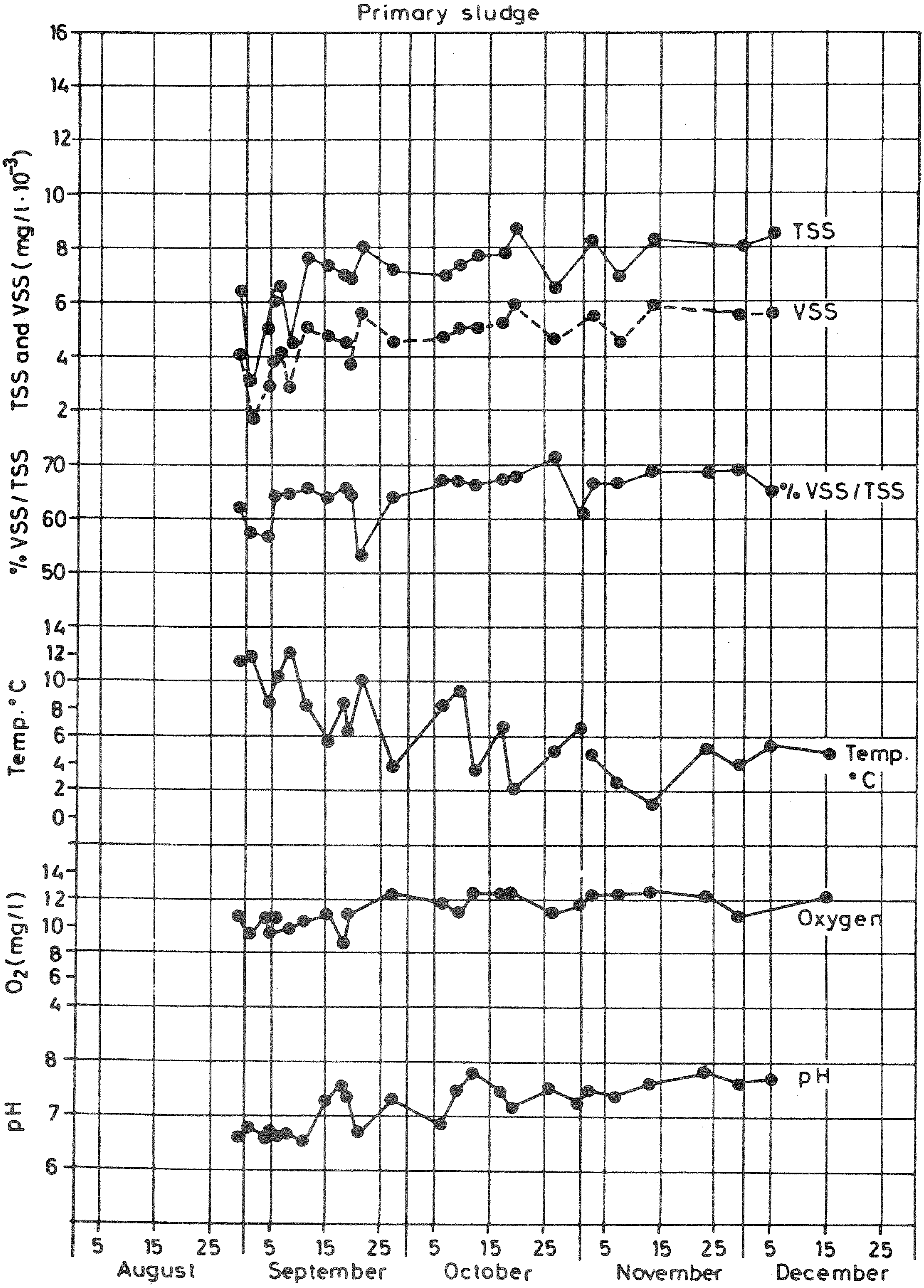


Figure 62. Digested Primary Sludge Data vs. Time.

solids did not seem to be influenced by the temperature to the same degree as the primary sludge. Again this is in agreement with the pilot studies where the temperature coefficient (θ) was found to be higher for primary sludge than for mixed primary-chemical sludge (See Figure 63).

Both pH and alkalinity increased in the digester treating primary sludge throughout the test period. This was expected since a reduction in temperature would slow down the overall process and deamination would cause the pH to rise. Surprisingly enough, the same increase in pH and alkalinity was not experienced in the digester treating mixed primary-chemical sludge. Again this indicates the efficiency of this unit was more independent of the temperature (See Figures 64 and 65) than the unit treating primary sludge.

Oxygen concentration was between 10 and 12 mg/l O_2 in the digester treating mixed primary-chemical sludge. The vanes on the aerator were not submerged deep enough during this period and a drop in oxygenation capacity resulted. Readjustment of the tank volume solved this problem.

The total phosphorus content in both digesters seemed to fluctuate early in the test period. These fluctuations, however, seemed to follow the fluctuations in suspended solids. In other words, the phosphorus content in primary sludge and mixed primary-chemical sludge were found to be approximately 150 mg/l-P and 270 mg/l-P respectively.

The content of orthophosphate in the supernatant remained below 1.0 mg/l-P throughout the test period for both types of sludges. For mixed primary-chemical sludge this was in agreement with our pilot studies. However, this was below what was found for primary sludge during the pilot studies.

Total nitrogen content seemed to be approximately the same in both digesters. Wide fluctuations were experienced, but seemed to follow fluctuations in in total suspended solids. The nitrogen content in the full-size aerobic digesters was in agreement with values obtained in our pilot study.

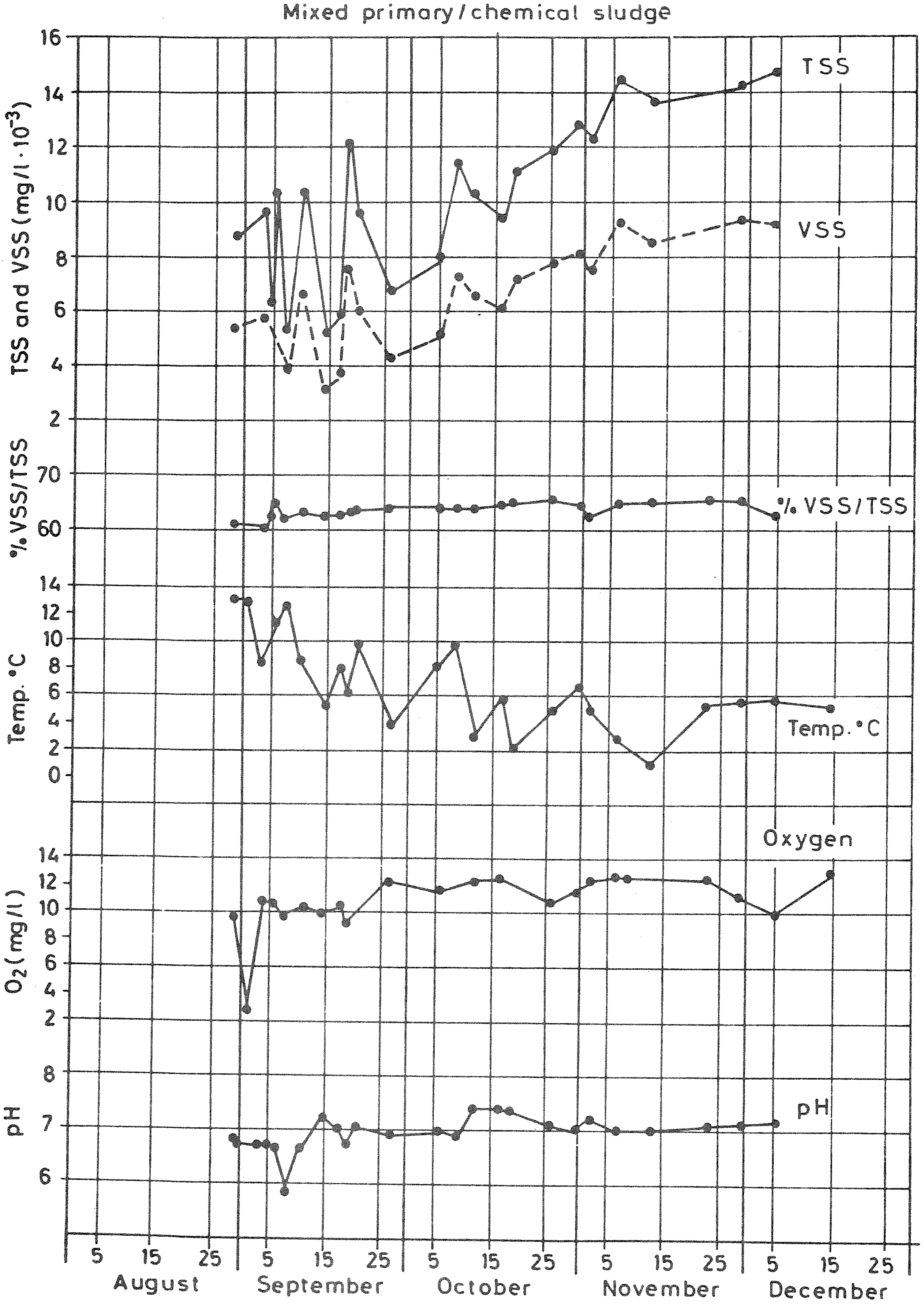


Figure 63. Digested Mixed Primary-Chemical Sludge Data vs. Time.

Primary sludge

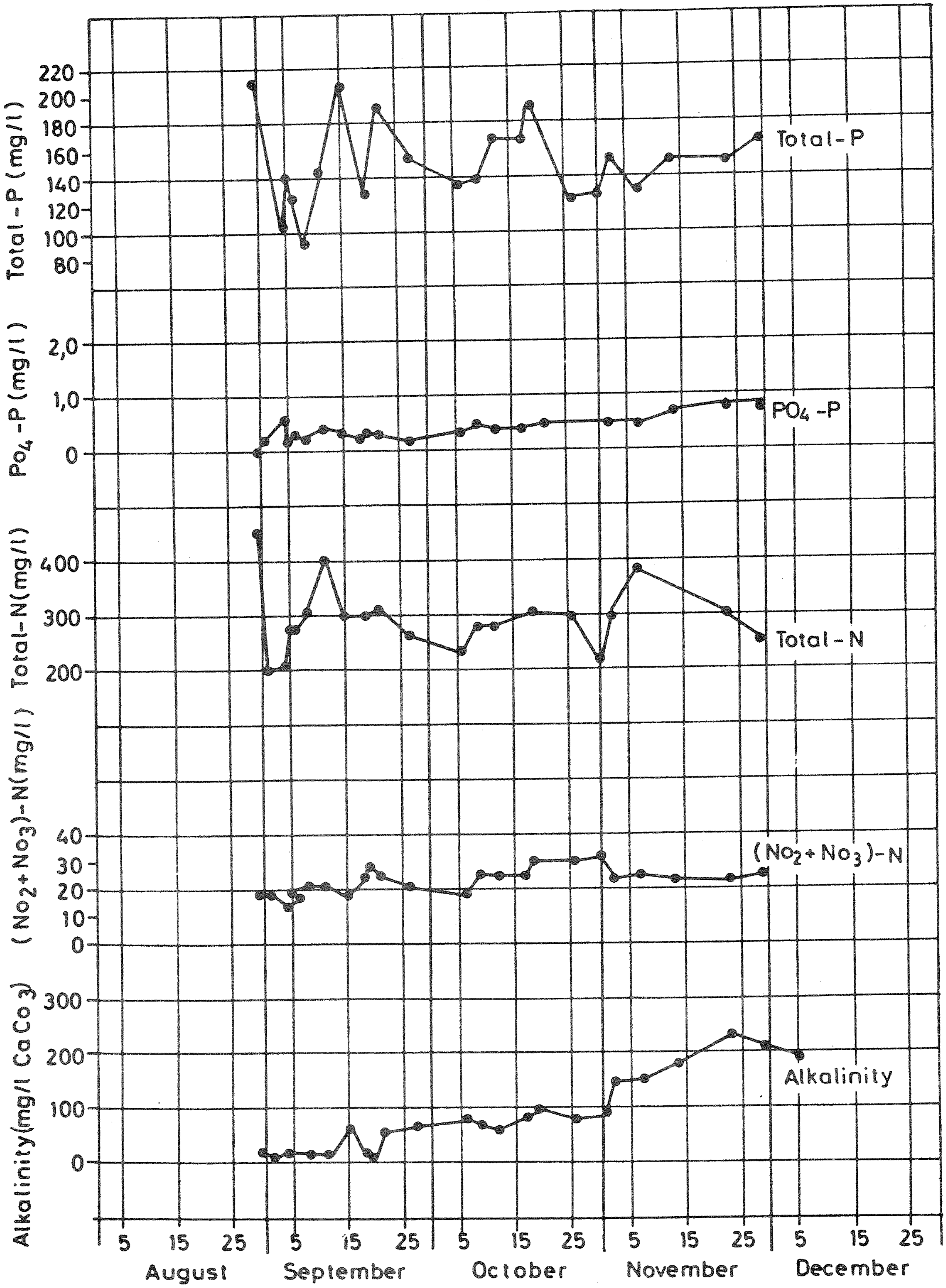


Figure 64. Digested Primary Sludge Data vs. Time.

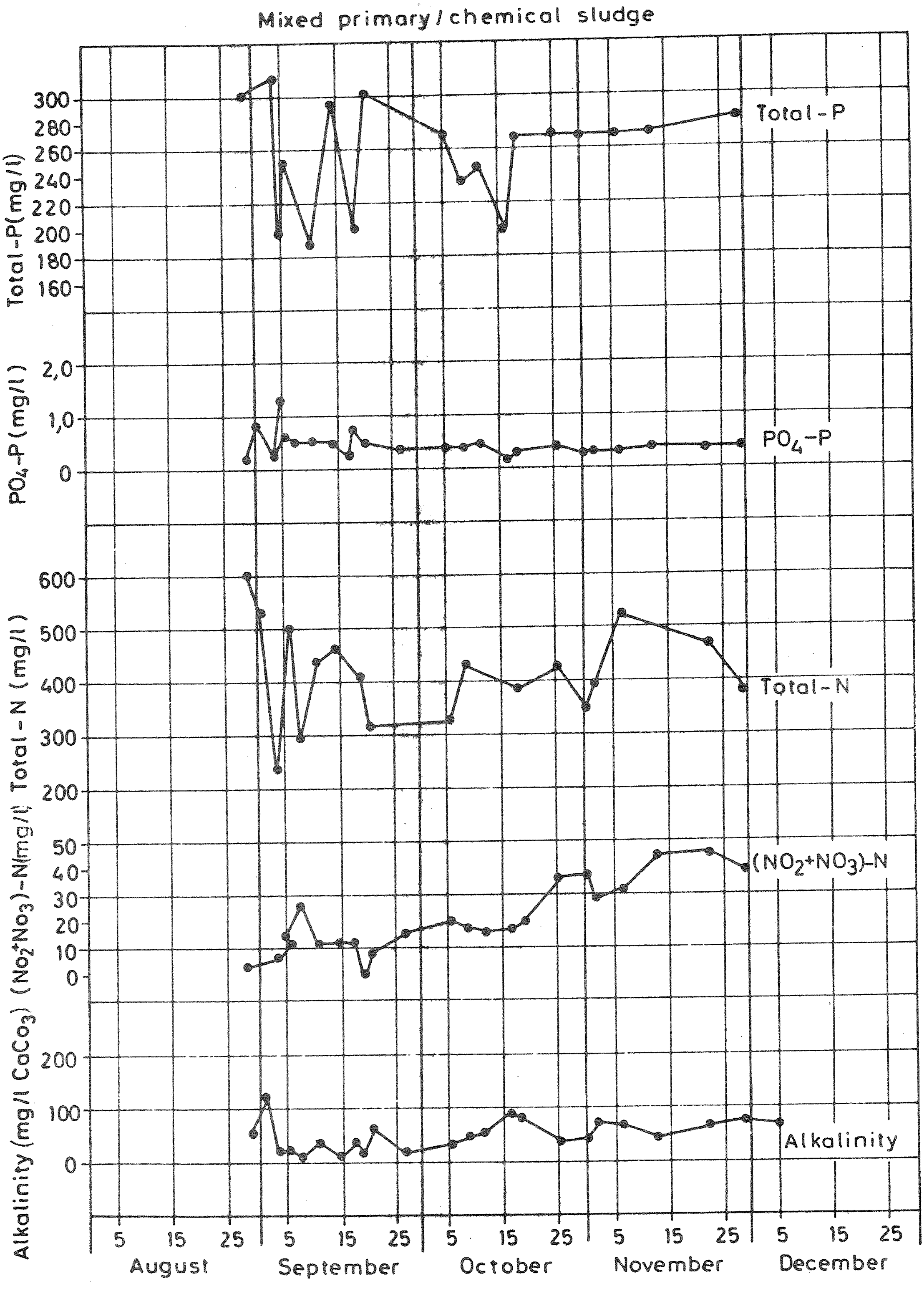


Figure 65. Digested Mixed Primary-Chemical Sludge vs. Time.

Content of nitrite and nitrate indicated that nitrification was taking place in both digesters. An ever increasing content of nitrite and nitrate in the digester treating mixed primary-chemical sludge gave the impression that nitrification was more apt to happen in this unit. This is something that the pilot studies also indicated.

Variations in Sludge Characteristics during the Test Period

Sedimentation and filtration properties were investigated using the test procedures outlined under "Analytical Procedures."

The sedimentation properties of the two types of sludges are shown in Figure 66. Both types of sludges showed better ability to settle than similar sludges during the pilot study. The reason for this is that the outside digesters carry a lower suspended solids concentration than the pilot units operating at 7°C and 12°C. Mixed primary-chemical sludge settles faster (higher interface velocity) than primary sludge. The same was the case during the pilot study.

The sedimentation test also was performed on samples taken at different locations in the aerobic digester to find out if the sedimentation properties would vary at different locations. However, identical results were obtained at the different locations in the digester. Specific resistance to filtration showed large variations during the test period. This is shown in Table 16 below.

Raw primary sludge and digested mixed primary-chemical sludge had the largest fluctuations in filtration properties. In the case of primary sludge, this was expected, but certainly not in the case of mixed primary-chemical sludge. However, during the pilot study a slight increase in specific resistance to filtration at 7°C was experienced, and therefore it was not unexpected to find values higher than in the untreated sludges. Untreated chemical sludge prior

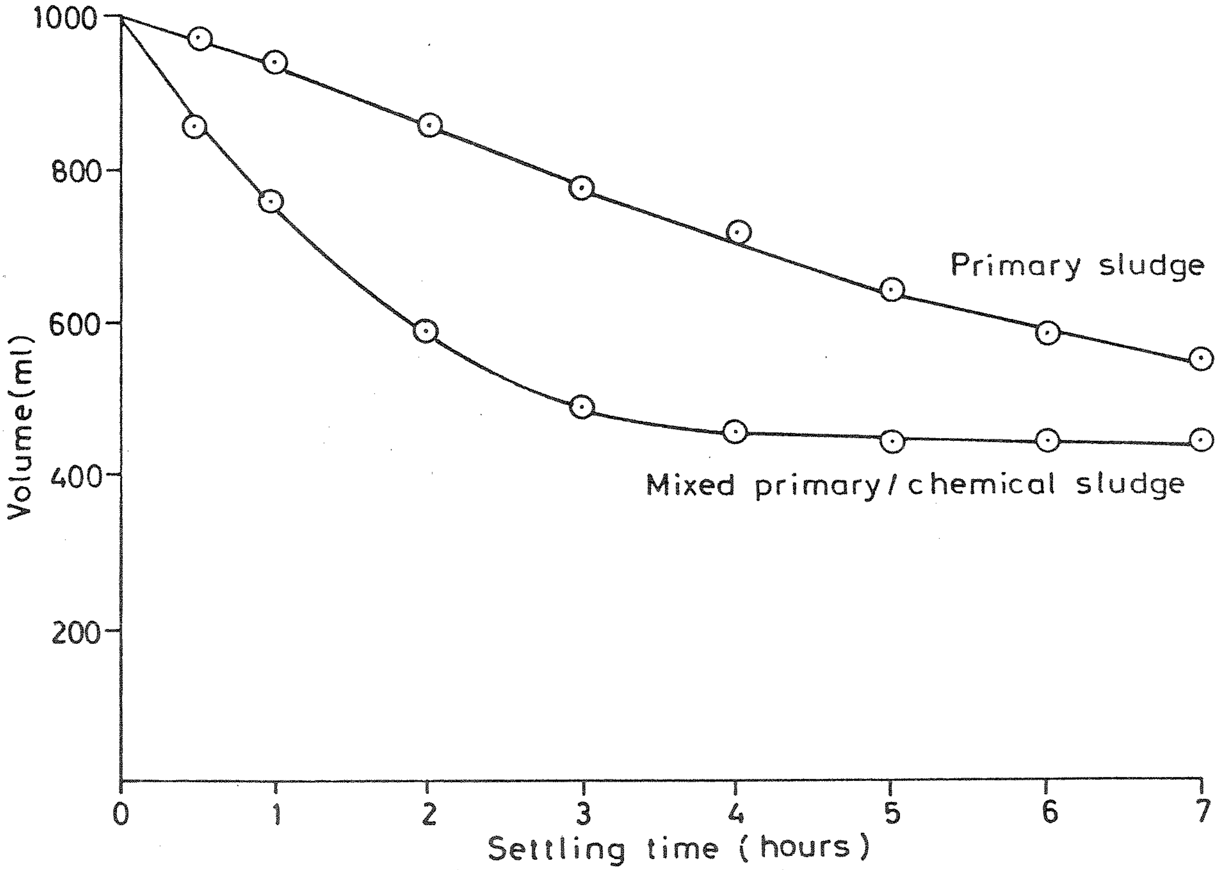


Figure 66. Settling Curves - Primary and Mixed Primary-Chemical Sludge.

to mixing with untreated primary sludge had the lowest specific resistance to filtration.

Type of Sludge	Specific resistance to filtration s^2/g		
	High	Low	Average
Primary (raw)	$19.68 \cdot 10^9$	$0.48 \cdot 10^9$	$3.08 \cdot 10^9$
Chemical (raw)	$3.57 \cdot 10^9$	$0.38 \cdot 10^9$	$1.59 \cdot 10^9$
Primary (digested)	$6.03 \cdot 10^9$	$1.25 \cdot 10^9$	$2.51 \cdot 10^9$
Mixed prim/chem (digested)	$12.58 \cdot 10^9$	$0.74 \cdot 10^9$	$3.39 \cdot 10^9$

Table 16. SPECIFIC RESISTANCE TO FILTRATION - FULL-SCALE DIGESTERS

Capillary suction time (CST) also was measured throughout the test period. CST/%TSS correlated well with specific resistance to filtration except in the case of raw primary sludge (See Figure 67). The reason for this has been mentioned earlier.

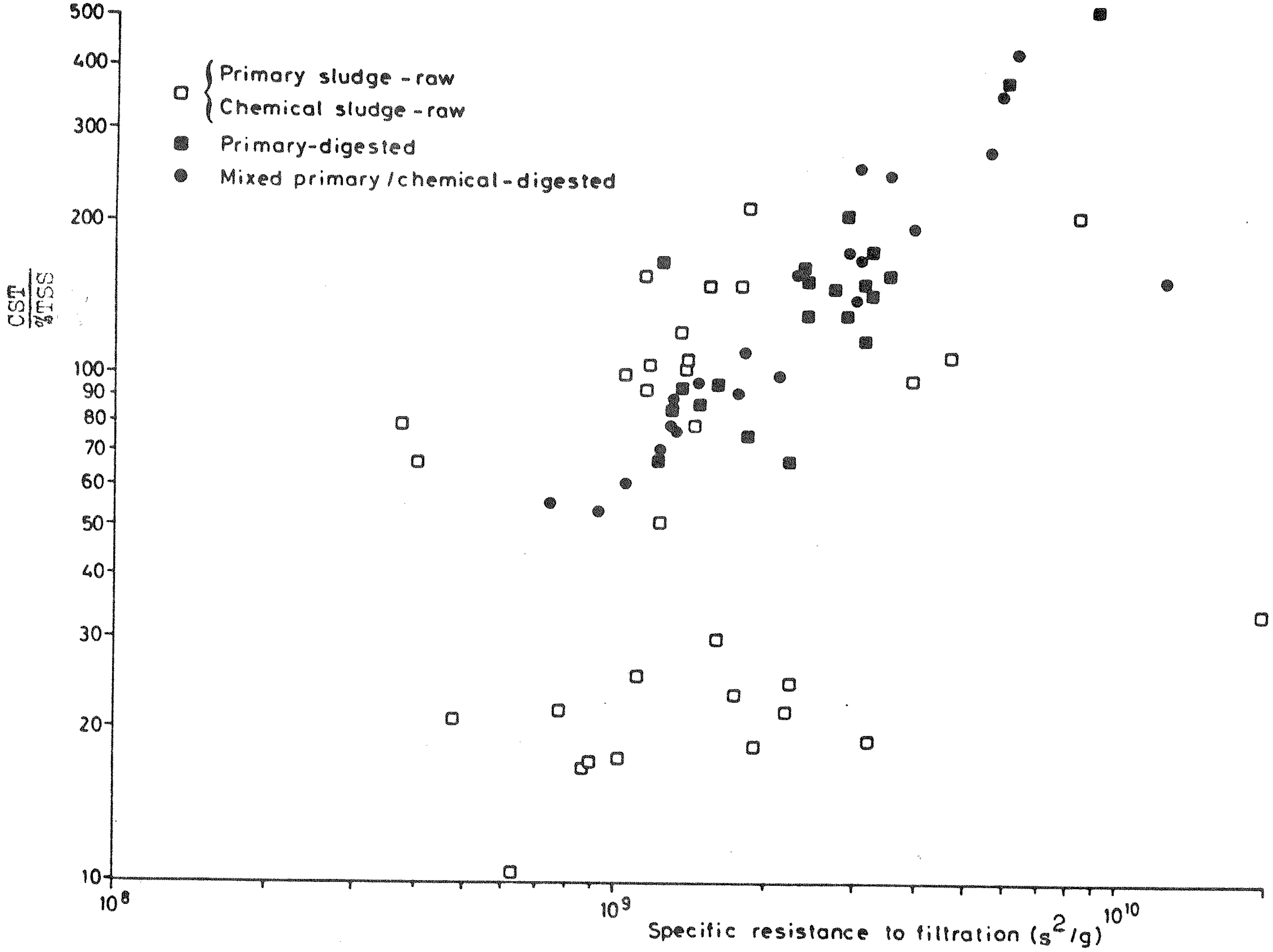


Figure 67. CST/%TSS vs. Specific Resistance to Filtration.

CONCLUSIONS

The following conclusions can be drawn from the results of this research:

1) Aerobic digestion of sludge from a primary-chemical treatment plant using alum will not be inhibited by the aluminum content in the sludge mixture.

2) The influence of temperature on the reductions of volatile suspended solids (VSS) is slightly greater on primary sludge than on mixed primary-chemical sludge. Based on the Q_{10} concept, the values were determined to be 2.72 for primary sludge and 2.19 for mixed primary-chemical sludge. The rate of decay constant (K_T) based on the reductions of volatile suspended solids was slightly higher for primary sludge at 25°C, but lower than for mixed primary-chemical sludge at 7°C, 12°C and 18°C.

3) Chemical oxygen demand (COD) was removed at approximately the same rate as the volatile suspended solids for both primary and mixed primary-chemical sludge.

4) pH would increase with increasing detention time up to approximately 10 days and then it would normally decrease slightly with detention times in excess fo 10 days. pH was never found to inhibit the digestion process by extremely high or low values. At times wide fluctuations in pH were experienced.

5) The alkalinity was reduced during the digestion process for both types of sludge. Higher reductions of alkalinity were generally experienced in the units treating mixed primary-chemical sludge. Values less than 10 mg/l $CaCO_3$ were not uncommon (initial value 230 mg/l $CaCO_3$).

6) Total nitrogen content in the sludge (solids and liquid) was reduced during the digestion process. Higher reductions were found at higher temperatures.

7) Nitrification took place in reactors treating both primary and mixed

primary-chemical sludge. The high content of aluminum in the mixed primary-chemical sludge did not inhibit the nitrifiers.

8) The nitrogen content as percentage of dry volatile suspended solids would increase during the digestion process in spite of a total nitrogen loss in the sludge (solids and liquid).

9) The oxygen uptake rate would normally decrease with increasing detention time and with decreasing temperature. Higher organisms in the heterogenous population would influence the oxygen uptake rate and make the oxygen uptake rate less valuable as a parameter to measure sludge stability.

10) ATP content per unit volatile suspended solids would increase during the early stages of the process (5-10 days) and then stay fairly constant with increasing detention time. ATP measurements indicated a very low content of active biomass during aerobic digestion.

11) Increasing reactor temperature would increase interface velocity during sedimentation for both primary and mixed primary-chemical sludge.

12) At low temperatures (less than 12°C) interface velocity is decreased for short detention times (5-10 days).

13) Sludge Volume Index (SVI) is not indicative of sedimentation properties of primary and mixed primary-chemical sludge.

14) Total water volume (per cent of total volume) drained from a sludge will increase with increasing detention time for both primary and mixed primary-chemical sludge.

15) Untreated primary sludge has poorer drainage properties than untreated mixed primary-chemical sludge.

16) Between 85 and 90 per cent of the water in the treated sludge can be removed by drainage.

17) Final solids concentration in the sludge cake after drainage tests is nearly independent of both the reactor temperature and the degree of stabilization.

18) Quality of the filtrate will improve with increasing detention times for both types of sludge investigated. Drained water can be discharged directly to the receiving water without being piped back to the plant inlet.

19) Filtration properties, measured as specific resistance to filtration or capillary suction time, generally improved with increasing detention times, except mixed primary-chemical sludge stabilized at 7°C and 12°C.

20) Primary sludge which stabilized at 7°C did not show any significant change in filtration properties.

21) Measurements of specific resistance to filtration and capillary suction time (CST) gave the same result. A straight line relationship was found between CST/%TSS and specific resistance to filtration on a logarithmic scale. A better correlation was found between these two parameters for mixed primary-chemical sludge than for primary sludge alone.

22) Sludge compressibility increased with increasing detention time for both primary and mixed primary-chemical sludge. Mixed primary-chemical sludge had higher initial compressibility than primary sludge, but showed less change in compressibility during the digestion process.

23) Total phosphorus content in the sludge (solids and liquid) will not change during aerobic stabilization.

24) Orthophosphate concentration in the liquid phase is less in mixed primary-chemical sludge than in primary sludge.

25) The phosphorus content as percentage of dry volatile suspended solids will increase during the digestion process for both primary and mixed primary-chemical sludge.

26) During anoxic storage of primary sludge at different degrees of stability, phosphorus always will be released from the solid phase to the liquid phase. The rate of release is high during the first 3 to 4 days and a maximum value is reached after 10 to 12 days of storage.

27) Ultimate orthophosphate release ($mgPO_4/mgVSS$) will decrease with increasing detention time.

28) No release of phosphorus during anoxic storage of mixed primary-chemical sludge will take place.

29) Higher organisms were found in all reactors regardless of temperature and type of sludge. Under no circumstances did the high concentrations of aluminum inhibit growth of higher organisms.

30) Stalked ciliates were more abundant at low temperatures than at high temperatures.

31) Less reductions of volatile suspended solids were found in full-scale digesters than in the pilot units. Low temperature and wide fluctuations in temperature were the probable reason for this.

32) Mixed primary-chemical sludge from the full-size aerobic digester shows better sedimentation properties than primary sludge.

33) Specific resistance to filtration and capillary suction time showed large

variations with time in both full-scale digesters.

34) From a practical standpoint, mixed primary-chemical sludge (raw or digested) was easier to work with (less clogging of pumps, easier to sample, etc.) than primary sludge. At a primary-chemical treatment plant the sludges should be mixed rather than kept separate.

35) Rüffer's lead acetate test or the modified expression given by Rawn and Bant can be used as a rough measure of the degree of stability of sludges.

SIGNIFICANCE OF RESEARCH AND DESIGN RECOMMENDATIONS

Results obtained in this research project provide valuable information in the design of aerobic digesters treating primary or mixed primary-chemical sludge. First, the reduction rates of total suspended solids (TSS) and volatile suspended solids at different temperatures must be known in order for the design engineer to select the proper detention time to obtain a certain reduction in these solids. In addition, with a known reduction of TSS and VSS, the amount of dry solids for dewatering and final disposal can be estimated.

Thickening of digested sludge is done either in the digester unit itself or in a separate thickener. The sedimentation properties of the digested sludge must be known in order to determine the proper thickener dimensions and the volume of thickened sludge. Valuable data on the sedimentation properties and how it varies with detention time and temperature is given in this dissertation.

Selection of the proper type and size of dewatering equipment often is a difficult phase in the design of a sewage treatment facility. If the plant is small, drying beds often are the answer. An effort was made in this study to give valuable information on the drainage properties of aerobically digested sludge. From the information on the water content of the filtercake after drainage, the amount of sludge that has to be removed from a drying bed can be estimated.

Mechanical dewatering equipment such as a vacuum filter, sieve-belt press or centrifuge can be used to dewater aerobically digested sludge. However, to estimate the performance of mechanical dewatering equipment, the specific resistance to filtration and compressibility should be known. This was recognized by the author and tests to determine these properties were made.

Since the problem of phosphorus release during storage of digested sludge has been raised, the author also made an effort to provide enough information so that this question could be answered.

Based on the results obtained in this research project, the author would recommend the use of aerobic digestion as a method of stabilizing primary- and mixed primary-chemical sludge in Norway. The author is not, however, of the opinion that other alternatives should not be investigated. For large plants anaerobic digestion might be a less costly solution.

The major reasons for recommending aerobic digestion in Norway are:

1) Most treatment plants in Norway will treat waste from less than 3000 people (more than 60 percent of all rural municipalities and towns in Norway have less than 3000 people and only 8 percent have more than 10,000 people). Therefore, aerobic digestion will be less costly than anaerobic digestion in most cases.

2) Aerobically digested sludge will create no odor problem when dewatered on a drying bed or disposed of in a sanitary landfill.

3) Aerobic digesters have no sophisticated mechanical equipment that is difficult to operate or maintain, The need for highly trained operators, therefore, is less than for anaerobic digesters. Only regular maintenance of diffusors and blowers are necessary. At the present time no training is required by the Norwegian government to operate wastewater treatment plants, although a short course is available once a year.

4) The sludge supernatant from aerobic digesters is low in biochemical oxygen demand(BOD)and total suspended solids (TSS) and will in most cases meet the Norwegian governmental requirements for release to the receiving water. Therefore, there would be no need for recycling the supernatant to the plant inlet. This would not be the case with anaerobic digestion.

5) Aerobic digestion will generally improve the sedimentation, filtration and drainage properties of the sludge. It is the author's experience that this

is not the case with anaerobically digested sludge.

6) Since toxic waste or high hydraulic loadings can upset biological treatment plants and cause a complete loss of solids, the aerobic digester can serve as a "buffer tank" for biological solids. Sludge from the aerobic digester can be used to reestablish normal plant conditions.

7) An additional advantage with aerobic digestion is that no precautions are necessary to prevent explosions from methane gas.

Since a comparison often must be made between aerobic and anaerobic digestion, the author feels the advantages with anaerobic digestion should also be mentioned. First, the influence of the surrounding temperature will not affect a heated digester. Second, the use of the methane gas will reduce the cost of digestion for larger plants. Therefore, before a decision is made on which process to use, it is important to make complete cost estimates of both processes.

Based on the pilot study and the experience gained from the full-scale aerobic digesters, the following recommendations for design can be given. The author would like to stress that these recommendations will only be valid for the types of sludges investigated in this study.

1) The hydraulic detention time in the aerobic digester should not be less than the values given below. These values are based on approximately 35-45 percent reduction of volatile suspended solids.

Sludge	Detention Time - Days			
Temperature	7°C	12°C	18°C	25°C
Primary	35-45	25-30	12-18	8-13
Mixed prim/chem	35-45	25-30	12-20	7-15

Table 17. REQUIRED DETENTION TIME (days)FOR DIFFERENT TEMPERATURES

The aerobic digester should be designed so that the required amount of oxidation will take place during the colder time of the year.

2) Aerobic digesters should have a building to prevent severe low temperatures during the winter and ice formation in the digester.

3) Surface aerators should not be used. These aerators create a fine spray of water in the building and thus create a possible health hazard for plant operators. These aerators would also require the water level in the unit to be maintained at a certain level, which may not be practicable.

4) Theoretical air requirements must not be based on oxygen uptake rates, but on the air required to maintain the sludge in suspension. Design values should be approximately 25-40 $l/min/m^3$ digester volume (high values for primary sludge).

5) Sock-type diffusors should be used to minimize clogging. Air piping and diffusor assembly should be designed to facilitate cleaning.

6) Dewatering of digested primary sludge should be made as soon as possible after the withdrawal of sludge from the digester to prevent release of phosphorus to the supernatant. This does not have to be considered during digestion of mixed primary-chemical sludge.

RECOMMENDATIONS FOR FUTURE STUDY

Recommendations for future study are the following:

1) Further field observations of aerobic digesters treating primary and mixed primary-chemical sludge should be made to find the fluctuations in digester efficiency over a period of one year or more and from different locations.

2) Aerobic digestion of iron sludge mixed with primary sludge should be investigated in a similar manner to what was done in this research project.

3) There is a need for reliable methods to measure the degree of stability of sludges. Future work should therefore be focused on practical methods that can be used by plant personnel to measure the degree of stability of sludges withdrawn from an aerobic digester. Standard procedures for performing the tests should be made so that results from different plants can be compared.

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APPENDIX A

UNTREATED SLUDGE DATA - PILOT UNITS

SUMMARY SHEET

PRIMARY SLUDGE (UNTREATED)

Sludge	Date	NH_4-N mg/1-N	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N
Prim.	Jul.26	-	-	20664	16806	81.3	26900	188	32	660	0.01
"	Aug. 3	-	-	19355	15081	77.9	16506	-	33	416	0.07
"	" 11	-	-	24362	20046	82.3	21580	110	27	1080	0.02
"	" 18	-	-	16727	15527	92.8	16727	105	26	-	0.02
"	" 25	-	-	19890	14930	75.1	16810	131	34	735	0.02
"	" 28	-	360	21418	16506	77.0	15840	136	32	776	0.02
"	" 30	-	232	21050	15961	75.8	20839	133	32	706	0.04
"	Sep. 1	-	360	18681	15165	81.2	21705	152	23	552	0.03
"	" 8	-	-	19964	16933	84.8	16978	87	53	784	0.18
"	" 11	-	316	18907	15950	84.3	18261	66	58	698	0.10
"	" 13	-	324	18711	15695	83.9	20136	162	44	640	0.06
"	" 15	-	296	19421	17234	88.7	10960	-	45	624	0.18
"	" 18	-	-	21548	19215	89.2	27049	131	48	646	0.03
"	" 20	-	260	21409	19195	89.7	26845	137	55	513	0.03
"	" 21	-	276	20533	17843	86.9	24876	174	49	593	0.03
"	" 27	-	-	21193	19708	93.0	20992	135	33	701	0.02
"	Oct. 4	-	239	24075	22608	93.9	21128	147	44	464	0.03
"	" 5	-	185	21454	19621	91.5	27025	187	36	624	0.01
"	" 9	-	208	21665	19831	91.5	29311	-	-	-	-
"	" 11	-	231	21269	19599	92.1	32142	-	-	-	-
"	" 12	-	195	21524	20241	94.0	29947	77	25	551	< 0.01
"	" 19	-	138	20698	19192	92.7	28815	-	21	526	0.05
"	" 27	-	142	20069	17203	85.7	21797	119	23	431	< 0.01
"	Nov. 3	-	192	19691	16880	85.7	29058	153	30	557	< 0.01
"	" 10	-	169	19563	17360	88.7	21207	115	3	423	< 0.01
"	" 17	-	155	20229	18420	91.1	24146	122	7	390	< 0.01
"	" 20	-	144	20616	18863	91.5	24320	98	28	365	0.02

SUMMARY SHEET

PRIMARY SLUDGE (UNTREATED) - continued:

Sludge	Date	NH_4-N mg/1-N	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N
Prim.	Nov.22	-	168	20796	19012	91.4	27396	98	30	477	0.02
"	" 27	93.1	97	19154	17547	91.6	26160	144	35	486	0.02
"	" 28	-	116	21218	18962	89.4	25700	128	25	494	0.01
"	" 29	6.0	149	19300	17426	90.3	26415	136	28	392	0.01
"	Dec. 4	91.8	188	19410	17346	89.4	20740	113	42	456	0.05
"	" 6	28.3	118	20861	15947	76.4	21845	86	14	357	0.02
"	" 7	-	116	21017	17044	81.1	22308	72	9	-	0.06
"	" 11	22.1	120	23888	19734	82.6	24488	72	16	394	0.03
"	" 13	93.2	130	24421	20232	82.8	23300	105	19	584	0.08
"	" 14	-	117	21967	19540	89.0	25819	95	21	517	0.03
"	" 21	-	178	23748	-	-	-	154	44	632	0.10
"	Jan. 1	-	206	22009	18156	82.5	-	155	38	685	0.04

SUMMARY SHEET

MIXED PRIMARY/CHEMICAL(UNTREATED)

Sludge	Date	NH_4-N mg/1-N	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N
Pr/Ch	Jul. 7	-	-	15808	12294	77.8	23100	360	0.45	685	< 0.01
"	Aug. 3	-	-	14414	10131	70.3	12160	249	0.32	327	0.07
"	" 11	-	-	17528	13996	79.8	11960	313	0.11	685	0.02
"	" 18	-	-	13600	10680	78.5	11400	207	0.27	392	0.07
"	" 25	-	-	17470	11400	65.3					
"	" 29	-	210	16324	11004	67.4	15320	304	0.18	512	0.09
"	" 31	-	184	16859	8500	50.4	14286	306	0.45	392	0.02
"	Sep. 1		148	15285	11016	72.1	14885	306	0.45	678	< 0.01
"	" 8	-	-	16304	12537	76.9	12794	314	1.30	672	0.01
"	" 12	-	236	16799	12503	74.4	17304	325	1.80	720	0.04
"	" 14	-	266	16773	12779	76.1	19120	272	0.90	776	0.02
"	" 15	-	214	18511	14362	77.6	29770	-	1.10	-	< 0.01
"	" 19	-	251	18309	14380	78.5	17488	248	0.39	435	0.02
"	" 21	-	240	17899	13451	75.2	18848	350	0.70	678	< 0.01
"	" 27	-	-	17985	14681	81.6	19171	314	-	649	< 0.01
"	Oct. 5	-	141	17281	14399	83.3	19492	363	1.50	624	< 0.01
"	" 5	-	186	16733	13404	80.1	18566	366	0.06	483	0.03
"	" 10	-	-	17403	14462	83.1	17944	-	-	-	-
"	" 12	-	-	18109	15116	83.5	23928	297	0.90	560	0.01
"	" 12	-	194	16908	14015	82.0	22027	-	-	-	-
"	" 19	-	141	17270	14051	81.4	21201	348	0.40	547	< 0.01
"	" 27	-	144	17527	12996	74.1	21024	310	0.90	365	< 0.01
"	Nov. 3	-	154	18450	14235	77.2	20300	292	0.60	620	< 0.01
"	" 10	-	179	17447	13969	80.1	22230	220	4.40	486	< 0.01
"	" 17	-	145	17364	14517	83.6	22230	246	7.0	474	0.01
"	" 21	-	197	16524	13683	82.8	20301	292	6.4	471	< 0.01
"	" 23	-	123	17317	14532	83.9	20880	232	6.0	512	0.01

SUMMARY SHEET

MIXED PRIMARY/CHEMICAL (UNTREATED) - continued:

Sludge	Date	NH_4-N mg/1-N	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N
Pr/Ch	Nov.28	-	132	18607	14812	79.6	24800	328	1.50	474	< 0.01
"	" 28	33.6	126	18360	14873	81.0	22160	304	0.06	442	0.07
"	" 30	-	203	18208	14696	80.7	21804	306	0.70	420	0.08
"	Dec. 5	72.2	160	18129	14625	80.7	25254	304	0.50	471	0.02
"	" 7	21.6	36	17342	11604	65.4	17440	163	0.22	409	0.06
"	" 12	21.2	62	17440	11331	65.0	18361	172	0.23	350	0.04
"	" 14	-	129	19399	14761	76.1	20549	204	0.37	472	< 0.01
"	" 14	69.0	67	17037	10976	64.4	14039	168	0.18	336	0.07
"	" 21	-	188	21053	-	-	25165	269	1.00	635	0.03
"	Jan. 5	-	204	19915	14273	71.7	25200	270	-	610	0.04

SUMMARY SHEET

CHEMICAL SLUDGE (UNTREATED)

Sludge	Date	NH_4-N mg/1-N	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N
Chem.	Jul. 26	-	-	12682	8624	68.0	11400	391	0.60	470	< 0.01
"	Aug. 8	-	-	13040	7480	57.4	9660	380	0.28	380	0.05
"	" 8	-	-	12742	7954	62.4	11806	470	0.30	510	0.01
"	" 25	-	-	13826	6320	45.7	11200	464	0.12	616	< 0.01
"	Sep. 1	-	84	12532	8166	65.2	11769	563	0.18	473	< 0.01
"	" 8	-	-	13335	8844	66.3	11956	344	-	666	< 0.01
"	" 15	-	106	15247	9610	63.0	14064	480	0.23	666	< 0.01
"	" 21	-	159	16567	10432	63.0	17568	526	0.16	-	< 0.01
"	" 27	-	-	14948	9956	66.6	14221	411	0.32	701	< 0.01
"	Oct. 5	-	89	12536	8654	69.0	13395	519	1.40	469	0.03
"	" 12	-	164	14896	10628	71.3	19736	392	0.41	568	< 0.01
"	" 19	-	126	14360	9760	68.0	20643	530	0.35	681	< 0.01
"	" 27	-	138	15038	9920	66.0	20552	449	0.49	608	< 0.01
"	Nov. 3	-	151	15080	9855	65.4	17250	408	0.60	604	0.01
"	" 10	-	188	14551	10624	73.0	19072	291	0.90	543	< 0.01
"	" 17	-	133	14799	11020	74.5	20219	364	2.30	541	0.01
"	" 28	-	134	15220	10676	70.1	19540	544	0.38	435	< 0.01
"	Dec. 7	-	5	14550	6668	45.8	9030	243	0.19	308	0.40
"	" 14	-	99	14716	8456	57.5	13440	320	0.18	428	< 0.01
"	" 21	-	136	15966	-	-	14960	432	0.24	587	0.01
"	Jan. 5	-	162	15057	8604	57.1	14800	392	-	564	0.03

APPENDIX B

DIGESTED SLUDGE DATA - PILOT UNITS

SUMMARY SHEET

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/1	pH	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% VSS/TSS	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N	NH_4-N mg/1-N	O_2-uptake mg/gVSS/hr
Prim.	Aug.30	5	7	6.95	6.65	82.2	-	-	77.6	20200	128.0	1.9	720	0.02	-	1.10
"	Sep.13	5	7	1.50	6.90	142.0	19775	16236	82.1	17208	125.5	6.4	640	0.01	-	1.96
"	Sep.20	5	7	4.90	7.45	297.0	21106	18146	86.0	22800	134.9	20.0	602	0.04	-	1.55
"	Oct. 4	5	7	6.50	7.25	258.0	19902	17699	88.9	-	155.2	16.0	720	0.02	-	1.43
"	Oct.11	5	7	7.40	7.40	222.0	19789	17638	89.1	22079	-	-	-	-	-	1.31
Average						200.2	20143	17422		20572	135.9	11.1	671	0.03.		1.47
Prim.	Aug.30	10	7	6.30	7.05	127.9	-	16296	-	16880	128.0	1.4	640	0.03	-	0.90
"	Sep.13	10	7	7.45	6.55	54.0	16598	-	79.5	13708	113.0	2.9	640	0.01	-	0.41
"	Sep.20	10	7	7.95	7.20	131.0	16993	13665	80.4	18100	120.0	7.5	523	0.02	-	1.27
"	Oct. 4	10	7	8.10	7.15	137.0	19423	16196	83.4	15811	-	10.0	368	0.02	-	1.08
"	Oct.11	10	7	7.50	7.25	172.0	17450	14787	84.7	17818	-	-	-	-	-	1.21
Average						124.4	17616	15528		16463	120.3	5.5	543	0.02		1.17
Prim.	Aug.30	15	7	7.90	7.25	146.1			74.9	16946	130.0	1.4	702	0.01	-	1.01
"	Sep.13	15	7	8.10	6.80	60.0	18003	13616	75.6	15760	113.0	2.8	512	0.01	-	1.10
"	Sep.20	15	7	8.40	7.00	71.0	18531	14406	78.2	18750	162.4	4.4	390	0.02	-	0.83
"	Oct. 4	15	7	8.70	7.10	113.5	15202	10172	81.7	-	138.4	6.5	416	0.03	-	-
"	Oct.11	15	7	8.30	7.15	134.0	16971	14337	84.5	18498	-	-	-	-	-	0.96
Average						104.9	17176	13155		17489	136.0	3.8	528	0.02		0.98

S U M M A R Y   S H E E T

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/1	pH	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N	NH_4-N mg/1-N	O_2-uptake mg/gVSS/hr
Prim.	Aug.30	25	7	8.25	7.05	95.2	-	-	64.4	14258	133.0	0.7	967	0.09	-	0.93
"	Sep.13	25	7	9.00	6.55	60.0	16379	11737	71.7	15576	113.0	1.9	672	0.01	-	0.92
"	Sep.20	25	7	9.10	6.90	68.0	17425	12841	73.7	14100	140.4	2.9	402	0.05	-	0.70
"	Oct. 4	25	7	9.65	6.50	53.5	15841	12300	77.6	14779	135.8	4.6	155	8.5	-	0.83
"	Oct.11	25	7	8.60	7.00	75.5	15446	12283	79.6	15805	-	-	-	-	-	0.98
Average						70.4	16273	12292		14904	130.6	2.5	549	2.16		0.87
Prim.	Aug.30	35	7	9.10	6.85	61.4	-	-	70.0	12326	131.0	0.5	792	3.3	-	1.00
"	Sep.13	35	7	9.70	5.70	32.0	16222	11577	71.4	14832	113.0	1.8	520	11.2	-	0.93
"	Sep.20	35	7	10.50	5.55	15.0	16944	12541	74.0	16900	150.4	4.8	371	29.0	-	0.66
"	Oct. 4	35	7	10.50	6.15	30.5	14663	11164	76.1	12077	124.9	6.4	533	19.0	-	0.56
"	Oct.11	35	7	9.00	6.90	42.0	14586	11845	81.2	15834	-	-	-	-	-	0.84
Average						36.2	15616	11782		14394	129.8	3.4	554	15.6		0.80

S U M M A R Y   S H E E T

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/1	pH	Alkalinity mg/1 $CACO_3$	TSS (mg/1)	VSS (mg/1)	$\frac{VSS}{TSS}$ %	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N	NH_4-N mg/1-N	O_2-uptake mg/g VSS/h
Prim.	Nov.22	5	12	5.15	6.80	81.0	18910	16617	88.0	20720	112.0	5.8	480	0.02	-	2.06
"	Nov.29	5	12	6.60	6.85	73	20390	18259	89.6	20960	104.0	7.8	474	0.01	-	1.63
"	Dec. 6	5	12	7.70	6.70	64	18148	16574	91.3	22800	102.0	12.0	518	0.03	-	1.23
"	Dec.11	5	12	8.80	7.15	65	21142	17460	82.6	24216	81.6	2.1	542	0.03	-	-
Average						71	19648	17228		22174	99.9	6.9	504	0.03		1.64
Prim.	Nov.22	10	12	6.05	6.95	100	17675	15259	86.3	19384	115.4	7.1	517	0.02	-	1.57
"	Nov.29	10	12	6.20	7.05	104	17664	15473	87.6	18000	112.0	5.5	442	0.05	-	1.67
"	Dec. 6	10	12	4,20	6.80	90	16103	14259	88.6	19843	107.4	6.6	489	0.02	-	1.26
"	Dec.11	10	12	7.00	7.10	87	19363	16148	83.4	19616	93.6	2.9	541	0.04	-	-
Average						95	17701	15285		19211	107.1	5.5	497	0.03		1.50
Prim.	Nov.22	15	12	6.05	7.00	101	15492	13075	84.4	17886	113.2	7.5	525	0.03	-	2.20
"	Nov.29	15	12	6.80	7.10	114	16309	14084	86.4	17760	120.0	5.7	435	0.01	-	1.87
"	Dec. 6	15	12	5.10	6.95	104	15834	13609	86.0	18717	119.2	6.7	399	0.02	-	1.76
"	Dec.11	15	12	7.80	7.25	94	15071	12355	82.0	16872	89.6	3.3	578	0.04	-	-
Average						103	15677	13281		17809	110.5	5.8	484	0.03		1.94
Prim.	Nov.22	25	12	8.50	7.20	110	14528	11944	82.2	18768	130.8	3.3	495	3.0	-	1.51
"	Nov.29	25	12	8.70	7.30	112	14865	12480	84.0	14800	120.0	2.9	422	0.06	-	1.39
"	Dec. 6	25	12	8.00	7.25	106	14146	11797	83.4	17440	163.2	4.0	486	0.10	-	1.12
"	Dec.11	25	12	9.20	7.40	100	13729	11062	80.6	14896	97.6	1.9	588	0.05	-	-
Average						107	14317	11821		16476	127.9	3.0	498	0.80		1.34
Prim.	Nov.22	35	12	8.60	7.20	106	13270	10510	79.2	16981	128.3	4.6	505	2.4	-	1.94
"	Nov.29	35	12	8.90	7.20	103	13600	11062	80.9	14204	122.4	2.7	392	2.2	-	1.91
"	Dec. 6	35	12	8.50	7.30	110	13766	11161	81.8	15440	118.4	3.3	467	0.04	-	1.40
"	Dec.11	35	12	8.90	7.40	107	13658	10827	79.3	14928	97.6	1.2	664	0.65	-	-
Average						107	13574	10875		15388	116.7	3.0	455	1.32		1.75

SUMMARY SHEET

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/l	pH	Alkalinity mg/l $CaCO_3$	TSS (mg/l)	VSS (mg/l)	% $\frac{VSS}{TSS}$	COD mg/l	Total-P mg/l-P	PO_4-P mg/l-P	Kjeldahl-N mg/l-N	NO_2+NO_3 mg/l-N	NH_4-N mg/l-N	O_2-uptake mg/gVSS/hr
Prim.	Nov.20	5	18	3.60	7.10	91	15398	13659	88.7	21200	122.4	11.0	410	0.02	-	3.95
"	Nov.27	5	18	7.85	7.20	82	18071	16033	88.7	20400	104.0	13.0	474	0.02	27.5	2.06
"	Dec. 4	5	18	5.85	6.85	66	17899	15834	88.5	28078	107.4	13.0	483	0.03	14.4	1.96
"	Dec.13	5	18	5.70	7.15	88	20772	19037	91.2	26500	100.0	1.9	618	0.02	61.0	1.39
Average						82	17123	15173		23295	108.5	9.7	496	0.02	34.3	2.34
Prim.	Nov.20	10	18	7.20	7.50	123	15043	12742	84.7	18080	130.6	21.0	480	0.03	-	2.55
"	Nov.27	10	18	5.90	7.10	92	16412	14209	86.6	19840	112.0	-	461	0.02	17.9	1.86
"	Dec. 4	10	18	5.15	6.90	70	16231	14180	87.4	21840	102.3	14.0	437	0.02	21.2	2.12
"	Dec.13	10	18	6.80	7.15	91	17194	14241	82.8	18240	96.0	5.0	569	0.02	26.9	1.69
Average						94	15895	13710		19500	110.2	13.3	487	0.02	-	2.06
Prim.	Nov.20	15	18	6.45	7.45	137	12087	9715	80.4	-	122.4	10.0	582	0.02	-	-
"	Nov.27	15	18	6.40	7.25	130	11420	9299	81.4	15280	128.0	13.0	454	0.03	16.0	3.23
"	Dec. 4	15	18	6.85	7.20	102	13535	11341	83.8	19440	97.6	10.0	480	0.03	23.0	2.38
"	Dec.13	15	18	6.95	7.20	99	14335	11196	78.1	17230	100.0	4.6	588	0.02	41.1	1.61
Average						117	12847	10118		17317	112.0	9.4	526	0.03	23.[illegible]	2.40
Prim.	Nov.20	25	18	7.75	7.40	95	10136	8018	79.1	11360	106.4	12.0	418	4.4	-	2.99
"	Nov.27	25	18	6.80	7.25	122	10265	8144	79.3	12824	112.0	14.0	416	0.01	14.4	2.95
"	Dec. 4	25	18	6.85	7.25	104	10967	8804	80.3	15680	97.6	9.3	390	0.11	14.4	2.73
"	Dec.13	25	18	6.50	7.05	116	11080	8447	76.2	12560	104.0	5.6	350	0.05	43.5	2.13
Average						109	10456	8322		13106	105.0	10.2	394	1.14	24.1	2.70
Prim.	Nov.20	35	18	8.30	7.10	50	10015	7541	75.3	11360	155.2	12.0	453	1.6	-	2.71
"	Nov.27	35	18	8.20	7.20	109	10079	7679	76.2	11440	120.0	14.0	403	0.78	11.2	2.58
"	Dec. 4	35	18	7.30	7.30	104	10405	8093	77.8	16160	114.4	12.0	429	0.09	23.0	2.10
"	Dec.13	35	18	7.85	7.10	100	10845	8145	75.1	11680	106.4	7.4	565	0.03	35.3	1.99
Average						91	10166	7771		12660	124.0	11.4	463	0.63	23.1	2.34

SUMMARY SHEET

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/1	pH	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N	NH_4-N mg/1-N	O_2-uptake mg/gVSS/hr
Prim.	Aug.28	5	25	4.30	6.60	79.2	17352	12850	74.0	12540	112.0	2.5	672	0.01	-	4.35
"	Sep.11	5	25	2.90	6.35	40.4	16778	13052	77.8	-	128.0	3.7	686	<0.01	27.5	2.81
"	Sep.18	5	25	0.25	7.30	251.0	17538	14032	80.0	21800	130.8	26.0	698	0.04	14.4	2.05
	Oct. 9	5	25	3.2	7.10	97.7	15807	13845	87.6	16358	-	-	-	-	61.0	-
Average					6.84	117.1	16869	13445		16899	124.0	10.7	685	0.02	34.3	3.07
Prim.	Aug.28	10	25	5.75	6.90	92.4	16973	12216	72.2	12060	128.0	2.1	672	0.01	-	2.57
"	Sep.11	10	25	3.70	6.95	67.6	13357	10288	77.0	-	11.0	3.0	549	<0.01	17.9	3.27
"	Sep.18	10	25	5.05	7.15	99.0	15208	11261	74.1	14050	160.0	5.3	-	0.02	21.2	2.46
"	Oct. 9	10	25	3.65	7.10	101.0	11233	8974	79.9	11845	-	-	-	-	26.9	-
Average						90.0	14193	10684		12652	133	3.5	611	0.01	22.0	2.77
Prim.	Aug.28	15	25	6.60	7.20	80.8	14961	10020	67.0	11700	110	1.9	604	0.01	-	3.12
"	Sep.11	15	25	4.55	7.00	59.2	10252	6781	66.2		115	1.7	629	0.03	16.0	3.80
"	Sep.18	15	25	3.70	7.05	88.0	14210	10176	71.6	11500	128	4.4	525	0.15	23.0	2.46
"	Oct. 9	15	25	5.60	7.30	112.2	10254	7904	77.1	11325	-	-	-	-	31.4	-
Average						85.1	12419	8720		11508	118	2.7	586	0.06	23.5	3.12
Prim.	Aug.28	25	25	8.25	6.35	52.8	9664	6020	62.3	8350	110	4.2	455	32.0		2.79
"	Sep.11	25	25	6.95	7.15	52.8	10581	6555	61.9	-	125	1.8	511	0.66	14.4	2.93
"	Sep.18	25	25	5.95	6.90	58.0	10971	7240	66.0	7480	112	5.7	352	2.9	14.4	2.73
"	Oct. 9	25	25	6.90	7.10	65.0	9727	6825	70.2	14214	-	-	-	-	43.5	-
Average						57.2	10236	6660		10015	116	3.9	439	11.9	24.1	2.81
Prim.	Aug.28	35	25	8.05	4.70	15.6	10406	6779	64.4	8600	-	13.0	459	58.0	-	2.19
"	Sep.11	35	25	6.95	7.10	56.0	10526	6331	60.1		122	3.2	652	4.5	11.2	2.36
"	Sep.18	35	25	5.65	7.00	64.0	-	-		8150	104	6.5	314	1.45	23.0	2.16
"	Oct. 9	35	25	6.30	7.10	75.6	10009	6753	67.5	9883	-	-	-	-	35.2	-
Average						52.8	10314	6621		8878	113	7.6	475	21.3	23.1	2.24

SUMMARY SHEET

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/l	pH	Alkalinity mg/l $CaCO_3$	TSS (mg/l)	VSS (mg/l)	% $\frac{VSS}{TSS}$	COD mg/l	Total-P mg/l-P	PO_4-P mg/l-P	Kjeldahl-N mg/l-N	NO_2+NO_3 mg/l-N	NH_4-N mg/l-N	O_2-uptake mg/gVSS/hr
Prim/Ch	Aug. 31	5	7	9.55	6.35	25.7	16718	-	-	13668	264	0.80	464	< 0.01	-	1.26
"	Sep.14	5	7	7.85	6.90	83.0	15759	11587	73.5	14769	262	14.0	446	0.04	-	1.97
"	Sep.21	5	7	9.35	7.10	98.0	16471	12696	77.1	16400	349	12.0	-	0.02	-	1.14
"	Oct. 5	5	7	7.05	6.70	43.0	15670	12201	77.9	-	353	1.70	564	0.02	-	1.98
"	Oct.12	5	7	9.60	6.80	39.9	16125	13011	80.7	17618	-	-	-	-	-	1.75
Average						57.9	16006	12374		15613	307	7.1	491	0.02		
Prim/Ch	Aug. 31	10	7	10.30	6.30	19.0	16165	-	-	11284	288	0.7	568	< 0.01	-	0.60
"	Sep.14	10	7	8.80	6.35	26.0	15301	10711	61.9	14128	240	1.2	-	< 0.01	-	1.34
"	Sep.21	10	7	8.65	6.80	41.0	15678	11411	72.8	14340	339	0.8	634	0.01	-	1.00
"	Oct. 5	10	7	8.55	6.75	40.0	14103	10482	74.3		392	0.6	706	0.05	-	1.43
"	Oct.12	10	7	9.75	7.05	66.2	15043	11614	77.2	15326	-	-	-	-	-	1.29
Average						38.4	15031	11055		13769	315	0.8	636	0.02		1.17
Prim/Ch	Aug. 31	15	7	9.10	6.75	54.1	15363	-	-	10428	264	1.5	320	< 0.01	-	1.33
"	Sep.14	15	7	8.40	6.35	27.0	14244	9536	66.9	11104	320	1.3	360	< 0.01	-	1.13
"	Sep.21	15	7	8.40	6.80	11.0	15476	11306	73.1	12670	301	0.5	462	0.01	-	0.95
"	Oct. 5	15	7	8.25	7.00	80.0	13287	9583	72.6		362	0.6	597	0.04	-	1.25
"	Oct.12	15	7	9.50	7.15	80.9	14303	10679	74.7	14821	-	-	-	-	-	1.12
Average						50.6	14328	10276		12255	312	1.0	435	0.02		1.17

S U M M A R Y   S H E E T

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/1	pH	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD . mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N	NH_4-N mg/1-N	O_2-uptake mg/gVSS/hr
Prim/Ch	Aug.31	25	7	10.00	7.00	77.0	13931	-	-	11636	248	0.9	464	0.4	-	1.37
"	Sep.14	25	7	9.75	6.55	38.0	13252	8466	63.9	10124	200	0.7	568	6.6	-	0.99
"	Sep.21	25	7	9.70	6.30	16.0	14317	9694	67.7	11100	290	0.5	543	14.0	-	1.05
"	Oct. 5	25	7	9.10	6.80	37.0	13272	9310	70.2		313	0.4	480	3.8	-	1.08
"	Oct.12	25	7	10.60	6.90	35.7	13396	9589	71.6	13536	-	-	-	-	-	1.13
Average						40.7	13559	9265		11599	263	0.6	514	6.2		1.12
Prim/Ch	Aug.31	35	7	10.10	7.20	103.0	11998	-	-	8364	248	1.1	416	1.4	-	1.95
"	Sep.14	35	7	9.90	5.95	18.0	12816	8174	63.8	9424	-	0.4	360	20.0	-	0.73
"	Sep.21	35	7	9.70	6.20	15.6	13101	8784	67.1	10120	422	0.7	321	19.0	-	0.62
"	Oct. 5	35	7	9.55	6.60	21.0	12932	8826	68.3		344	0.2	533	0.09	-	0.91
"	Oct.12	35	7	10.70	6.70	18.5	12892	8947	69.4	12470	-	-	-	-	-	1.11
Average						35.2	12935	8683		10094	338	0.6	408	10.1		1.06

S U M M A R Y S H E E T

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/1	pH	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N	NH_4-N mg/1-N	O_2-uptake mg/gVSS/hr
Prim/Ch	Nov. 23	5	12	7,85	6,95	75	14528	11491	79,1	14720	248,0	0,9	461	0,01	-	2,35
"	Nov. 30	5	12	7,90	6,95	61	14812	11759	79,4	17692	269,2	1,3	412	0,01		2,25
"	Dec. 7	5	12	7,75	6,75	32	15882	11946	75,2	14480	269,6	0,8	747	0,01	15,7	1,61
"	Dec. 12	5	12	10,40	6,30	9	15893	10642	65,0	14446	203,8	0,1	412	0,01	8,9	-
Average						56	15279	11459		15335	247,7	0,8	428	0,01	12,3	2.07
Prim/Ch	Nov. 23	10	12	8,30	6,95	76	13746	10451	76,0	14800	248,0	0,6	467	0,02	-	2,22
"	Nov. 30	10	12	4,60	6,80	64	13378	10278	76,8	14196	266,7	0,5	427	5,0		3,04
"	Dec. 7	10	12	7,35	6,80	50	13379	9893	73,9	13760	260,8	0,4	625	0,02	20,8	2.18
"	Dec. 12	10	12	9,30	6,55	19	13817	9204	67,0	14912	236,8	0,3	503	0,09	12,8	-
Average						52	13580	9957		14417	253,1	0,5	466	1,28	16,8	2.48
Prim/Ch	Nov. 23	15	12	8,75	6,50	41	14019	10603	75,6	15920	240,0	0,4	480	22,0	-	2,49
"	Nov. 30	15	12	8,60	6,80	37	12489	9361	75,0	13040	256,0	-	358	18,0	-	2,76
"	Dec. 7	15	12	8,65	6,95	42	12652	9305	73,6	13600	252,8	0,6		4,3	14,7	1,68
"	Dec. 12	15	12	9,50	6,65	22	12865	8635	67,2	10184	248,8	0,6	496	3,9	8,9	-
Average						36	13006	9476		13186	249,4	0,5	445	12,1	11,8	2.31
Prim/Ch	Nov. 23	25	12	8,60	6,55	55	13664	10113	74,0	13647	251,0	0,4	496	12,0	-	1,96
"	Nov. 30	25	12	9,30	6,70	25	12030	8766	72,9	12720	288,0	0,3	429	19,0	-	2,87
"	Dec. 7	25	12	8,40	6,90	38	12465	8971	72,0	12979	291,4	0,3		7,4	14,7	1,74
"	Dec. 12	25	12	9,60	6,75	26	12108	8103	66,9	17168	280,0	0,7	510	7,4	10,4	
Average						36	12567	8988		13115	277,6	0,4	478	11,5	12,6	2.19
Prim/Ch	Nov. 23	35	12	8,60	6,55	42	12637	9055	71,7	13200	256,6	0,5	525	15,0	-	1,99
"	Nov. 30	35	12	7,80	6,65	28	11945	8426	70,5	12560	280,0	0,5	448	15,0	-	1,92
"	Dec. 7	35	12	8,70	6,65	18	11330	7989	70,5	10960	244,8	0,6	528	21,0	14,7	1,73
"	Dec. 12	35	12	9,60	6,60	18	11387	7642	65,0	11504	277,6	-	542	18,0	10,4	1,28
Average						27	11825	8278		12056	264,8	0,5	511	17,3	12,6	1.73

SUMMARY SHEET

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/1	pH	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N	NH_4 -N mg/1-N	O_2-uptake mg/gVSS/hr
Prim/Ch	Nov.21	5	18	2,80	7,00	117	12138	9745	80,3	14800	248,0	0,8	499	< 0,01	-	6,96
"	Nov.28	5	18	4,50	6,95	84	12701	9868	77,7	13538	230,8	0,7	480	0,01	10,8	5,05
"	Dec. 5	5	18	5,80	6,75	55	14372	11149	77,6	19680	289,6	0,5	454	0,01	23,7	3,77
"	Dec.14	5	18	8,70	6,25	5	14808	9552	64,5	24150	161,5	0,2	388	< 0,01	35,6	-
Average						85	13505	10079		16006	256	0,6	455	0,01	23,4	5,26
Prim/Ch	Nov.21	10	18	3,60	6,95	97	11694	8521	71,6	13333	251,0	0,5	461	0,02	-	4,58
"	Nov.28	10	18	5,50	6,90	76	12814	9727	75,9	14740	237,0	0,8	444	0,02	14,8	3,70
"	Dec. 5	10	18	5,15	6,90	77	13166	9869	75,0	17280	236,8	0,5	480	0,02	29,4	4,16
"	Dec.14	10	18	8,20	6,55	18	13290	8450	63,6	25097	215,7	0,2	536	< 0,01	32,0	-
Average						67	12791	9142		15118	235,1	0,5	480	0,02	25,4	4,15
Prim/Ch	Nov.21	15	18	6,10	6,75	56	11476	8043	70,1	11360	288,0	0,7	487	12,0	-	4,10
"	Nov.28	15	18	6,25	6,80	74	10843	7647	70,5	10160	256,0	0,9	381	2,8	16,0	3,30
"	Dec. 5	15	18	5,40	6,90	67	11328	8059	71,1	12364	279,3	0,4	384	0,1	21,5	3,80
"	Dec.14	15	18	7,90	6,65	22	12625	8163	64,6	13804	247,8	0,3	484	0,04	40,2	-
Average						55	11568	7978		11922	267,8	0,6	434	3,7	25,9	3,73
Prim/Ch	Nov.21	25	18	7,60	6,65	28	10862	7309	67,3	9725	266,7	0,9	335	16,0	-	3,12
"	Nov.28	25	18	7,60	6,25	21	10689	7289	68,2	10960	296,0	1,2	337	28,0	12,8	2,80
"	Dec. 5	25	18	6,65	6,25	16	10306	7092	68,8	10960	244,8	0,6	416	29,0	29,4	3,29
"	Dec.14	25	18	8,30	6,45	12	10829	6877	63,5	9412	255,7	0,6	467	23,0		-
Average						19	10717	7142		10264	265,8	0,8	389	24,0	21,1	3,07
Prim/Ch	Nov.21	35	18	7,90	6,30	20	10151	6583	64,9	9520	264,0	0,5	364	33,0	-	3,01
"	Nov.28	35	18	7,90	6,20	18	9968	6574	66,0	9434	249,1	0,7	313	19,0	18,1	2,74
"	Dec. 5	35	18	7,65	6,45	19	10119	6699	66,2	9846	278,5	0,4	388	26,0	14,2	2,51
"	Dec.14	35	18	8,60	6,60	14	10042	6271	62,4	9040	252,8	0,2	377	19,0		-
Average						18	10070	6532		9460	261,1	0,5	361	24,3	16,2	2,75

S U M M A R Y   S H E E T

Sludge	Date	Det.t. days	Temp. ^oC	O_2 mg/1	pH	Alkalinity mg/1 $CaCO_3$	TSS (mg/1)	VSS (mg/1)	% $\frac{VSS}{TSS}$	COD mg/1	Total-P mg/1-P	PO_4-P mg/1-P	Kjeldahl-N mg/1-N	NO_2+NO_3 mg/1-N	NH_4 -N mg/1-N	O_2-uptake mg/gVSS/hr
Prim/Ch	Aug. 7	5	25	6.20	6.50	33.4	12420	7673	61.5	14371	297	1.0	488	2.8	-	4.46
"	Aug. 9	5	25	6.40	6.22	35.4	13460	7945	-	9159	289	1.0	563	11.0	-	5.13
"	Aug.29	5	25	7.20	6.10	36.0	12977	8390	64.7	11200	248	0.02	-	0.02	-	2.86
"	Sep.12	5	25	2.40	6.60	44.0	13988	9616	68.7	11170	275	1.4	520	0.01	-	4.49
"	Sep.19	5	25	2.95	6.40	71.0	13464	9682	71.9	-	264	0.8	499	0.07	-	4.65
"	Oct.10	5	25	5.00	6.75	-	13887	10694	77.0	17332	-	-	-	-	-	-
Average						44.0	13262	8661		12646	275	0.8	518	2.78		4.32
Prim/Ch	Aug. 7	10	25	6.20	5.90	21.2	12630	8181	64.5	10238	257	0.3	515	24.0	-	2.93
"	Aug. 9	10	25	5.85	6.35	58.3	13390	8080	-	9792	310	0.9	574	39.0	-	4.46
"	Aug.29	10	25	7.35	6.10	9.20	12296	7215	58.8	7860	264	3.6	464	3.6	-	2.86
"	Sep.12	10	25	5.15	6.10	13.8	12381	7756	62.7	9760	269	0.8	531	9.0	-	2.49
"	Sep.19	10	25	3.50	6.05	62.0	12703	8539	67.2	-	220	0.6	413	1.4	-	-
"	Oct.10	10	25	6.25	6.60	-	12056	8577	71.4	13528	-	-	-	-	-	-
Average							12680	7954		10236	264	1.2	499	15.4		3.19
Prim/Ch	Aug. 7	15	25	6.80	6.00	21.2	11490	7325	62.5	6965	-	3.4	-	42.0	-	2.46
"	Aug. 9	15	25	7.10	5.60	15.0	11720	7120	-	7962	316	2.2	293	58.0	-	3.37
"	Aug.29	15	25	7.85	6.15	0.4	11923	7071	59.3	8350	376	3.2	568	3.2	-	2.29
"	Sep.12	15	25	5.45	6.00	17.4	11948	7238	60.6	9550	263	0.5	416	10.0	-	2.71
"	Sep.19	15	25	4.85	6.15	51.0	11999	8031	66.9	-	294	0.9	370	2.5	-	-
"	Oct.10	15	25	5.65	6.65	-	11590	7794	68.2	14785	-	-	-	-	-	-
Average							11816	7357		9522	312	2,0	412	23,1		2.71

SUMMARY SHEET

Sludge	Date	Det.t. days	Temp. °C	O_2 mg/l	pH	Alkalinity mg/l $CaCO_3$	TSS (mg/l)	VSS (mg/l)	% $\frac{VSS}{TSS}$	COD mg/l	Total-P mg/l-P	PO_4-P mg/l-P	Kjeldahl-N mg/l-N	NO_2+NO_3 mg/l-N	NH_4-N mg/l-N	O_2-uptake mg/gVSS/hr
Prim/Ch	Aug. 7	25	25	6.40	6.00	11.1	10570	6757	64.0	9440	266	1.3	-	31.0	-	2.22
"	Aug. 9	25	25	7.30	5.50	10.2	11740	7350	-	11597	-	0.9	476	43.0	-	2.69
"	Aug.29	25	25	7.80	5.30	9.6	10630	6487	60.9	7600	248	-	464	35.0	-	1.51
"	Sep.12	25	25	5.85	5.80	6.0	11548	6657	57.7	5650	275	0.31	512	17.0	-	1.80
"	Sep.19	25	25	5.75	6.10	24.0	12458	7874	63.2	-	392	1.1	321	8.7	-	1.75
"	Oct.10	25	25	6.85	6.00	-	11111	7029	63.5	11819	-	-	-	-	-	-
Average							11389	7025		9221	295	0.9	443	26.9		1.99
Prim/Ch	Aug. 7	35	25	6.50	7.10	52.5	10380	6528	63.0	7695	220	2.3	-	20.0	-	2.75
"	Aug. 9	35	25	6.80	6.60	29.0	10800	6485	-	5298	252	3.3	-	88.0	-	3.05
"	Aug.29	35	25	7.95	5.30	1.2	9937	6050	60.9	7240	235	-	149	26.0	-	0.89
"	Sep.12	35	25	6.40	5.75	4.2	10636	6120	57.5	7380	251	0.3	512	16.0	-	2.35
"	Sep.19	35	25	5.20	5.55	12.0	12321	7862	63.8	-	272	0.4	328	18.0	-	1.60
"	Oct.10	35	25	7.10	6.40	-	11145	7029	63.1	10667	-	-	-	-	-	-
Average							10815	6609		7656	246	1.6	330	33.6		2.13

APPENDIX C

UNTREATED SLUDGE DATA - FULL-SCALE UNITS

PRIMARY SLUDGE (UNTREATED)

SUMMARY SHEET

FULL SCALE UNITS

Date	Temp. °C	pH	Sludge volume ml	TSS mg/l	VSS mg/l	% VSS/TSS	SVI ml/g	Sp. resist. to filtr. (s^2/g)	CST (s)
Aug. 30	13.9	5.90	300	8258	6402		36		
Sep. 1	14.5	5.60	460	13919	10700	76.90	33		
" 4	14.4	5.65	430	8188	6424	78.47	53		69
" 5		5.80	180	12863	10802	83.98	14	4.73x10^9	138
" 6		6.15	400	14068	12355	87.83	28	3.93 "	137
" 8	14.0	6.25	890	20641	17589	85.22	43	8.54 "	410
" 11	12.3	6.95	690	22783	17077	74.96	26	1.86 "	
" 15	11.1	6.55	250	3797	3505	92.33	66		13
" 18	11.5	7.85	60	1430	1115	77.97	43	1.47 "	11
" 19	11.3	6.05	875	11177	9512	55.11	78	19.68 "	22
" 21	11.5		795	11323	9745	86.06	70	3.25 "	21
" 27	10.1	6.00	980	27215	24319	89.36	36	2.23 "	43
Oct. 6		6.95	980	17477	15454	88.00	56	0.63 "	19
" 9	10.3	6.80	930	17678	16056	90.83	53	0.90 "	29
" 12		6.30	950			82.43	21	0.88 "	73
" 17	8.1	6.45	630	12743	11588	90.90	50	0.48 "	27
" 19	7.5	7.00	820	15606	13907	89.12	53	1.02 "	24
" 26		6.80	485	7268	6687	92.01	67	2.21 "	16
" 31		8.81	915	19968			46	1.23 "	101
Nov. 2		6.77	740	7640	6566	85.95	97	2.14 "	19
" 7		6.62	475	11786	10380	88.07	40	1.91 "	22
" 13		8.00	960	15277	13577	88.87	63	1.11 "	37
" 23									
" 29		7.02	420	5864	5335	90.90	72	1.76 "	14
Dec. 5		7.18	800	20250	15920	98.62	40	1.61 "	61

PRIMARY SLUDGE (UNTREATED) - continued:

FULL SCALE UNITS

Date	COD mg/l	Tot-P mg/l-P	PO_4-P mg/l-P	NO_2-NO_3 mg/l-N	Tot-N mg/l	Alkalinity mg/l $CaCO_3$			
Aug. 30	1418	108	15.0	0.04	463	400			
Sep. 1	16950	131	37.0	< 0.01	587	180			
" 4	10580	94	41.0	0.02	311	126			
" 5									
" 6	8750	99	28.0	0.02	323				
" 8	18420	138	50.0	0.26	790	244			
" 11	19750	167		< 0.01	589	600			
" 13				<		244			
" 15	40300	256	7.4	0.01		134			
" 18						13			
" 19	12600	106	46.0	0.08	520	51			
" 21	15520	151	24.0	0.01		158			
" 27	23750	258	40.0	0.01	909	201			
Oct. 6	37000	233	22.0	0.01	813	384			
" 9	31100	208	16.0	< 0.01	778	252			
" 12	38300	176	30.0	< 0.10	928	230			
" 17	19820	117	16.0	0.01	663	172			
" 19	21930	146	15.0	< 0.01	468	346			
" 26	10800	147	7.0	< 0.01	256	156			
" 31	23900	171	1.2		400	282			
Nov. 2	10360	78	8.1	< 0.01	252	134			
" 7	13220	81	12.0	< 0.01	303	160			
" 13	16070	85	4.5	0.01	487				
" 23									
" 29	7490	80	6.0	< 0.01	111	154			
Dec. 5						105			

APPENDIX D

DIGESTED SLUDGE DATA - FULL-SCALE UNITS

SUMMARY SHEET

DIGESTED PRIMARY SLUDGE

FULL SCALE UNITS

Date	Temp. °C	O_2 mg/l	O_2-uptake mg/l/min	pH	Sludge volume ml	TSS mg/l	VSS mg/l	% $\frac{VSS}{TSS}$	SVI ml/g
Aug. 30	11.7	10.7	0.17	6.60	960	6582	4082	62.00	146
Sep. 1	12.0	9.7	0.11	6.80	780	3163	1820	57.50	247
" 4	8.4	10.6	0.24	6.60	970	5092	2901	56.97	191
" 5		9.6	0.13	6.75	980	6102	3922	64.27	161
" 6	10.6	10.6	0.10	6.70	960	6496	4206	64.76	148
" 8	12.1	9.7	0.10	6.70	415	4501	2917	64.81	92
" 11	8.2	10.4	0.10	6.55	975	7752	5124	66.11	126
" 15	5.6	10.9	0.12	7.25	970	7466	4774	63.94	130
" 18	8.6	8.7	0.10	7.55	980	6976	4573	65.56	141
" 19	6.3	11.0	0.02	7.40	960	5811	3864	64.66	163
" 21	10.1		0.21	6.75	975	8138	5551	52.87	120
" 27	3.8	12.4	0.25	7.35	970	7200	4634	64.37	135
Oct. 6	8.1	11.7	0.12	6.85	900	7020	4700	66.95	128
" 9	9.4	11.0	0.13	7.50	970	7383	4963	67.22	182
" 12	3.5	12.4	0.04	7.80	985	7678	5087	66.26	128
" 17	6.5	12.4	0.29	7.45	980	7865	5208	67.39	125
" 19	2.1	12.4	0.10	7.15	985	8664	5905	68.16	114
" 26	5.0	10.8	0.19	7.48	965	6444	4594	71.29	149
" 31	6.7	11.6	0.27	7.30	975			61.25	79
Nov. 2	4.5	12.3	0.12	7.47	980	8361	5532	66.23	117
" 7	2.5	12.4		7.40	985	6952	4632	66.63	142
" 13	1.0	12.6	0.11	7.62	990	8405	5780	88.76	118
" 23	5.2	12.2	0.17	7.77	990			68.92	240
" 29	4.0	10.8	0.11	7.59	995	8021	5563	69.35	124
Dec. 5	5.4		0.12	7.71	990	8600	5600	65.12	115

DIGESTED PRIMARY SLUDGE - continued: FULL SCALE UNITS

Date	COD mg/l	Tot-P mg/l-P	PO_4-P mg/l-P	NO_2-NO_3 mg/l-N	Tot-N mg/l-N	Alkalinity mg/l $CaCO_3$	Sp. resist. to filtr. (s^2/g)	CST (s)	
Aug. 30	5300	210	0.03	18	453	15			
Sep. 1	3110		0.24	18	202	12			
" 4	3520	105	0.65	14	209	20		110	
" 5	4920	140	0.23	19	279		2.73×10^9	89	
" 6	5200	125	0.37	17	281		1.25 "	107	
" 8	3310	94	0.27	22	307	15	2.43 "	68	
" 11	6120	144	0.42	21	406	15	2.29 "		
" 15	10020	208	0.33	18	299	64		71	
" 18			0.27	24		18	1.21 "	47	
" 19	5050	131	0.33	28	305	11	1.44 "	52	
" 21	9920	193	0.36	25	313	57	1.31 "	69	
" 27	6500	156	0.23	21	267	61	1.61 "	69	
Oct. 6	5420	134	0.36	18	231	77	2.27 "	47	
" 9	7010	138	0.50	25	279	65	1.36 "	69	
" 12	6940	168	0.39	25	284	56	3.18 "	89	
" 17	7470	168	0.40	25		80	3.25 "	114	
" 19	6530	193	0.50	31	303		3.59 "	134	
" 26	5610	123	0.49	30	295		2.94 "	130	
" 31	6560	131	0.53	31	219		1.83 "	93	
Nov. 2	8340	155	0.50	24	301		2.39 "	133	
" 7	6300	131	0.50	25	384		2.78 "	101	
" 13	8370	154	0.70	24			2.44 "	130	
" 23	7600	152	0.80	23	301		6.03 "	154	
" 29	7380	168	0.80	25	258		3.29 "	139	
Dec. 5							3.19 "	128	

SUMMARY SHEET

DIGESTED MIXED PRIMARY/CHEMICAL SLUDGE

FULL SCALE UNITS

Date	Temp. °C	O_2 mg/l	O_2-uptake mg/l/min	pH	sludge volum ml	TSS mg/l	VSS mg/l	% $\frac{VSS}{TSS}$	SVI ml/g
Aug. 30	12.5	9.8	0.20	6.80	955	8832	5396	61.0	108
Sep. 1	12.4	2.8	0.27	6.70	270				13
" 4	8.4	10.8	0.18	6.70	380	9647	5800	60.1	40
" 5		10.3	0.13	6.70	890	6375	3956	62.1	140
" 6	11.4	10.4	0.01	6.65	680	10389	6703	64.5	66
" 8	12.7	9.8	0.24	5.85	410	5288	3261	61.7	78
" 9	8.6	10.4	0.22	6.65	985	10313	6497	63.0	96
" 15	5.3	10.0	0.55	7.20	380	5201	3241	62.3	73
" 18	8.1	10.4	0.06	7.05	535	5854	3666	62.6	91
" 19	6.2	9.2	0.46	6.75	980	12149	7569	62.8	81
" 21	9.9		0.13	7.05	860	9550	6035	63.2	96
" 27	3.8	12.4	0.04	6.90	970	6566	4183	63.7	148
Oct. 6	8.1	11.5	0.13	7.00	950	8011	5062	63.2	119
" 9	9.6		0.11	6.90	975	11340	7212	64.1	86
" 12	3.0	12.4	0.11	7.40	980	10235	6528	63.7	96
" 17	5.8	12.4	0.27	7.35	980	9278	5951	64.1	106
" 19	2.2		0.17	7.35	980	11005	7116	64.7	89
" 26	5.0	10.7	0.18	7.10	980	11867	7720	65.1	83
" 31	6.6	11.7	0.25	7.00	985	12726	8116	63.8	77
Nov. 2	5.0	12.3	0.15	7.18	985	12070	7478	62.0	82
" 7	3.0	12.6	-	7.00	998	14361	9248	64.4	70
" 13	1.1	12.6	0.11	7.00	998	13101	8441	64.4	76
" 23	5.2	12.3	0.12	7.06	995			65.0	136
" 29	4.5	11.0	0.09	7.11	995	14195	9142	64.4	70
Dec. 5	5.6	9.9	0.12	7.16	995	14750	9130	61.9	68

DIGESTED MIXED PRIMARY/CHEMICAL SLUDGE - continued: FULL SCALE UNITS

Date	COD mg/1	Tot-P mg/1-P	PO_4-P mg/1-P	NO_2-NO_3 mg/1-N	Tot-N mg/1-N	Alkalinity mg/1 $CaCO_3$	Sp. resist to filtr. (s^2/g)	CST (s)	
Aug. 30	9930	300	0.22	3.80	604	52			
Sep. 1	6520		0.80			124			
" 4	9750	315	0.29	7.00	535	20		237	
" 5	4530	198	1.30	15.00	240	20	9.17×10^9	334	
" 6	8690	250	0.60	13.00	500		5.65 "	284	
" 8	3900		0.47	26.00	299	10	5.98 "	186	
" 11	7960	191	0.50	12.00	436	34	3.33 "		
" 15	12200	296	0.50	11.30	463	10		89	
" 18			0.26	12.00		36	2.12 "	58	
" 19	9960	200	0.70	0.80	409	17	12.58 "	185	
" 21	14720	301	0.52	8.00	320	68	3.98 "	186	
" 27	6120		0.36	16.00		16	1.32 "	58	
Oct. 6		172	0.44	20.00	325	29	1.30 "	63	
" 9	9360	236	0.38	17.00	430	46	0.94 "	60	
" 12	9000	245	0.43	16.00		54	0.74 "	57	
" 17	5500	198	0.18	17.00		86	1.06 "	56	
" 19	6890	267	0.30	20.00	381	79	1.33 "	85	
" 26	11610	270	0.39	35.00	422	32	1.43 "	113	
" 31	14220	270	0.29	37.00	346	47	1.24 "	90	
Nov. 2	10850	270	0.33	28.00	390	71	1.78 "	111	
" 7	8370	270	0.27	32.00	518	65	1.82 "	159	
" 13	12000	272	0.37	45.00		44	2.94 "	218	
" 23	12800		0.37	46.00	467	66	6.32 "	312	
" 29	15500	288	0.35	39.00	377	78	3.16 "	238	
Dec. 5						66	3.05 "	206	

APPENDIX E

SPECIFIC RESISTANCE TO FILTRATION AND CAPILLARY SUCTION TIME - PILOT UNITS

Sludge	Det.t days	Temp^{o}C	Capillary suction time (s)					Specific resistance to filtration ($s^2/gx10^8$)					
			Series 1	Series 2	Series 3	Series 4	Ave-rage	Series 1	Series 2	Series 3	Series 4	Series 5	Ave-rage
Prim.	0	7	460.8	343.9	142.6	203.7	190.1	104.0	77.5	63.9	56.8	73.5	55.2
"	5	"	454.9	357.8	270.1	126.8	302.4	106.0	112.0	84.9	41.8	38.1	76.6
"	10	"	230.9	558.5	441.7	491.5	430.7	24.8	56.4	97.3	74.0	42.8	59.1
"	15	"	281.7	451.1	477.0	564.2	443.5	22.9	53.7	73.3	80.3	40.6	54.2
"	25	"	484.8	406.6	280.9	281.5	363.5	39.9	36.8	35.0	42.3	31.7	37.1
"	35	"	508.4	295.8	228.2	149.3	295.4	40.4	56.1	50.0	21.1	12.3	36.0
Prim.	0	12	43.0	58.6	121.3	-	190.1	34.8	43.7	21.0	108.4	-	55.2
"	5	"	194.9	221.8	399.3	-	272.0	35.3	31.9	56.5	89.0	-	62.0
"	10	"	219.8	241.2	202.7	-	221.2	37.7	6.8	29.5	68.0	-	35.5
"	15	"	130.0	89.7	69.7	-	96.5	14.8	7.5	5.3	4.1	-	7.9
"	25	"	128.2	103.5	87.1	-	106.3	13.6	12.1	9.9	9.4	-	11.3
"	35	"	76.0	68.2	96.7	-	80.3	8.6	9.4	13.1	20.3	-	12.9
Prim.	0	18	39.2	61.0	56.7	-	190.1	20.9	38.3	47.9	21.1	-	55.2
"	5	"	98.5	89.6	98.8	-	95.6	19.8	20.3	43.7	24.7	-	27.1
"	10	"	129.3	41.4	138.1	-	102.9	72.6	36.2	58.5	46.5	-	53.5
"	15	"	29.8	23.5	49.0	-	34.1	4.5	2.4	6.8	10.3	-	6.0
"	25	"	16.1	16.6	15.9	-	16.2	0.8	1.7	1.7	1.0	-	1.3
"	35	"	18.0	17.0	19.1	-	18.0	0.9	1.2	2.1	1.6	-	1.5
Prim.	0	25	448.4	295.3	196.9	-	190.1	47.6	43.9	72.5	68.9	48.5	55.2
"	5	"	42.8	276.1	451.8	-	256.9	3.2	6.9	16.0	113.0	6.2	29.1
"	10	"	26.1	59.3	62.1	-	49.2	16.4	8.8	10.2	9.6	43.8	17.8
"	15	"	37.4	34.5	33.8	-	35.2	15.4	8.0	4.3	3.0	5.6	7.3
"	25	"	85.2	70.9	22.5	-	59.5	27.7	19.8	10.4	2.5	2.6	12.6
"	35	"	86.3	57.4	25.3	-	56.3	47.0	24.4	13.5	2.8	2.2	18.0

Sludge	Det.t (days)	Temp °C	Capillary suction time (s)					Specific resistance to filtration ($s^2/gx10^8$)							
			Series 1	Series 2	Series 3	Series 4	Average	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7	Average
P/C	0	7	115.1	229.9	140.7	130.5	157.4	8.0	14.8	9.1	10.3	-	-	-	10.1
"	5	"	215.2	658.1	627.5	360.3	465.3	18.8	106.0	88.1	43.3	86.1	-	-	65.5
"	10	"	181.1	150.2	83.8	46.3	115.4	15.7	25.7	15.7	7.6	19.7	-	-	16.9
"	15	"	431.7	187.3	70.0	37.9	181.7	52.2	28.3	8.4	5.8	8.3	-	-	20.6
"	25	"	445.1	233.3	124.5	46.7	212.4	67.5	31.3	15.3	6.5	3.3	-	-	24.8
"	35	"	460.2	88.9	53.8	42.5	161.4	73.5	12.3	5.0	8.3	5.3	-	-	20.9
P/C	0	12	272.2	150.5	36.1	-	157.4	18.1	5.1	4.8	-	-	-	-	10.1
"	5	"	311.2	530.8	449.1	-	430.4	57.1	84.3	30.4	-	-	-	-	57.9
"	10	"	344.0	197.4	200.9	-	247.4	62.5	30.7	31.3	-	-	-	-	41.5
"	15	"	109.2	112.5	216.0	-	145.9	13.7	15.1	37.2	-	-	-	-	22.0
"	25.	"	91.3	69.1	80.8	-	80.4	11.6	9.1	9.3	-	-	-	-	10.0
"	35	"	58.1	43.0	46.3	-	49.1	4.9	3.1	4.2	-	-	-	-	4.1
P/C	0	18	308.1	129.9	138.6	-	157.4	24.6	5.3	4.5	-	-	-	-	10.1
"	5	"	22.4	26.6	42.6	-	30.5	2.3	4.5	2.9	-	-	-	-	3.2
"	10	"	28.0	71.7	154.3	-	84.7	4.0	16.5	32.3	-	-	-	-	17.6
"	15	"	19.9	20.5	29.7	-	23.4	1.8	2.0	3.9	-	-	-	-	2.6
"	25	"	21.2	14.1	15.9	-	17.1	1.3	0.7	0.7	-	-	-	-	0.9
"	35	"	22.4	16.5	29.2	-	22.7	1.4	1.4	1.6	-	-	-	-	1.5
P/C	0	25	79.6	96.0	218.9	-	157.4	7.1	-	-	6.2	14.0	-	-	10.1
"	5	"	192.8	55.7	141.8	167.5	139.5	14.2	18.0	6.1	4.3	18.5	18.0	24.0	14.8
"	10	"	97.9	74.4	126.3	60.1	89.7	13.4	23.6	3.2	6.1	10.9	15.5	1.2	10.6
"	15	"	-	39.4	76.6	47.8	54.6	-	-	7.0	3.9	8.6	6.9	0.9	5.5
"	25	"	-	69.3	63.4	30.0	54.2	-	-	16.6	7.1	4.4	3.2	5.1	7.3
"	35	"	-	68.3	66.7	30.3	55.1	-	-	6.4	5.3	5.7	2.9	4.0	4.9

APPENDIX F

COMPRESSIBILITY DATA - PILOT UNITS

SUMMARY SHEET COMPRESSIBILITY DATA

Sludge	Det. t days	Temp. ^oC	Specific resist.to filtr.($s^2/gx10^8$)			Compressibility
			200 g/cm^2	500 g/cm^2	800 g/cm^2	
Prim.	0	7	40.9	73.5	69.3	0.28
"	5	"	-	-	-	-
"	10	"	23.9	42.8	38.0	0.38
"	15	"	21.4	40.6	45.3	0.53
"	25	"	14.8	31.7	37.0	0.65
"	35	"	5.5	12.3	16.6	0.81
Prim.	0	12	14.5	17.6	17.0	0.15
"	5	"	65.9	89.0	84.6	0.24
"	10	"	67.4	68.0	72.4	0.15
"	15	"	1.7	4.1	5.6	0.92
"	25	"	4.4	9.4	12.1	0.77
"	35	"	9.3	20.3	26.9	0.80
Prim.	0	18	13.2	21.1	20.1	0.39
"	5	"	18.8	24.7	34.1	0.37
"	10	"	30.2	46.5	48.8	0.40
"	15	"	6.3	10.3	13.9	0.58
"	25	"	0.5	1.0	1.5	0.71
"	35	"	0.7	1.6	2.7	1.02
Prim.	0	25	38.9	48.5	63.7	0.37
"	5	"	4.8	6.2	6.9	0.27
"	10	"	17.4	43.8	68.2	1.00
"	15	"	3.2	6.0	11.8	0.90
"	25	"	1.0	2.6	4.8	1.13
"	35	"	1.0	2.2	3.0	1.00

SUMMARY SHEET COMPRESSIBILITY DATA

Sludge	Det.t days	Temp. °C	Specific resist.to filtr.($s^2/g \times 10^8$) 200 g/cm^2	500 g/cm^2	800 g/cm^2	Compressibility
Pr/Ch	0	7	4.6	7.9	10.7	0.60
"	5	"	51.6	86.1	90.1	0.40
"	10	"	8.2	9.6	15.5	0.48
"	15	"	3.3	8.3	13.9	1.03
"	25	"	1.4	3.3	4.7	0.92
"	35	"	1.9	5.3	6.5	0.92
Pr/Ch	0	12	0.2	0.4	0.6	0.64
"	5	"	1.2	2.6	4.5	0.87
"	10	"	9.0	15.2	20.3	0.58
"	15	"	7.9	15.3	20.8	0.70
"	25	"	3.0	7.9	10.5	0.97
"	35	"	1.4	3.3	4.5	0.88
Pr/Ch	0	18	0.3	0.6	0.7	0.68
"	5	"	0.2	0.7	0.8	0.95
"	10	"	1.1	2.5	3.8	0.91
"	15	"	0.7	1.6	2.2	0.86
"	25	"	0.7	1.4	2.4	0.90
"	35	"	1.0	2.3	3.4	0.89
Pr/Ch	0	25	6.3	8.7	13.4	0.55
"	5	"	13.5	24.8	37.2	0.72
"	10	"	0.4	1.2	1.6	1.00
"	15	"	0.5	0.9	1.6	0.97
"	25	"	2.4	5.1	6.8	0.78
"	35	"	1.8	4.0	5.7	0.85

APPENDIX G

ADENOSINE TRIPHOSPHATE (ATP) DATA - PILOT UNITS

SUMMARY SHEET - ATP

Sludge	Det.t days	Temp°C	1 series		2 series		Average	
			ATP mg/l	ATP/VSS µg/mg	ATP mg/l	ATP/VSS µg/mg	ATP mg/l	ATP/VSS µg/mg
Prim.	0	25	0.67	0.0374	0.21	0.0117	0.44	0.0246
"	5	"	2.56	0.2094	1.62	0.1325	2.09	0.1710
"	10	"	3.47	0.3248	-	-	3.47	0.3248
"	15	"	3.08	0.3532	3.63	0.4163	3.36	0.3848
"	25	"	4.05	0.6081	3.68	0.5526	3.87	0.5803
"	35	"	3.36	0.5075	2.73	0.4123	3.05	0.4599
Prim.	0	18	0.75	0.0418	0.89	0.0496	0.82	0.0457
"	5	"	2.90	0.1911	3.90	0.2570	3.40	0.2241
"	10	"	3.50	0.2553	-	-	3.50	0.2553
"	15	"	4.10	0.4052	5.20	0.5139	4.65	0.4596
"	25	"	3.60	0.4326	4.30	0.5167	3.95	0.4747
"	35	"	3.50	0.4504	3.30	0.4247	3.40	0.4375
Prim.	0	12	0.61	0.0340	1.40	0.0780	1.01	0.0560
"	5	"	5.00	0.2902	3.40	0.1974	4.20	0.2438
"	10	"	3.20	0.2094	5.20	0.3402	4.20	0.2748
"	15	"	2.50	0.1882	4.20	0.3162	3.35	0.2522
"	25	"	3.30	0.2792	3.80	0.3215	3.55	0.3003
"	35	"	3.00	0.2759	3.00	0.2759	3.00	0.2759
Prim.	0	7	0.57	0.0316	-	-	0.57	0.0316
"	5	"	4.41	0.2531	1.12	0.0643	2.77	0.1587
"	10	"	4.73	0.3046	4.52	0.2911	4.63	0.2979
"	15	"	3.46	0.2630	3.39	0.2577	3.43	0.2604
"	25	"	3.05	0.2481	3.36	0.2734	3.21	0.2607
"	35	"	3.15	0.2674	3.26	0.2767	3.21	0.2720

SUMMARY SHEET - ATP

			1 series		2 series		Average	
Sludge	Det.t days	Temp°C	ATP mg/l	ATP/VSS ug/mg	ATP mg/l	ATP/VSS ug/mg	ATP mg/l	ATP/VSS ug/mg
Pr/Ch.	0	18	0.28	0.0212	0.60	0.0453	0.44	0.0333
"	5	"	2.30	0.2282	4.70	0.4663	3.50	0.3473
"	10	"	3.50	0.3829	4.10	0.4485	3.80	0.4157
"	15	"	2.70	0.3384	2.80	0.3510	2.75	0.3447
"	25	"	2.50	0.3500	2.20	0.3080	2.35	0.3290
"	35	"	2.70	0.4134	3.80	0.5818	3.25	0.4976
Pr/Ch.	0	12	0.62	0.0469	-	-	0.62	0.0469
"	5	"	3.30	0.2880	0.71	0.0620	2.01	0.1750
"	10	"	2.60	0.2611	1.00	0.1004	1.80	0.1808
"	15	"	0.78	0.0823	0.95	0.1003	0.87	0.0913
"	25	"	1.70	0.1891	1.30	0.1446	1.50	0.1669
"	35	"	1.60	0.1933	1.30	0.1570	1.45	0.1752