FACTORS AFFECTING THE FILTRATION CHARACTERISTICS OF AEROBICALLY DIGESTED SLUDGE

by

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INTRODUCTION

As a result of rapid population growth and industrial expansion, the earth's waste assimilation capacity is becoming seriously overloaded in many areas. This overloading becomes all too apparent when one looks at our fouled streams and lakes, polluted air and junk-strewn landscapes. The problem is most acute in and around large population and industrial centers, and in countries with high standards of living.

The earliest means of wastewater disposal was to dump the polluted water into an existing stream, lake or ocean. This solution was satisfactory as long as the receiving bodies of water were of sufficient size to take care of the waste loads naturally. Problems began when the waste load on any one portion of water became too large for the natural environment to handle. To alleviate the undesirable conditions generated, waste treatment methods were devised. The first type of sewage treatment was the removal of solid waste particles from the wastewater streams by means of sedimentation. This type of treatment accomplished the removal of a portion of the pollution load from the wastewater before it was released to the streams and it is still the only method of wastewater treatment employed by some towns and industries today.

As waste flows became larger and pollution loads on the receiving bodies of water increased, more efficient methods of liquid waste treatment were needed. In order to reduce the oxygen demand of wastewater on the receiving water, secondary treatment methods were developed. These secondary treatment methods employ biological cultures of microorganisms which are capable of using the solid and dissolved organic matter in sewage as food. After the organisms are exposed to the sewage and given time to metabolize much of the organic matter, they are removed from the waste stream and the remainder of the liquid is discharged as treated sewage. This biological method of treatment has been used successfully in the forms of trickling filters and activated sludge.

All conventional primary and secondary waste treatment processes produce large quantities of waste material known as sludge. This sludge varies in makeup and solids content depending upon the characteristics of the raw sewage and the treatment process which produced the sludge. Primary sludge consists of solid sewage particles which are removed from the sewage by sedimentation. Secondary sludges consist primarily of excess microorganisms produced during biological treatment. Raw sludges of both types are dilute mixtures containing mostly water with only 0.5 to 5.0 per cent solids depending upon the origin.

Generally raw sludge must undergo some further processing to reduce the volume and stabilize the organic material before final disposal. Conventional sludge processing methods employ some form of biological treatment and the most common biological sludge treatment is anaerobic sludge digestion. Methane gas, which is used to heat the digester, is given off during digestion and the sludge supernatant, which is high in biological oxygen demand and nutrients, is recycled back through the sewage treatment plant. The resulting sludge is stable and may or may not dewater readily depending on the source of the sludge before digestion. Primary sludge and sludge coming from trickling filters usually dewater readily after anaerobic digestion but activated sludge may become more difficult to dewater. (42)

Aerobic digestion is a more recent development in sludge treatment. This method uses the continuous aeration of sludge to keep aerobic organisms in the endogenous phase of respiration. During endogenous respiration cellular material is destroyed, and thus, solids are reduced and stabilized. The resulting supernatant has less pollution potential than anaerobic supernatant and the sludge may dewater more readily after digestion. (32) Activated sludge is particularly amenable to aerobic digestion because the required aerobic organisms are already developed and the dewatering problems commonly associated with anaerobically digested activated sludge do not develop.

After biological digestion, it is necessary to further concentrate the waste by dewatering before final disposal. Present dewatering methods include vacuum filtration, gravity sand bed drying, centrifugation, and lagooning. Vacuum filtration and sand bed drying are the most widely used sludge dewatering methods with the vacuum filtration generally confined to larger plants. Both methods involve a filtering action with the pressure differential being provided by gravity in the sand bed and by mechanical vacuum in the vacuum filter.

Final disposal methods include placement of sludge in land fill operations or on agriculture land, and incineration. The final disposal method employed depends on the volume of sludge produced and the availability of disposal sites.

The cost of handling and disposal of sewage sludge is a major expense in sewage treatment. Often half of the treatment plant expense is in the purchase and maintenance of sludge handling equipment. The sludge problem becomes particularly acute with activated sludge processes because of the large volumes of waste activated sludge produced and the nature of the activated sludge itself. Activated sludge can be very difficult to dispose of because it can be difficult to concentrate by sedimentation, to digest anaerobically, and to dewater mechanically. Despite these drawbacks, the activated sludge process has many advantages which make it a very popular method and a tremendous increase can be expected in its use in the future.

As a result of the expected increase in the use of activated sludge and the difficulty in dealing with the waste sludge produced, new methods of waste sludge handling are being sought. Aerobic digestion and sludge dewatering by vacuum filtration are two areas receiving particular attention. Vacuum filtration is being used successfully to dewater many types of sludges and has been shown to be effective in dewatering chemically conditioned activated sludge. Aerobic digestion has shown promise as an effective method of reducing waste activated sludge solids without contributing to the pollutional load on the plant and adversely affecting the dewatering properties of the sludges. Some investigators have even reported an improvement in activated sludge filterability and drainability as a result of aerobic digestion.

The object of this investigation was to study the effects of aerobic digestion on sludge dewatering and to attempt to determine the chemical and biological mechanisms affecting sludge filterability. This study should provide information which will lead to a better understanding of the phenomena of sludge dewatering, and this understanding can then be used to develop methods and procedures for handling sludge during processing that will improve the final dewatering properties. Such developments would lead to an overall improvement in the activated sludge sewage treatment process.

LITERATURE REVIEW

The handling and disposal of waste sludge from the activated sludge process is recognized as one of the major problems in sewage and industrial waste treatment today. As state and federal water quality standards become more strict, more and more emphasis is going to be placed on secondary and tertiary sewage treatment. This emphasis on advanced treatment will result in a substantial increase in waste sludge in future years. (40) In 1966, McCarty estimated that in fifteen years the volume of sludge that must be dewatered and disposed of would increase by sixty to seventy per cent. (21)

This increase in waste sludge is due not only to the increase in secondary treatment facilities, but also to the greater volumes of sludge produced in these plants. It is estimated that in an activated sludge plant treating domestic waste, the sludge flow is normally 1.5 to 3.0 per cent of the incoming plant flow, (33) and that with some advanced waste treatment facilities this sludge flow could reach as high as ten per cent of the incoming flow. Furthermore, the cost of handling these sludges is going to increase. Presently the cost of handling and disposing of primary and secondary sludge can run from twenty-five to sixty-five per cent of the total and operating cost of the treatment plants, (27) and secondary sludge is recognized as being more difficult and expensive to treat.

The common methods of handling sludge are outlined by McCarty. (21) These include thickening of sludge by gravity or flotation; biological treatment of sludge by aerobic or anaerobic digestion; dewatering sludge by drying beds, lagoons, vacuum filtration, or centrifugation; and disposing of sludge by land fill, soil conditioning, incineration, or discharge at sea. The choice of methods used in sludge treatment depends on many factors such as the nature and origin of the sludge, the volume of the sludge, and other individual treatment plant requirements. The object of all sludge treatment is to either reduce the volume of sludge, stabilize the sludge solids, or both.

The traditional method of sludge treatment has been based around the anaerobic digester. Sludge is concentrated, digested anaerobically, and dewatered. Anaerobic treatment has many advantages. McCarty (20) lists high degree of waste stabilization, low production of waste biological sludge, low nutrient requirement, no oxygen requirement, and methane production as the major advantages of anaerobic treatment. He does concede, however, that careful control of such factors as pH, temperature, and toxicity is very important to insure the proper operation of an anaerobic digester.

Although anaerobic digestion does reduce solids and produce a stable sludge, the resulting effluent is high in fertilizing elements, and the sludge can be difficult to dewater mechanically, or can require a high coagulant demand. (12, 40) Although all biological sludge can be difficult to dewater, anaerobically digested waste activated sludge is probably the most difficult and expensive sludge to dewater. (42)

Aerobic Digestion

One of the more promising methods of dealing with waste secondary sludge is by aerobic digestion. This method involves the aeration of waste sludge to promote aerobic auto-oxidation, thus reducing solids and stabilizing the sludge. Most of the work on aerobic digestion has dealt with the efficiency of solids reduction; however, some work has dealt with the dewatering characteristic of the digested sludge.

In 1956, Eckenfelder (9) reported on the aerobic digestion of waste sludge from a conventional activated sludge plant. The sludge was aerated at 25° C for seven days with a reported forty-eight per cent decrease in mixed liquor COD and a thirty-eight per cent decrease in suspended solids with a thirteen per cent decrease in volatile solids content. Eckenfelder reported an auto-oxidation rate of ten to twelve per cent per day at 25° C for the first five days. He further reported first order kinetics for the first five days with a rapidly decreasing auto-oxidation rate from five to seven days.

Murphy (26) in 1959 studied the effects of aeration on the filterability and settleability of sewage sludge. He used a 1:1 mixture of primary and secondary sludge aerated at 15° C. He concluded that the reduction in volatile solids up to six days was not appreciable. He found, however, that filterability increased with time up to 72 hours and then decreased from 72 to 144 hours. He also found that excessively vigorous aeration caused a reduction in both filterability and settleability.

Jaworski, Lawton, and Rohlich (15) aerated a mixture of primary and secondary sludge in continuous digestion studies. They concluded that the reduction of volatile solids is a function of detention time; however, beyond fifteen days digestion time, only small increases in reduction were obtained. In general, greater reductions in volatile solids were obtained at higher temperatures, up to 35° C, and lower loading rates. The drainability of the sludge was measured on gravity sand filters. It was found that sludge digested for five days usually exhibited poorer drainability than undigested sludge, while sludge digested for ten days or longer showed improved drainability.

With detention times of ten days or greater, the effect of temperature on drainability appeared to be of minor importance. Settling characteristics of sludge digested for 30 days or less were found to be generally poorer than those of the undigested sludge. Drying of the sludge produced little odor and supernatant BOD values were relatively low when compared to anaerobic digester liquors.

Lawton and Norman (18) continued the work started by Jaworski *et al*. (15) and their results agreed closely. They further concluded that increase in volatile solids reduction showed a high correlation with sludge age (the ratio of the weight of volatile solids in the digester to the daily weight of volatile solids fed to the system). It was also found that environments in which the pH was as low as 5.0 did not appear to significantly affect digestion efficiency.

Barnhart (1) studied the application of aerobic digestion to industrial waste treatment. He concluded that the solids reductions obtained were compatible to anaerobic digestion. He also reported that temperatures below 20° C were significantly retardant to digestion and that the rate of solids degradation varied widely with different types of sludge, but that fifteen days detention time was sufficient to accomplish acceptable digestion in all cases.

Carpenter and Blosser (5) investigated aerobic digestion of secondary boardmill and de-inking sludge from a conventional activated sludge plant. It was found that at 20° C the volatile solids were reduced from 69.5 to 64.4 per cent over a period of 27 days aeration. Increasing the temperature to 30° C increased the rate of solids reduction by 50 per cent and the addition of nitrogen and phosphorous resulted in a substantial increase in solids reduction. Thickening characteristics of the sludge were not significantly changed; however, a general degradation in filtration characteristics was noted upon aeration. The degradation was rapid with the filterability being materially changed within six hours. The degradation was thought to be due to mechanical breakdown of the floc and not a biological change.

Reynolds (33) aerated waste activated sludge from a biosorption plant. The waste was primarily domestic with a small portion coming from a slaughter house. The maximum stabilization time for 95 per cent destruction of the biodegradable solids was found to be 5.7 days. The sludge after stabilization would not further decompose and it readily gave up its water content when it was poured upon a sand drying bed.

Saunders (35) monitored the aerobic digestion of waste activated sludge to establish the extent of stabilization and to relate process and cellular parameters to the settleability and drainability of the sludge. The investigation showed that total and volatile suspended solids were reduced from 46 to 70 per cent and that cellular carbohydrates were reduced at a similar rate, indicating that the sludge was well stabilized. Sludge settleability and drainability were poor initially and could not be improved with digestion although the rate of drainage was improved. Since the sludge was well stabilized and drainability did not increase, it was concluded that sludge drainability was not necessarily a function of digestion.

Turpin (43) studied three different activated sludge wastes to relate process and cellular parameters to sludge drainability. The results of the study indicated that sludge drainability is improved by aerobic digestion and is closely correlated to the degree of stabilization achieved. The results also indicated that suspended solids reduction could be accomplished over a wide pH range. Dehydrogenase enzyme activity was found to decrease with digestion but there appeared to be no relationship between enzyme activity and drainability. Cellular protein per unit weight of suspended solids increased during digestion and it was found that the greater the amount of protein in the sludge, the better the sludge drained.

Moore (25) studied the effect of pH on aerobic sludge stabilization using batch aerobic digesters. Two digesters were used as controls while the pH in the other four digesters was maintained at respective values of 9.5, 7.0, 5.0, and 3.5 (± 0.5). The results of his studies showed that the aerobic digestion process is relatively insensitive to pH with regard to solids reduction, mixed liquor BOD reduction, and cellular carbohydrate and protein accumulation. There was a somewhat greater solids reduction in the digester which had pH control over those digesters which had no control. The one major difference noted in the six digesters was a striking improvement in flocculation characteristics in the sludge digested at the low pH with a corresponding development of a very large predator population in that unit. The improvement in flocculation characteristics and the removal of organic detritus and bacteria from the sludge by the predators was considered to be the cause of improved settleability, filterability, and drainage of the digested sludge.

Ritter (34) observed the operating characteristics of aerobic sludge digestion units at three contact stabilization plants in eastern Pennsylvania. The purpose of the study was to compare operating and design data in order to set forth workable procedures and practices that could be used in evaluating the effectiveness of the aerobic digestion process. Ritter outlined some present design criteria for aerobic digesters. These criteria were:

(a) Capacity of at least 3.0 to 5.0 cu ft/equivalent person served;

(b) Effective open drying bed space of about 1.0 sq ft/equivalent person served;

(c) Aeration rate of 20 cfm/1,000 cu ft of digester capacity.

He felt that the present design criteria for aerobic digesters is adequate for producing a stable sludge which dries readily. Some other conclusions from the study were:

(a) Anaerobic digestion accomplishes greater reduction in volatile solids than aerobic digestion;

(b) Primary sludge is aerobically digestible;

(c) Manual decanting produces a supernatant low in BOD and compatible with the treatment process.

(d) Tests performed did not show a marked increase in reduction rate of aerobic bacteria at sludge temperatures as high as 80°F based on observation of volatile solids.

(e) Operating costs that are mainly power costs are reasonably low considering the effectiveness of aerobic digestion. Average power costs in the plants studied are $2.18/yr/lb of BOD received/day, and $0.37/yr/capita served.

(f) The construction cost for aerobic digesters is less than that of anaerobic digesters. Operating cost of aerobic digesters serving communities of 3,000 people are less than operating costs of anaerobic digesters serving the same population because of the fuel cost to heat small anaerobic digesters. As the equivalent population served approaches 8,000, operating costs of anaerobic digesters are less than operating costs of aerobic digesters because fuel costs are minimized due to methane gas production.

(g) Addition of lime as a drying aid and alum as a coagulant increase digested sludge drainability and reduce drying time significantly. However, drying bed media becomes incrusted by chemicals, and the upper portion has to be removed.

The effect of aerobic digestion on dewatering does not seem to be consistent from the literature reviewed. An improvement in filterability was reported by Reynolds (33) and Turpin. (43) Moore (25) reported improved filterability only when the digester was operated at a low pH. Murphy (26) found that filterability improved with up to 72 hours of aeration and became worse from 72 to 144 hours, while Jaworski _et_ _al_. (15) reported a poor filterability at five days aeration with an improvement with aeration for ten days or more. Carpenter and Blosser (5) on the other hand, found a rapid and continued degradation in filterability with aerobic digestion.

Sludge Dewatering

The early work in sludge dewatering dealt mainly with anaerobically digested sludge, but many of the principles may be useful in the understanding of aerobic sludge dewatering.

In 1957, Trubnick and Mueller (42) discussed sludge characteristics as they applied to sludge dewatering on vacuum filters. The size, shape, and density of the solid particles were said to have a profound effect on filterability. Particles of irregular shapes and sizes and small particles tended to form compact mats under vacuum, leaving only a small ratio of voids for the migration of liquid. Viscosity of the filtrate was found to be inversely proportional to the filter rate. Viscosity varies with temperature with a doubling in viscosity between 55°C and 22°C; however, raising the temperature of filtrate for filter purposes was felt to be impractical.

The concentration of feed solids was also inversely proportional to filter rate. Moreover, there are some practical methods for changing the concentration of solids. Some of these methods are sludge thickening with mechanical rakes, secondary digesters with quiescent settling and elutriation.

The chemical composition of sludge was believed to greatly affect the requirements for chemical conditioning. Bicarbonate alkalinity was considered to be very important in this respect. The volatile matter in the sludge solids was also found to affect the chemical demand: the greater the alkalinity or volatile matter, the greater the chemical demand.

The compressibility of sludge was thought to have an effect on vacuum filter operation. All the sludge examined was found to be highly compressible, thus indicating that increases in vacuum exert only minor influences on filter yield for a given time. Sludge with low volatile matter content was found to have a lower compressibility coefficient.

The chemical and physical nature of sewage sludge is affected by the nature of the process producing the sludge. In general it was found that primary sludge was more filterable after chemical conditioning than was secondary sludge, and fresh sludge was more filterable than anaerobically digested sludge. The data indicated that anaerobically digested secondary sludge had the poorest filtering characteristics.

In 1967, Hamlin and El-Hattab (13) investigated the physical factors affecting the dewatering of primary sludge. Hamlin contended that specific resistance was not in itself a sufficient parameter to describe the behavior of sludge because tests showed that some sludge with the same specific resistance behaved differently when placed on drainage beds. The factors which Hamlin felt were important were: the presence of fine particles, the initial drainage rate, and the compressibility of the sludge.

Fine particles, he felt, tended to reduce porosity by filling the voids between the larger particles. The initial drainage rate was important because higher rates resulted in higher velocities within the pores which tended to carry the finer particles to the lower layers with resulting clogging of these layers. Higher velocities also tended to cause higher head losses which resulted in compression of the lower layers. Greater depths of sludge tended to cause greater compression of the lower layers resulting in the distortion of sludge particles and the alteration of void ratios.

Some unusual findings were that very high initial drainage rates resulted in an increase in the total volume drained. This was due to a breakthrough of fine particles and was confirmed by the higher BOD values of the initial drainage liquor. Another point of interest was that although fine particles inhibited drainage, they tended to assist evaporative dewatering.

Randall et al. (32) studied the factors affecting activated sludge dewaterability. Dewaterability was a term used to describe drainage rate as well as total drainable water. Drainage rate is most important in mechanical dewatering processes such as vacuum filtration, and total drainable water is usually most important in gravity dewatering operations such as sludge drying beds where evaporation is usually the ultimate rate controlling factor. The object of the study was to define the properties and characteristics of activated sludge that determine its drainability, and to evaluate the usefulness of various parameters for predicting the drainability of sludge prior to dewatering. Randall et al. concluded that gravity drainage from activated sludge was a two-stage process. The first stage occurred while the applied sludge was settling and compacting, and the second stage began when drainage pores started to develop in the settled sludge.

The experimental results showed that the solids concentration had a greater effect on gravity dewatering than any other single factor. Both total drainage and drainage rate decreased rapidly with increasing solids concentrations up to 2.5 per cent. This effect decreased rapidly and was virtually negligible above 3.0 per cent. The next most important factor in sludge drainability was described as microbial dispersion. Dispersion was not considered equivalent to microbial activity because, although it is true that sludges are dispersed when microbial activity is high, they are also dispersed when microbial respiration is extremely low. There was felt to be a medium free energy level (approximately 600 mg/l BOD for the mixed liquor) that was optimum for gravity dewatering. In general, the effect of a sludge property on drainability was felt to depend on how that property affected dispersion. In most cases, total drainage was also strongly affected by dispersion. However, the presence of hydroscopic material exerted a strong influence on total drainage as well.

Alkalinity and extracellular carbohydrates tended to improve sludge drainage rates. However, the magnitude of their effect was found to depend on the energy level of the microbial system, and the effect was negligible at high energy levels. Cellular protein, on the other hand, had only a weak inverse relationship to drainage rate.

Although BOD provided a good accurate measure to predict microbial dispersion, it was felt that BOD was not a practical parameter because of the time required to run the test. Therefore, a dehydrogenase enzyme test (11) was run. This test did not suffer from time considerations, was found to have a strong correlation with drainage rate, and appeared to be a reliable indicator for predicting the rate of gravity drainage. The results of the dehydrogenase enzyme studies indicated that an enzyme activity-solids ratio of less than 0.6 micromoles/gram of solids was assurance of good solids drainability.

Filtration and Drainage Prediction

The interpretation of laboratory filtration data for the prediction of vacuum filter and gravity drainage performance is a difficult task. The task is complicated by the number of variables present in any filtration operation. Initial solids content, volume of sludge filtered, area of filter surface, and pressure at which the filtration is carried out are all factors to be considered when interpreting any filtration information. (6)

Many experimental filtration techniques have been developed and used to simulate vacuum filtration (6) or gravity drainage. (16, 19, 28) The two most common methods used for laboratory investigations are the Buchner funnel test and the filter leaf test. The operation and characteristics of both of these tests have been discussed by Eckenfelder and O'Connor. (10) The Buchner funnel test, with the results reported as specific resistance, is considered to be adequate for comparing different filtration rates and for other related research purposes. (6) The specific resistance concept was developed in an attempt to include all of the sludge and filter parameters which would affect the filtration rate. However, there is evidence that the specific resistance of a sludge does vary with both solids concentration and pressure differences. (10) The filter leaf test is used for predicting actual vacuum filter operation. The leaf test is able to simulate a vacuum filter in the pickup, drying and discharge phases of filter operation. (36) Because of the ability of the filter leaf to simulate actual filter operations it is well suited for design. However, it is rarely used in experimental sludge characterization work.

Biological Flocculation

Flocculation of sludge is an important aspect of all phases of activated sludge treatment. This is true of the aeration tank, secondary settling tank, and filtration or gravity drainage.

Flocculation in mixed biological systems was originally thought to be due to a special group of bacteria which produced a zoogloeal growth. This zoogloeal growth was considered to be the basic structure for the flocculant growths formed in both trickling filters and activated sludge.

McKinney (22) studied pure cultures of some of the types of organisms found in activated sludge and found that many of the organisms were capable of forming flocs of the activated sludge type. He concluded that the so-called zoogloeal bacteria were not necessary for floc formation.

McKinney theorized that biological flocculation was similar to colloidal flocculation even though bacteria are larger than true colloids. The capsule and cell wall of bacteria were found to have only a negligible number of reactive groups. However, the cytoplasmic membrane readily ionizes to give bacteria a negative charge at the surface. This charge was found to be between -6 to -12 millivolts, which is below the ±20 to 30 millivolts required for a stable colloidal suspension. The electrostatic force of repulsion was considered to be small enough so that the van der Waals forces of attraction could cause flocculation. These forces were thought to be the major cause of biological flocculation.

Chemical bonding was considered to be negligible because of the low chemical reactivity of the capsular layer. Salt linkage or direct chemical bonding was also termed unimportant because the active chemical layers were well within the cells at the cytoplasmic membrane.

It was shown that some bacteria do not form flocs readily while other bacteria have a tendency to form flocs under some conditions and not under others. It was also found that floc-forming bacteria were non-motile and that most motile bacteria do not form flocs. From these observations, the theory was proposed that the ability of bacteria to form flocs is dependent on energy present in the system. High energy systems with high food to microorganism ratios tend to promote the growth of free swimming highly motile bacteria with little or no floc formation. Low energy systems with low food to microorganism ratios tend to promote non-motile bacteria and floc formation.

The requirements for biological floc formation, as proposed by McKinney, are a charge on the microorganisms below the critical zeta potential of ±20 to 30 millivolts and a low food to microorganism ratio in the system.

Tenney and Stumm, (41) like McKinney, felt that bacteria and other microorganisms such as viruses, algae, and protozoa, can be thought of as hydrophilic biocolloids, but they did not feel that a low zeta potential and attraction by van der Waal's forces alone can satisfactorily account for the phenomenon of bioflocculation. The stability of a bacterial suspension, it was felt, depends on the presence of surface-modifying agents in the medium. While hydrogen ions affect the charge characteristics of the cells, it was thought doubtful that the agglomeration of microorganisms is brought about by a simple reduction in charge density. Polymers of biological origin were felt to be of major importance in flocculation. Natural polymers such as complex polysaccharides and polyamino acids are excreted or exposed at the surface of bacteria predominantly during the declining-growth and endogenous-respiration phases. It was felt that possibly polymeric substances are excreted under all physiological conditions, but under conditions of prolific growth, new surfaces are created faster than surfaces can be covered with such polymers. The secreted polymeric molecules were thought to be of sufficient length to form bridges between microbial particles.

Busch and Stumm (3) confirm the concept that naturally occurring polymeric extracellular or cell-surface material is involved in bacterial aggregation. Although little is known of the chemical nature of the flocculent material produced by the cell, it was felt that different organisms probably produce different cell binding material. While extracellular polysaccharides or other polymers are synthesized during all growth phases, it was thought that perhaps an adequate concentration of polymer can accumulate per surface area only under conditions of declining or endogenous growth.

Busch and Stumm were able to isolate material containing cell-free flocculants from the supernatant of centrifuged activated sludge. This material in concentrations of 1 to 10 mg/l was then used to flocculate inorganic colloidal dispersions with negative surface potential. This procedure showed that some flocculating substance was present in activated sludge which was capable of inducing flocculations in a negative colloidal system such as found in an activated sludge culture.

Dean (7) agreed with Busch and Stumm that bacteria produce a great variety of polymeric substances that are exuded as slimes of capsular material. He found that the most common group of slimes consists of the polysaccharide gums and that another type of capsular material is composed of amino acids such as proteins and polypoptides of glutomic acids. Dean stated that although most polymeric flocculants should be adsorbed at the optimum flocculant dose, activated sludge probably contains an excess of polymer which contributes to its poor dewatering properties. Furthermore, it is characteristic of polymer flocculants that they act as dispersants when present in an excess over the optimum dose.

Flocculation by Protozoa

Protozoa and higher forms of life in mixed biological treatment systems have been implicated in the bioflocculation process for many years. In 1945, Watson (44) found that the feeding mechanism of ciliates involved the production of a mucus secretion to which the food and bacteria adhere before being ingested. This mucus was found to accumulate in the culture, especially in the neighborhood of the ciliates. Furthermore, the secretions were observed to cause the entanglement and flocculation of bacteria. McKinney (23) reported that the introduction of protozoa into cultures of slow floc forming bacteria tended to increase the floc formation in these cultures. He also observed that pure cultures of some ciliates formed flocs by themselves.

McKinney and Gram (23) studied the role of protozoa in activated sludge. They studied laboratory activated sludge units with and without protozoa present. Most bacteria found in activated sludge were able to utilize the soluble organic matter, produce new cells, and undergo flocculation in a manner similar to normal activated sludge. But, unlike normal activated sludge, the pure bacterial floc did not clarify the effluent completely upon quiescent settling. The motile, actively metabolizing bacteria remained in the supernatant after the floc had settled.

Ciliates introduced into the pure bacterial systems lived, to a large extent, on the free-swimming bacteria. The bacteria and ciliates formed a mutually favorable equilibrium with each other. Together they produced more floc, a cleaner effluent, a more stable effluent, and a more rapid rate of oxygen uptake than the bacteria alone.

Calaway (4) reported on the role of rotifers in activated sludge floc formation. He indicated that rotifers, like ciliates, were also able to secrete a mucus material which accumulates in the region of the rotifer and acts like a flocculating agent. Rotifers are also able to remove small clumps of bacteria, thus removing bacterial turbidity and possibly removing pore clogging particles from suspension.

Calaway stated that the presence of rotifers, like the presence of stalked ciliates, indicates an activated sludge in good condition. The progression of higher forms of life in a process was given as:

(a) Small flagellates, small amoebae, few free swimming ciliates, and unflocculated bacteria; to

(b) Few flagellates and amoebae, numerous free swimming ciliates, and partial flocculation of the bacteria; to

(c) Stalked ciliates and large bacterial flocs.

The absence of rotifers may indicate an intervening period of anaerobiosis because rotifers are aerobic animals. Furthermore, active rotifers are not as durable as are the ciliates and they require a long time to become reestablished.

Sludge Bulking

Sludge bulking is one of the major problems in the operation of activated sludge sewage treatment plants. The bulking of sludge is an inability of sludge to settle and compact to a small volume under quiescent conditions. Although no relationships have been found between the settleability and filterability of sludge, the factors affecting sludge bulking, such as the type and physiological state of the organisms, are also thought to be factors in sludge filterability.

Heukelekian (14) studied the effect of bound water on activated sludge bulking and arrived at the following conclusions which may be applicable to sludge dewatering:

(a) The bound water content of a zoogleal type bulking sludge is higher than that of a sludge with a low sludge volume index;

(b) The continuous aeration of a bulky zooglean type sludge, without feeding, resulted in a decrease of both the sludge volume index and the bound water simultaneously with a decrease in the sludge-oxygen demand;

(c) Chlorination of a zoogleal type bulky sludge gave an immediate decrease in sludge volume index and bound water. The action of chlorine appears to be a physical one since the addition of chlorine has an immediate effect;

(d) The increase in bound water and the increase in the sludge volume index are considered to be

> associated phenomena. They are the result of biochemical processes induced by excessive supply of available food in relation to the number of organisms.

Bhatla (2) also investigated sludge bulking and found that settling properties of sludge were affected by the dissolved oxygen levels maintained in the aeration tank. He concluded that sludge produced under high dissolved oxygen tensions generally had poorer settling properties than those produced under low tensions. He stated that this was probably because low oxygen tensions generated an unstable environment for filamentous organisms and retarded their growth. Dissolved oxygen below 2.5 mg/l stopped filamentous growth.

Summation

The review of the literature leads to some general conclusions regarding waste activated sludge:

(a) The handling and disposal of waste activated sludge is a major problem and expense in secondary sewage treatment;

(b) Aerobic digestion is a promising development for the handling of waste activated sludge from the standpoint of solids reduction, stabilization, and dewatering;

(c) Sludge dewatering is an extremely complicated phenomenon which is not well understood, but is known to be affected by physical, chemical, and biological processes;

(d) Biological flocculation and sludge bulking are phenomena associated with activated sludge which are affected by physical, chemical, and biological processes and may be related to the ability of sludge to dewater;

(e) A study of the effect of aerobic digestion on activated sludge dewatering would be a valuable and desirable undertaking.

EXPERIMENTAL METHODS

The object of this research was to conduct laboratory scale investigations of activated sludge dewatering. All operations were bench scale and all data were collected in the sanitary engineering laboratory on the Virginia Polytechnic Institute and State University campus.

General Procedures

The sludge used in the experiments was obtained from a small extended aeration waste treatment plant which treats domestic sewage, approximately 6,000 gallons per day, from a rest area located on Interstate 81 near the Radford, Virginia interchange. The plant has a comminuter but no primary settling. Aeration is by means of a surface aerator and the sludge is recycled to the aeration tank from the final settling tank by an air lift pump. The sludge samples were collected at the outlet of the return sludge line and transported directly to the laboratory. At the laboratory, sludge was either used immediately or stored at 4° C for future use. Sludge concentrations used in the experiments were usually between 1.5 and 2.0 per cent. Solids concentration of sludge was accomplished by allowing the sludge to settle and removing the required amount of supernatent.

Unless otherwise specified, aeration or aerobic digestion of sludge took place in what will be referred to as a standard aeration tube. Figure 1 shows the typical set-up for a standard aeration tube. The unit illustrated is a test tube with a diameter of 2.5 inches and a volume of approximately 1.5 liters. Air was supplied through a 1/8 inch diameter glass rod which extended to the bottom of the tube. The air flow was metered at all times and maintained at a rate of 600 ml of air per minute unless otherwise specified. This air flow rate provided sufficient energy to keep solids in suspension, and enough air to maintain the dissolved oxygen level above two milligrams per liter at all times. All aeration of sludge was done in a constant temperature room and, except for temperature studies, the temperature was maintained at 20° C.

Each day before samples were removed, the sides of the aeration tubes were scraped and rinsed with distilled water in order to resuspend any solids that had attached themselves to the sides. Any liquid lost by evaporation was replaced by adding distilled water to the aeration tubes to bring the level of liquid up to a level mark made after the previous sample was removed.

Samples were removed by pipetting the required volume directly from the aeration tubes. Pipets were wide mouth so as not to exclude or break up any floc formations.

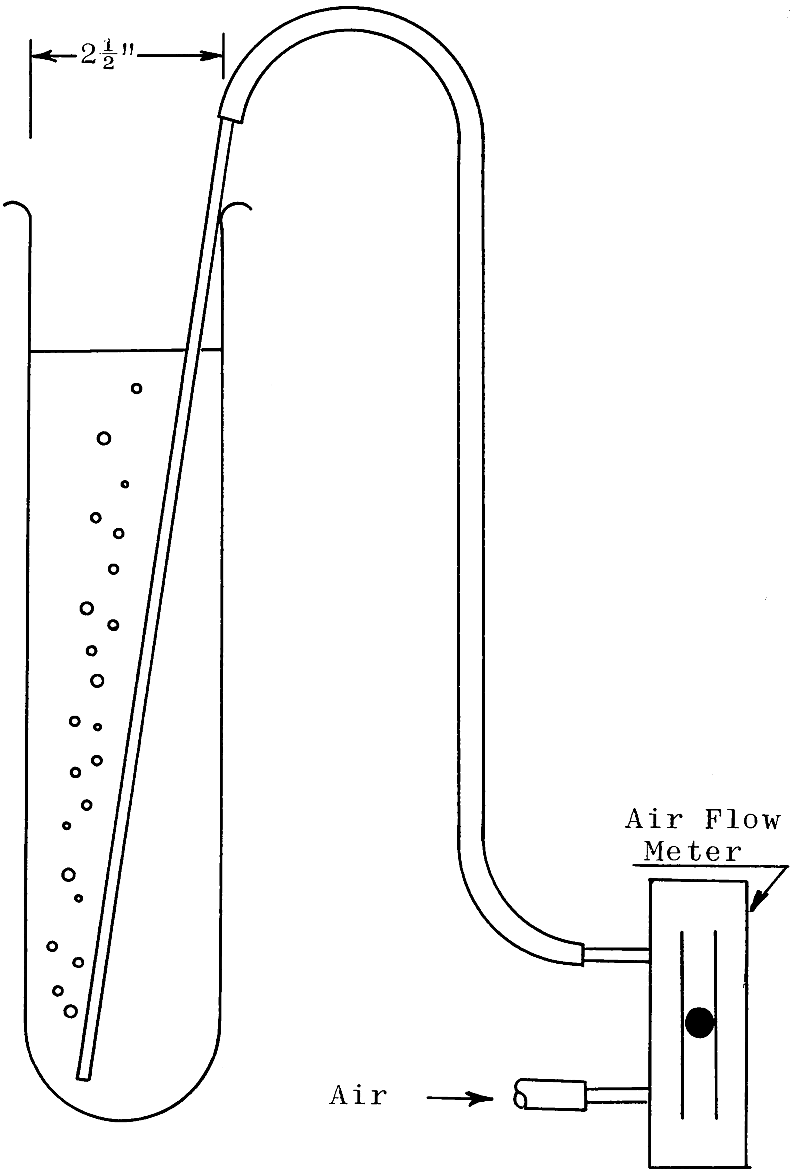

Figure 1. Standard Aeration Tube.

Care was taken to try to sample when the contents of the tubes were completely mixed so that representative samples would be obtained.

Special care was taken to treat all tubes the same throughout the aeration phase of an experiment. Only those factors being studied were altered during any one experiment. For example, when pH was studied, sludge from the same batch was divided between the tubes and the same temperature and air flow rates were maintained in all tubes. In this way, any difference in filtration characteristics between tubes within the experiment could be attributed to the effect of the different pH adjustments in the tubes. The direct comparison of results from one experiment to another was not always possible because the sludges used may have been collected at different times or stored for different lengths of time, but the trends of the experiments could be compared.

Analytical Procedures

The analytical testing procedures were chosen so that the tests measured the desired factors, gave consistent results, were reproducible and were easy to run. With these criteria in mind, the tests chosen were not always in accordance with standard procedures. However, they are comparable to standard tests and the results can be reproduced using the given descriptions.

Filtration Test

The filtration apparatus used in this investigation consisted of a nine centimeter diameter Buchner funnel with one piece of Whatman number 40 filter paper. The funnel was connected to a rubber stopper by means of a rubber tube. The stopper contained a second tube for vacuum application and was seated in a 100 ml graduated cylinder as shown in Figure 2. The test results were obtained in the following manner:

(1) Filter paper was placed in the Buchner funnel and 75 ml of distilled water was filtered to wet and seat the paper;

(2) The pinch clamp was closed, the cylinder emptied and replaced, and the vacuum was adjusted to 12 inches of mercury;

(3) 100 ml of sludge was placed in the funnel;

(4) The pinch clamp was opened and a stop watch was started;

(5) The time required to obtain 75 ml of filtrate was recorded.

The results of the test are reported as the time in seconds required to filter 75 ml of sludge.

The filtration test used for this work was developed for its simplicity, its reproducibility, and its ability to be compared to the same test within a given experiment.

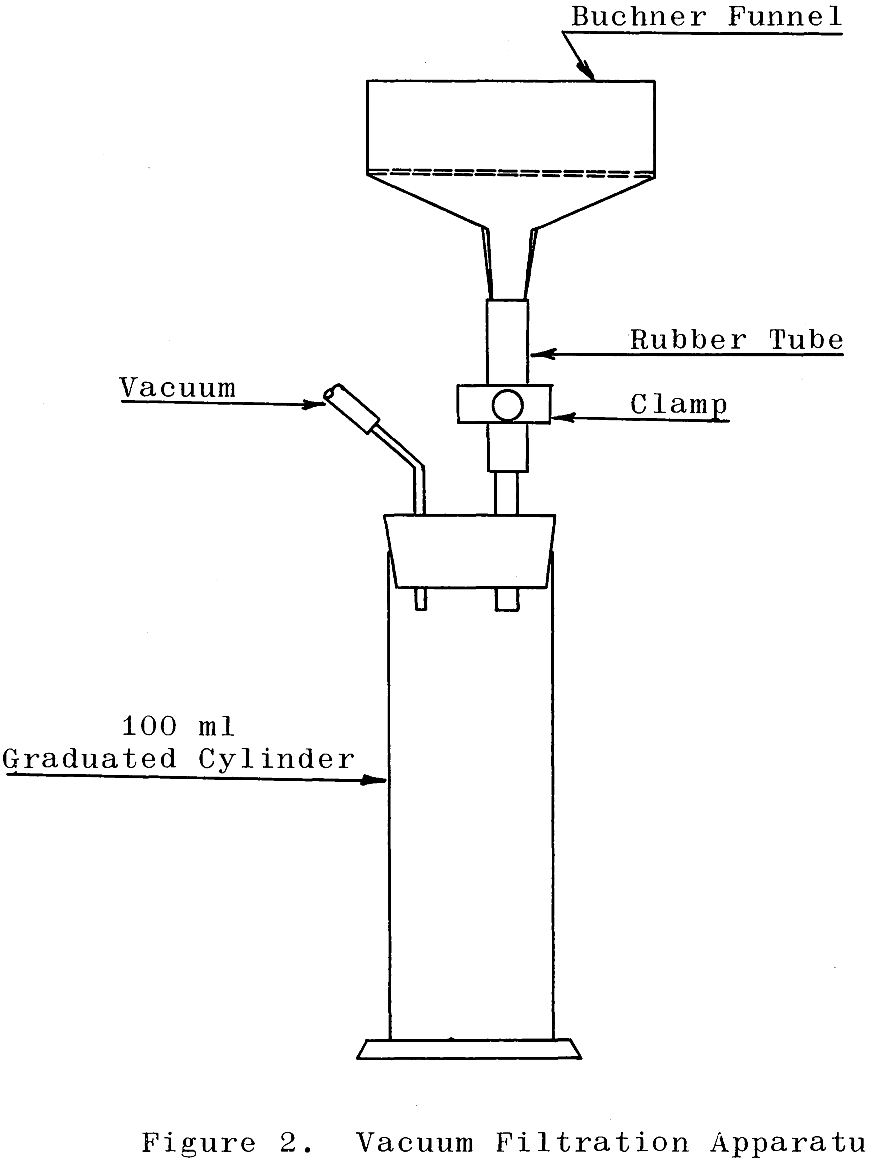

Figure 2. Vacuum Filtration Apparatus.

The purpose of the test was to give an indication of the rate of filtration and it was used for comparison purposes within a given experiment to indicate the trends of filtering for a sludge subject to different conditions. No attempt was made to provide information which could predict filter loadings or filter rates for actual vacuum filters. Such information would require the development of specific resistance and filter leaf data and was not considered to be within the scope of this investigation.

Preliminary investigations did indicate, however, that increases and decreases in specific resistance for a given sludge could be predicted by filtration time data from the test used in this investigation. Figure 3 shows the relationship between filtration time and specific resistance for a sludge which was aerated and tested over a nine day period. This figure does indicate a reasonable correlation between the two parameters.

Sand Bed Drainage Cylinder

A special sand drainage bed was constructed to test the effect of aerobic digestion on gravity dewatering. The sand bed consisted of a plexiglass cylinder with an inside diameter of 2-11/16 inches and a height of 12 inches. A one inch column of sand was supported within the cylinder on a wire and cloth base 1½ inches from the bottom. Drainage fluid was collected by a funnel attached to the bottom

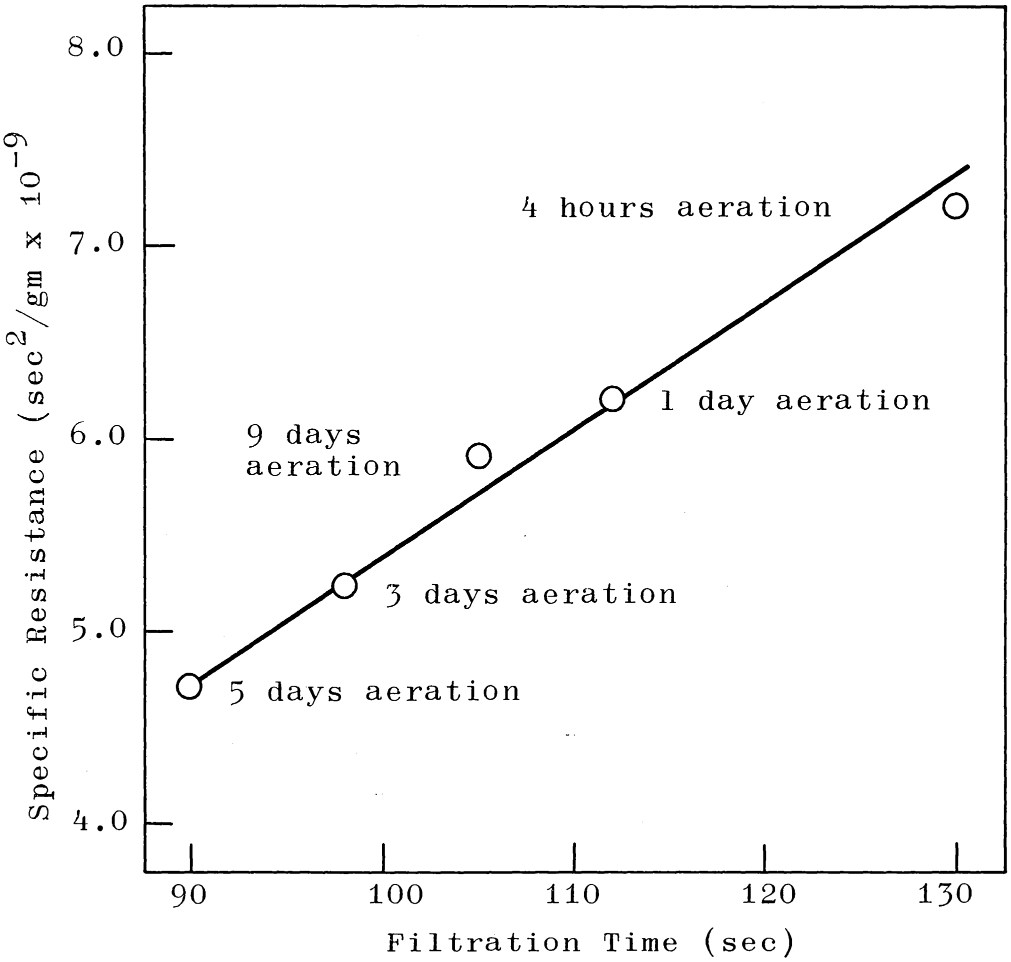

Figure 3. Relationship Between Filtration Time and Specific Resistance.

of the cylinder and the volume of drainage was measured in a 1,000 ml graduated cylinder. A diagram of the drainage cylinder is shown in Figure 4.

Before each drainage experiment the cylinder was prepared by placing one inch of fresh sand on the wire base and then washing and wetting the sand by running three liters of water through the cylinder. After the sand had thoroughly drained, one liter of sludge was carefully placed in the cylinder and the cylinder was covered to prevent loss of water by evaporation. The time was recorded at the start of the test and the volume of filtrate was checked throughout the drainage period. After all drainage had ceased, the total drainable water was recorded.

pH

The pH was determined by using a Leeds and Northrup stabilized pH meter assembly in conjunction with Leeds and Northrup glass-calomel electrodes. Before pH determinations, the meter was standardized against standard buffer solutions by Fisher Scientific.

Dissolved Oxygen (DO)

Dissolved oxygen concentrations were determined using a PCL Dissolved Oxygen meter purchased from Pollution Control Laboratory, San Antonio, Texas. The PCL Analyzer was calibrated at the temperature of the sample before each set of dissolved oxygen measurements.

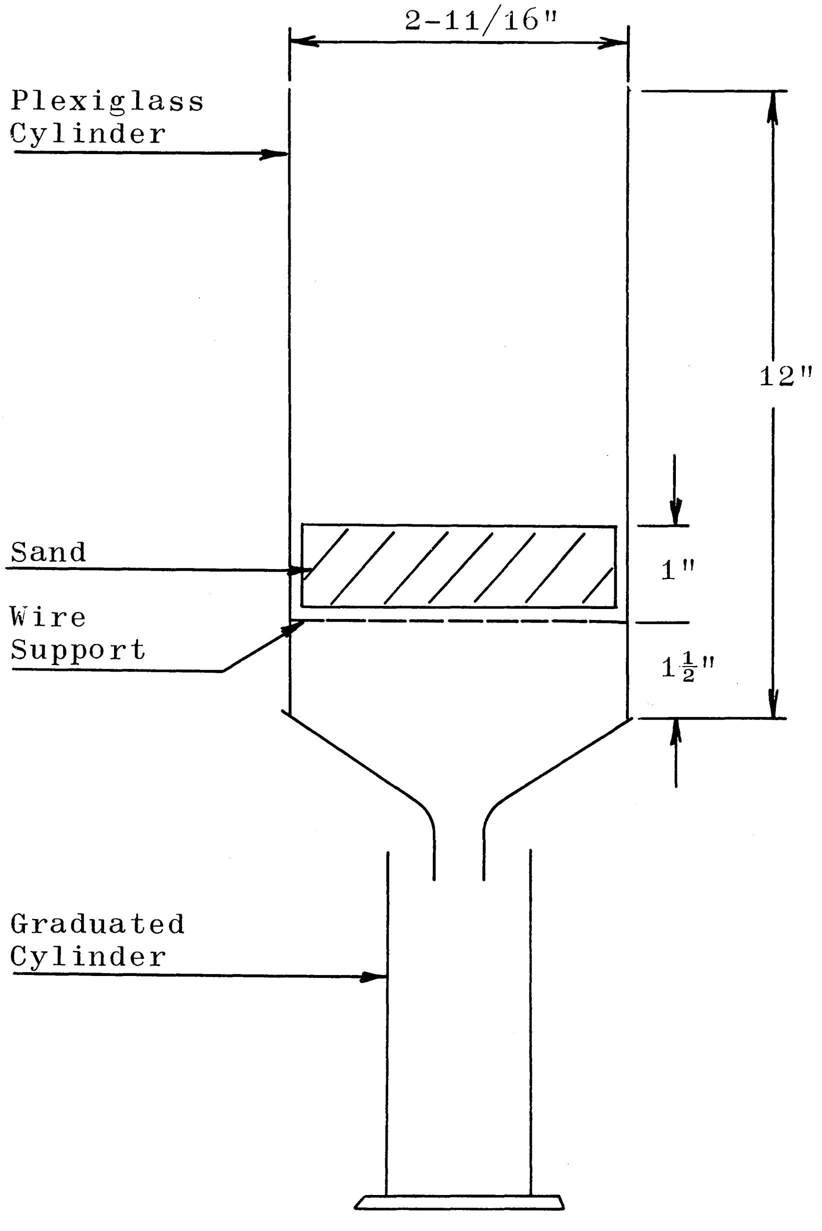

Figure 4. Sand Bed Drainage Cylinder.

Oxygen Uptake

Oxygen uptake rates were measured by placing sludge in a standard BOD bottle which contained a magnetic stirring bar. The bottle was sealed with a self stirring dissolved oxygen probe manufactured by Yellow Springs Instrument Company. The contents of the bottle were stirred while dissolved oxygen readings were recorded at periodic time intervals. The oxygen uptake rate was found by calculating the slope of the plot of dissolved oxygen with time. The rate was given in terms of mg/l DO depleted in one hour.

Total Organic Carbon (TOC)

Total organic carbon was determined using a Beckman model 915 Total Organic Carbon Analyzer. Twenty microliter samples were injected with a Hamilton Microliter Syringe. All procedures used were in accordance with the Beckman model 915 instruction manual. Total carbon and inorganic carbon were determined, and the total organic carbon was found by subtraction. Samples were first filtered through a 0.45 micron millipore filter to remove all solids.

Zeta Potential

Zeta potential and specific conductance were measured with a Zeta-Meter by Zeta-Meter, Inc., in conjunction with a Riddick Type II electrophoresis cell. Measurements were taken using the 8X objective and all other procedures were in accordance with the Zeta-Meter Manual, second edition, Zeta-Meter, Inc.

Chlorine

Total available chlorine determinations were made using a Hach Model DR-EL Portable Water Engineer's Laboratory. The procedure used was basically an orthotolidine method. All procedures were in accordance with the Methods Manual, Sixth Edition, provided with the kit.

Total and Volatile Suspended Solids

All total and volatile suspended solids concentrations were determined by the Gooch crucible method as described in *Standard Methods for the Examination of Water and Wastewater*. (38) Sample volumes used were 10 ml. Because of the high suspended solids, the drying time at 103° C was 24 hours, and at 600°C was one hour.

BOD and COD

The BOD and COD determinations were made in accordance with the procedure outlined in *Standard Methods for the Examination of Water and Wastewater* (38) and using the simplifications as outlined in *Simplified Laboratory Procedures for Wastewater Examinations* (37) where applicable. Dissolved oxygen measurements for the BOD test were made using a self-stirring dissolved oxygen probe manufactured by Yellow Springs Instrument Company.

Alkalinity

The procedure outlined in *Standard Methods for the Examination of Water and Wastewater* (38) was used for alkalinity determinations with the exception that samples consisted of 10 ml of filtrate instead of the recommended 100 ml size.

Dehydrogenase Enzyme

The dehydrogenase enzyme activity measurements were made using the method presented by Ford, Young and Eckenfelder. (11) The test is based on the ability of aerobic dehydrogenase enzymes to pass electrons to certain reducible dyestuffs as well as to oxygen. A tetrazolium salt (triphenzltetrazolium chloride or TTC) is used as a hydrogen acceptor and the oxidation of substrate results in the reduced form, triphenyl formazan (TF), which has a red color. The intensity of the red color is taken as a measure of dehydrogenase activity.

The test was conducted by placing 5 ml of sludge and 5 ml of tris-buffer (pH 8.4) in each of four tubes, bringing the solution to 37° C in a water bath, placing 1 ml of TTC in three of the four tubes and 1 ml of distilled water in the one remaining tube, incubating the mixture for 15 minutes at 37° C, and stopping the reaction with 39 ml of ethyl alcohol. The contents of the tubes were then centrifuged to remove the solids, and the percentage transmission, as compared to the tube with distilled water, was then read on a Bausch and Lomb Model 20 spectrophotometer at a wave length of 490 mμ. The concentrations were then determined by comparing the absorbence with a standard curve of TF concentrations and absorbence, and reported as TF concentration.

Carbohydrates

Carbohydrate concentrations were determined by the Anthrone method described by Ramanathan, Gaudy and Cook. (29) The carbohydrate concentration was measured for the sludge mixed liquor and for the sludge filtrate after filtering through a 0.45 micron millipore filter. The analysis consisted of placing 3 ml of appropriate dilutions of the sample to be tested and known concentrations of dextrose in test tubes, cooling the contents of the tubes in ice water, injecting 9 ml of anthrone reagent, placing the tubes in boiling water for exactly 15 minutes, and cooling the contents to room temperature. The per cent transmission for the samples and known standards was then determined with a Bausch and Lomb Model 20 spectrophotometer at a wave length of 540 mμ. Concentrations of carbohydrate were determined by comparison with the known standards.

Protein

The Folin-Ciocalteu method as described by Ramanathan, Gaudy, and Cook (29) was used to determine protein concentrations. The protein concentrations of the sludge mixed liquor and the sludge filtrate were measured after filtering the sample through an 0.45 micron millipore filter. The analysis consisted of placing 1.20 ml of appropriate dilutions of sample to be tested and known concentrations of bovine serum albumin in test tubes, adding 6 ml freshly prepared alkaline copper solution to each tube and mixing. After 10 minutes, 0.3 ml Folin-Giocalteu reagent was added and mixed, and 30 minutes were allowed for development.

The per cent transmission of the samples and known standards was then measured by a Bausch and Lomb model 20 spectrophotometer at a wave length of 500 mμ. Concentrations of protein were determined by comparison with the known standards.

Mechanically Mixed Aeration Vessel

For the study of dissolved oxygen concentration during digestion, a special mechanically mixed aeration vessel was used. The digesters consisted of 2800 ml Erlenmeyer flasks. Mechanical stirrers were used to provide mixing and aeration was used to provide oxygen as shown in Figure 5. All propeller speeds were the same and at such a velocity as to provide rapid enough mixing so that any

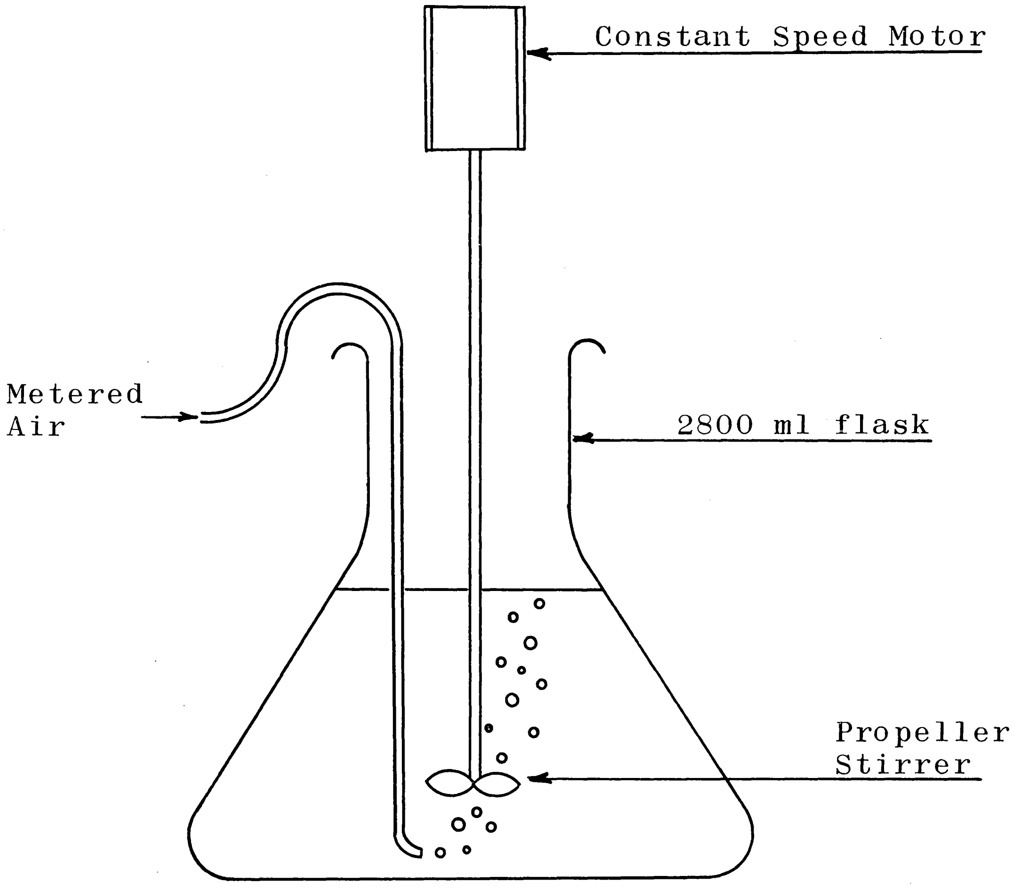

Figure 5. Aeration Flask for Dissolved Oxygen Study.

additional mixing by aeration was considered negligible. All sludge handling procedures used with this apparatus were the same as those used with the standard aeration tubes.

RESULTS

The overall objectives of this research were to develop a better understanding of the effects of aerobic digestion on the filtering qualities of activated sludge and to provide information which could be used to develop techniques for improving aerobic digestion from a sludge filtering standpoint. The results reported in the first portion of this chapter are concerned with a characterization of the effects of aerobic digestion on the chemical and biological characteristics of activated sludge and with the relationship of these characteristics to the filterability of the sludge. The second portion of the chapter describes an investigation of different operating parameters and techniques used in aerobic digestion conducted to determine the effects of these parameters on sludge filterability.

Each experiment is reported individually with a brief explanation of the purpose and characteristics of the experiment preceding the actual results. Results are presented in graphical and numerical form, and unusual or significant characteristics of the results are pointed out. The results are discussed in a separate chapter.

General Characteristics

In order to determine the general chemical and biological characteristics of the activated sludge used in the experiments and to determine the effect of aerobic digestion on these parameters, a batch digestion experiment was conducted in which several sludge parameters were monitored throughout the aeration period. The factors studied during the experiment were suspended solids, BOD, COD, oxygen uptake, dehydrogenase enzyme activity, carbohydrate, protein, pH, and alkalinity. Filtration tests were also conducted along with the other tests to determine what relationships exist between filtration rate and the other sludge characteristics.

A large plexiglass cylinder was used as a batch digester so that a sufficient volume of sludge was available for sampling. Aeration was provided through a perforated ring in the bottom of the cylinder and the air rate was sufficient to maintain a dissolved oxygen concentration above 6.0 mg/l and to provide constant mixing of the sludge contents throughout the aeration period.

Because the air flow and mixing rate in the large plexiglass cylinder could not be controlled, a second digester consisting of a standard aeration tube was run in parallel with the large digester. Filtration samples were taken from the standard aeration tube instead of the larger digester because it had been determined through preliminary study that the filtration characteristics of a digesting sludge can be affected by changing aeration and mixing conditions in the digester. It was assumed that the chemical and biological characteristics of the sludge in the two digesters were similar even though the physical conditions were different.

Figure 6 shows the variation in time to filter 75 ml sludge with the aeration time. The original filtration time was 132 seconds. After six hours of aeration the filtration time increased to 137 seconds, and then decreased from six hours to five days of aeration to a low of 91 seconds. Filtration times remained fairly constant between five and eight days, then increased slightly to 96 seconds on the tenth day. Preliminary tests indicated that the filtration characteristics of this sludge are typical for the sludge under study. That is, there was an initial improvement in filtering characteristics for the first five days of aeration with a consistent or decreasing filtration rate after six days of aeration.

Suspended solids concentration of the sludge changed only slightly during the 10 days of aeration. Figure 7 shows that the suspended solids decreased steadily after the first day of aeration but the maximum decrease in 10 days was only 6.7 per cent of the initial suspended solids.

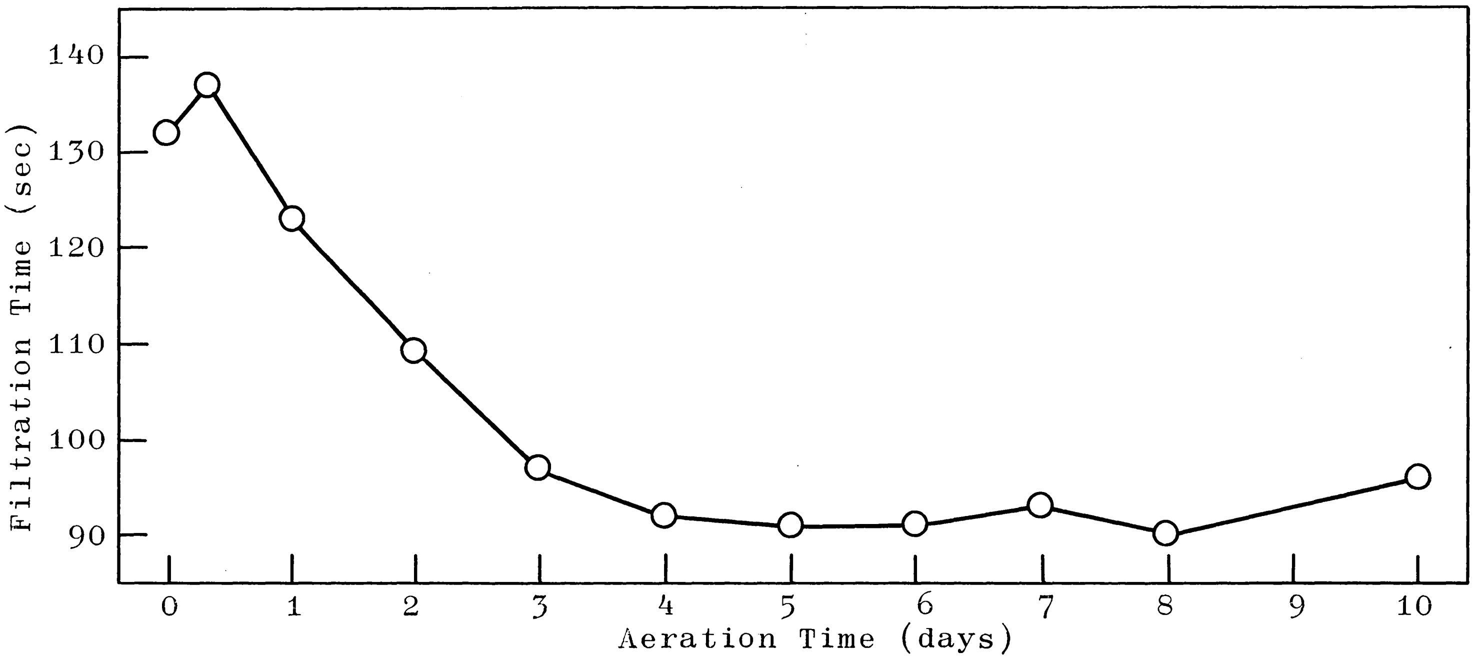

Figure 6. Variation in Filtration Time with Aeration Time.

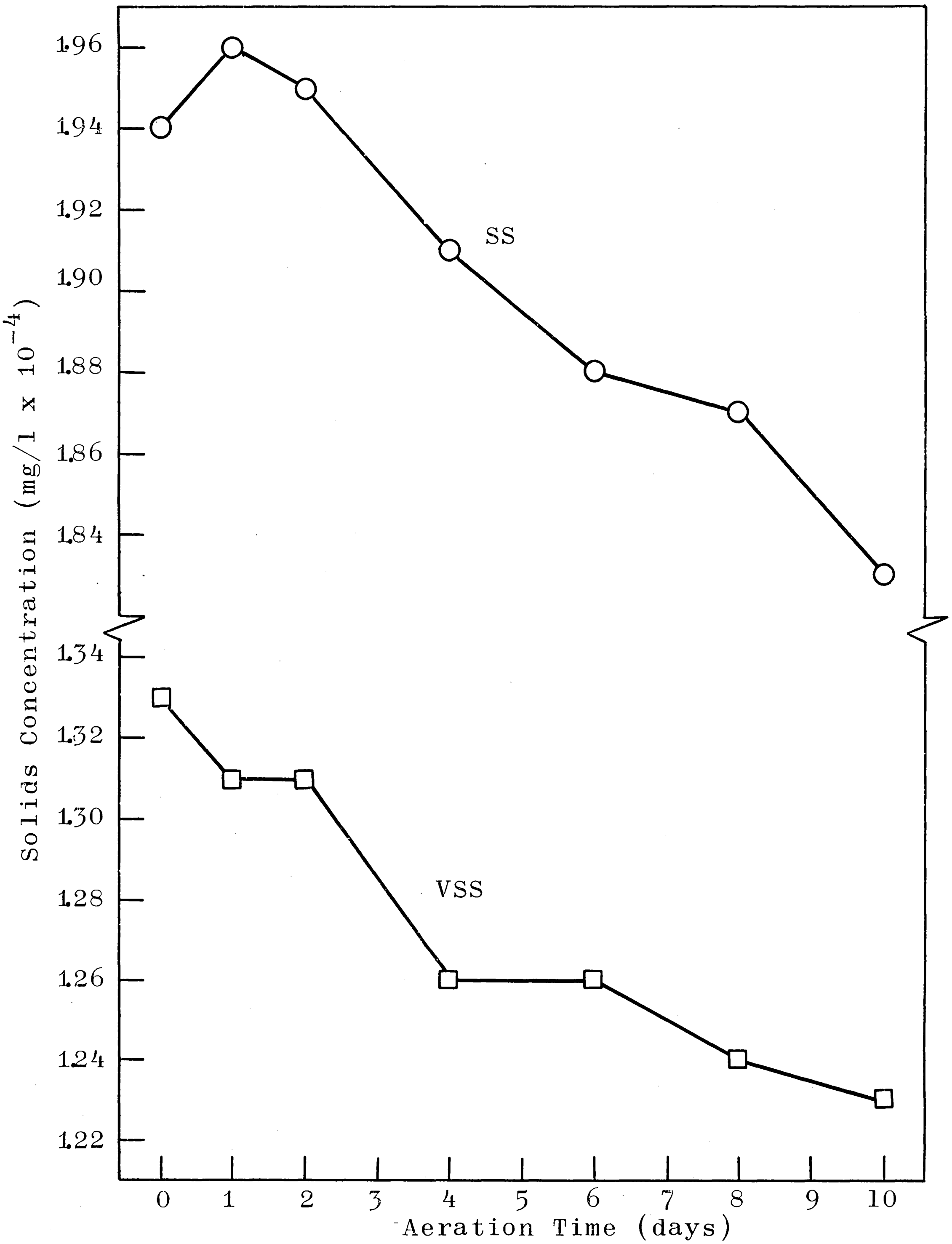

Figure 7. Variation in Suspended Solids Concentration with Aeration Time.

The decrease in volatile suspended solids paralleled the decrease in total suspended solids. The per cent volatile suspended solids remained between 66 to 69 per cent of the total suspended solids throughout the ten days of aeration.

Three tests, the five day BOD, the oxygen uptake, and the dehydrogenase enzyme test, were used to indicate the possible and actual biological activity of the sludge. The results of these tests are shown in Figure 8. The five day BOD test was run on diluted samples of the sludge mixed liquor. No seed was used with the assumption that viable organisms were already present. The BOD initially was 2,600 mg/l but showed a general decline throughout the aeration period to a minimum BOD of 1,360 mg/l at eight days of aeration.

The oxygen uptake of the sludge declined steadily from an initial rate of 21 mg/l/hr to a final ten day rate of 5.4 mg/l/hr. The decline in oxygen uptake was fastest in the early stages of aeration and became more gradual as aeration proceeded. The dehydrogenase enzyme activity increased in the first day of aeration, then declined steadily from the first to the tenth day of aeration. The initial low enzyme activity may have been a result of the sludge being subject to anaerobic conditions during the collection, transportation and preparation stages of the experiment.

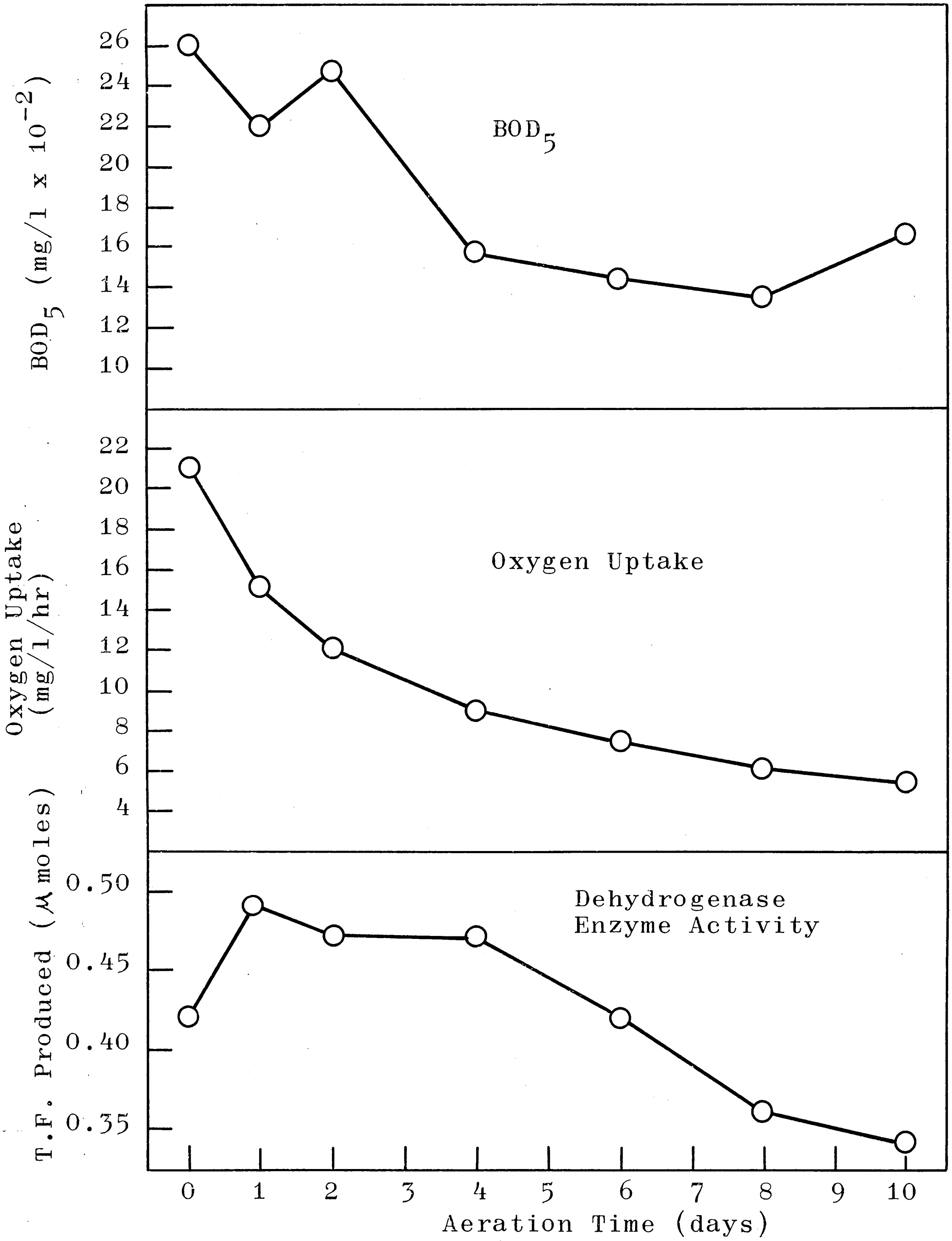

Figure 8. Variation in BOD$_5$, Oxygen Uptake and Dehydrogenase Enzyme Activity with Aeration Time.

The COD and TOC of the filtrate from a 0.45 micron millipore filter was determined in order to estimate the pollution potential of the dissolved material. The results of these determinations are shown in Figure 9. Both the COD and the TOC showed a rapid decrease in the first six hours of aeration. After the first day of aeration, the COD remained fairly constant at approximately 25 mg/l for the remainder of the digestion period. The TOC on the other hand, continued to decline for two days before it leveled off at approximately 14 mg/l.

The carbohydrate concentration of the sludge mixed liquor and filtrate was determined and the results are shown in Figure 10. The initial sludge mixed liquor had a carbohydrate concentration of approximately 450 mg/l. This concentration decreased in the first two days of aeration to approximately 200 mg/l and stayed fairly constant throughout the remainder of the aeration period. The filtrate carbohydrate concentration, on the other hand, started low at 6 mg/l and rose steadily during aeration to 20 mg/l in ten days. The protein concentration of the sludge mixed liquor and filtrate was also determined and the results are shown in Figure 11. Both the sludge and filtrate protein concentration dropped initially, then showed a general increase throughout the last eight days of aeration.

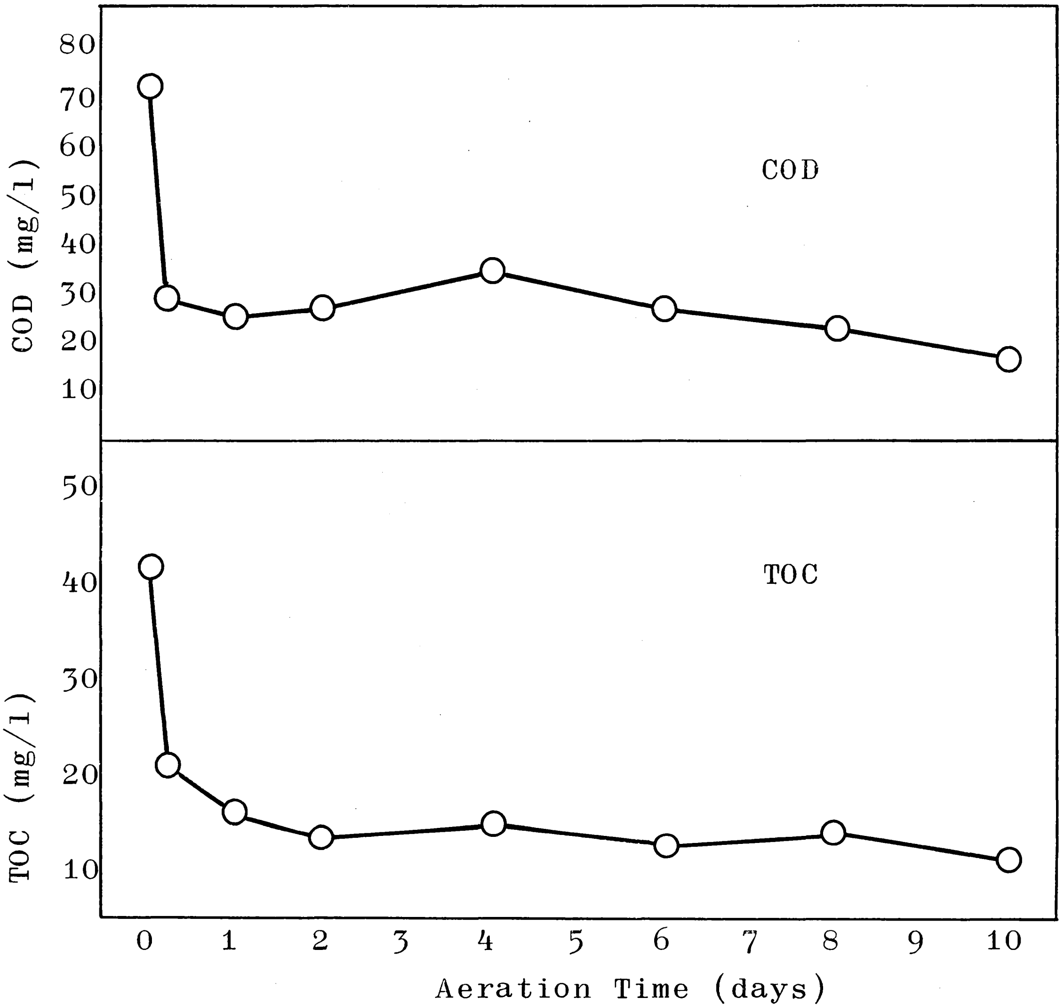

Figure 9. Chemical Oxygen Demand and Total Organic Carbon Concentrations.

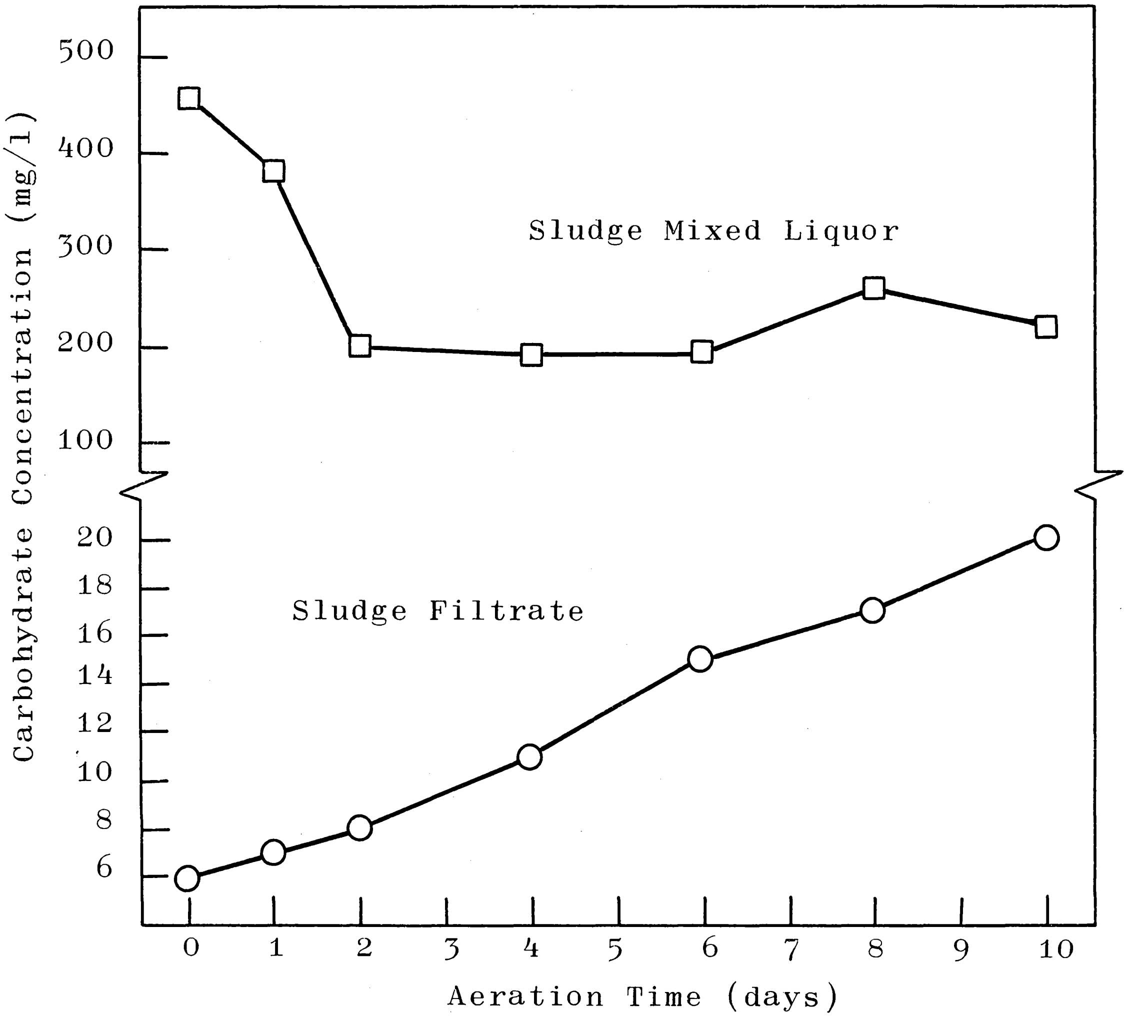

Figure 10. Variation in Carbohydrate Concentration with Aeration Time.

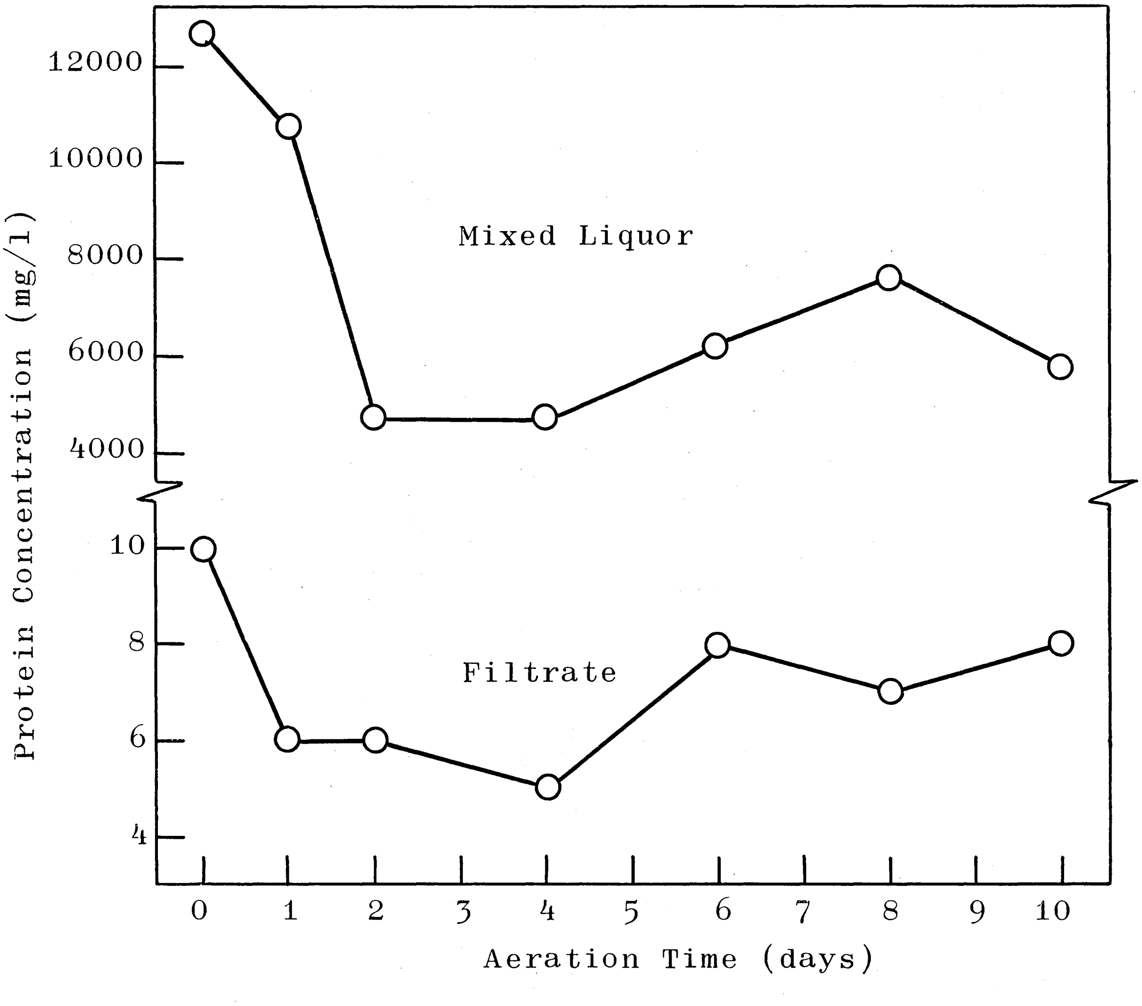

Figure 11. Variation in Protein Concentration with Aeration Time.

The variation in pH and filtrate alkalinity is shown in Figure 12. The pH rose the first day from an initial value of 6.9 to a high of 7.5. After the first day, the pH dropped steadily to a low of 5.8 on the tenth day. The alkalinity test indicated that only bicarbonate alkalinity was present in the filtrate. Initially the alkalinity was 260 mg/l but dropped rapidly in the first six hours to 85 mg/l. Then the concentration continued to drop steadily but less rapidly for the remainder of the aeration period to a low of 10 mg/l on the tenth day.

Zeta Potential and Specific Conductance

McKinney (22) has reported that a zeta potential below 20 to 30 millivolts is required for colloidal flocculation and that most bacteria have a potential below this range. This experiment was conducted in order to study the change in zeta potential and specific conductance with aerobic digestion. To study the zeta potential of the sludge under investigation and to determine how this parameter varies with time, the zeta potential, pH, specific conductance, and filtration rates were measured during a standard aeration tube run. Zeta potential and specific conductance were measured with a Zeta-Meter according to the instructions provided with the meter. The results of these measurements are shown in Figure 13.

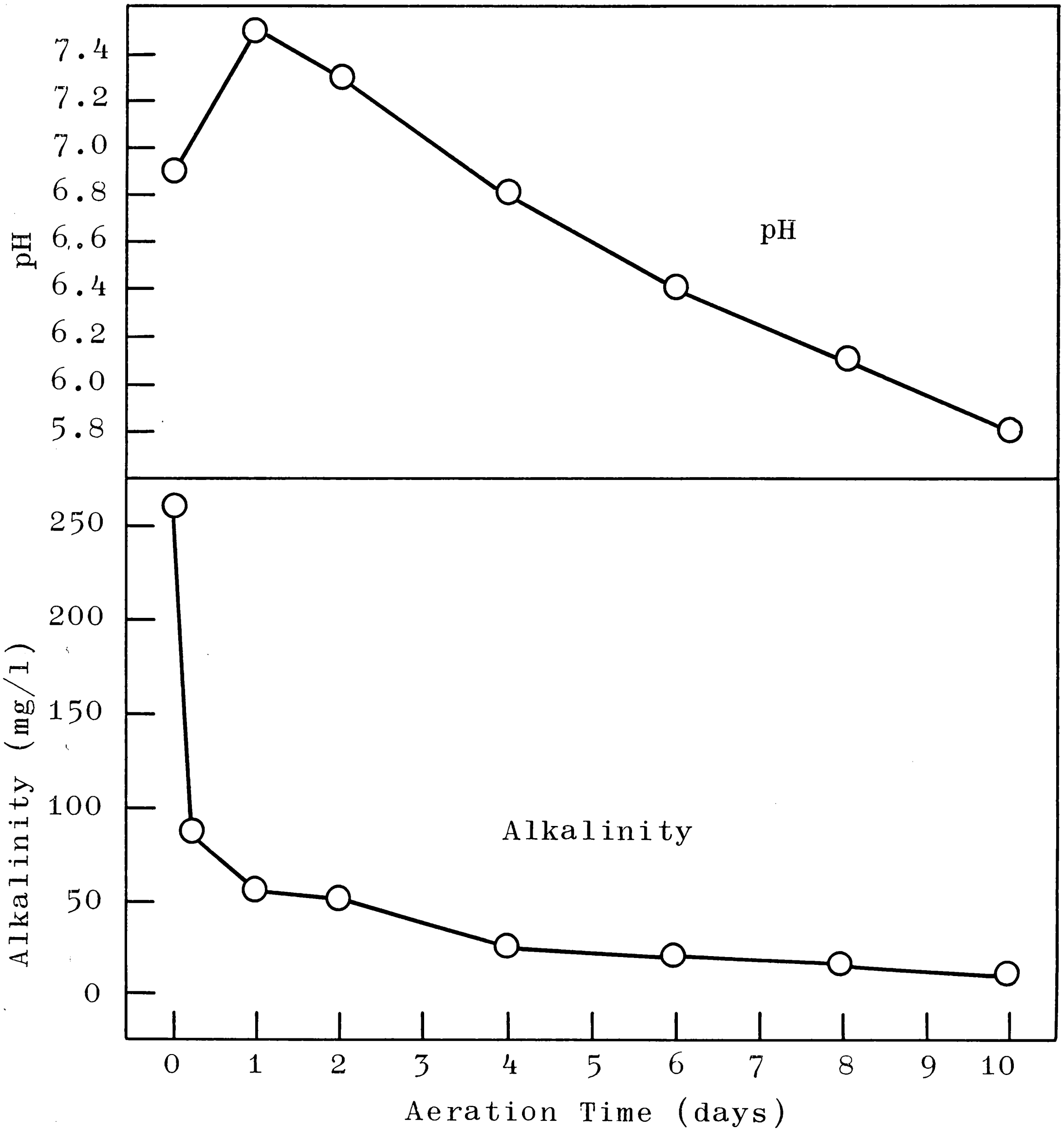

Figure 12. Variation in pH and Alkalinity with Aeration Time.

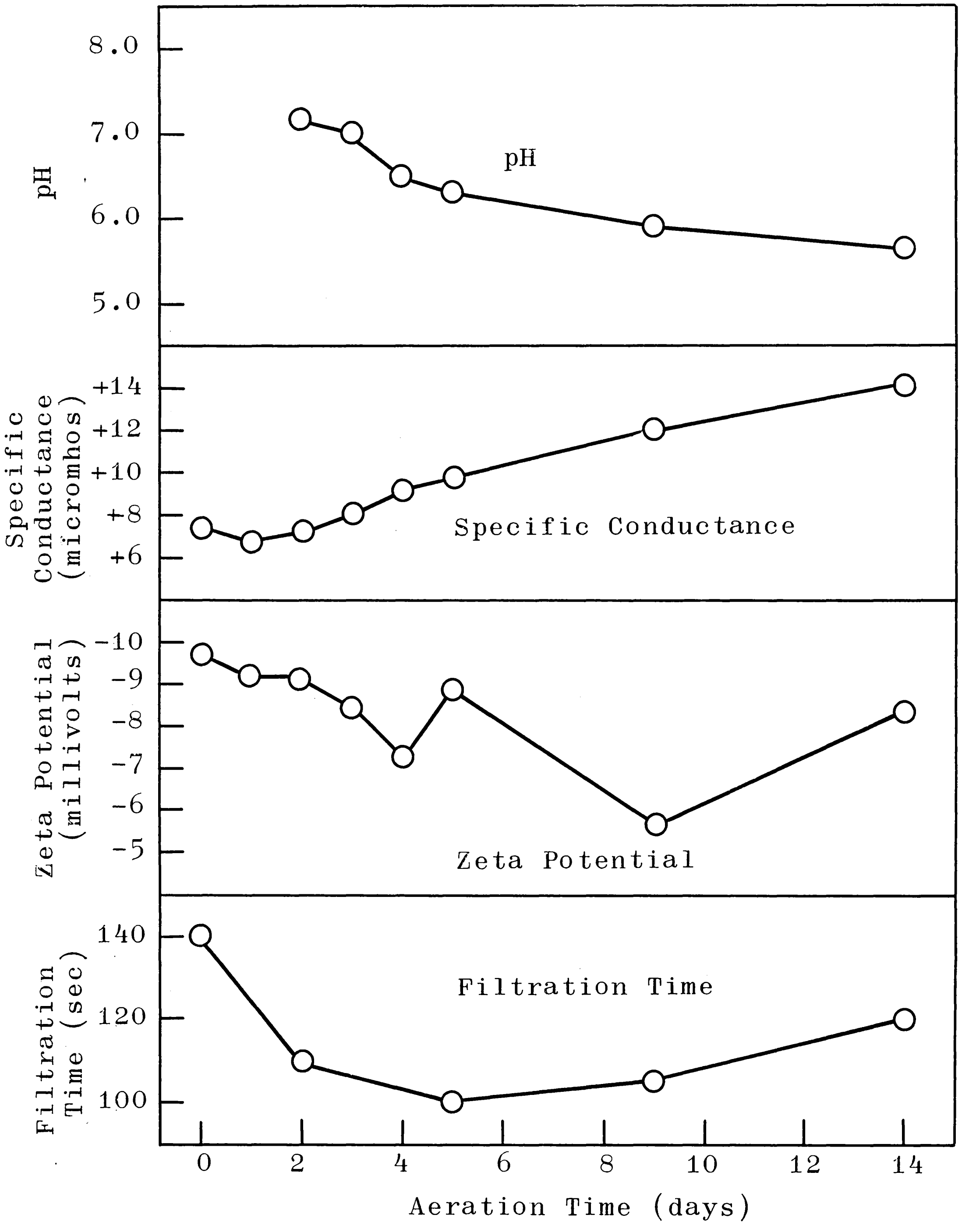

Figure 13. Variation in pH, Specific Conductance, Zeta Potential and Filtration Time with Aeration Time.

The filtration rate showed the typical decrease in filtration time for the first five days of aeration with a gradual increase in filtration time from five to fourteen days. The zeta potential, on the other hand, showed a gradual decrease throughout the aeration period from an initial high of -9.7 millivolts to a low of -5.6 millivolts. The potential was well within the zero to twenty millivolt range reported to be required for colloidal flocculation. The specific conductance started out at 740 micromhos, went down to 681 after the first day of aeration, then steadily climbed to 1400 micromhos after fourteen days of aeration. The pH, on the other hand, declined steadily as has been observed in other experiments. By the second day of aeration, the pH was 7.3, and it declined at a decreasing rate to a low of 5.6 at fourteen days of aeration.

Dissolved Oxygen

The dissolved oxygen concentration has been found to have an effect on activated sludge bulking. Bhatla (2) concluded that a high oxygen tension in the aeration tank could result in sludge bulking. It was felt that there was a possibility that the dissolved oxygen concentration in aerobic sludge digesters could have an effect on sludge dewatering.

Since aeration is used to mix the sludge as well as to provide oxygen in the standard aeration tubes, a different digestion arrangement was used. This digestion apparatus is described in the "Experimental Methods" chapter. Air rates remained constant throughout the study at 524, 148, 34, and zero ml per minute. Aeration was continued for six days while testing for dissolved oxygen and filtration rates was conducted periodically throughout the aeration time.

Figure 14 shows how the dissolved oxygen concentration in the four aeration flasks varied with aeration time. The dissolved oxygen concentration in the two high air flow flasks rose rapidly, and in the first four hours both vessels showed a D.O. level above 2 mg/l. The flask with an air flow of 34 ml per minute took almost three days to show any measurable dissolved oxygen. After three days, the oxygen level rose rapidly to greater than 5 mg/l.

Figure 15 shows the variation in filtration rate with aeration time. The two sludges aerated at the highest rates showed similar trends toward improvement in filtration with the higher air rate developing a slightly better filtration rate. The digester with the lowest air flow rate produced a sludge with variable filterability. During the time when no D.O. could be measured in the sludge, the filtration rate was worse than the initial rate. After measurable dissolved oxygen was detected in the sludge, filtration improved from its initial level. Finally, after six days

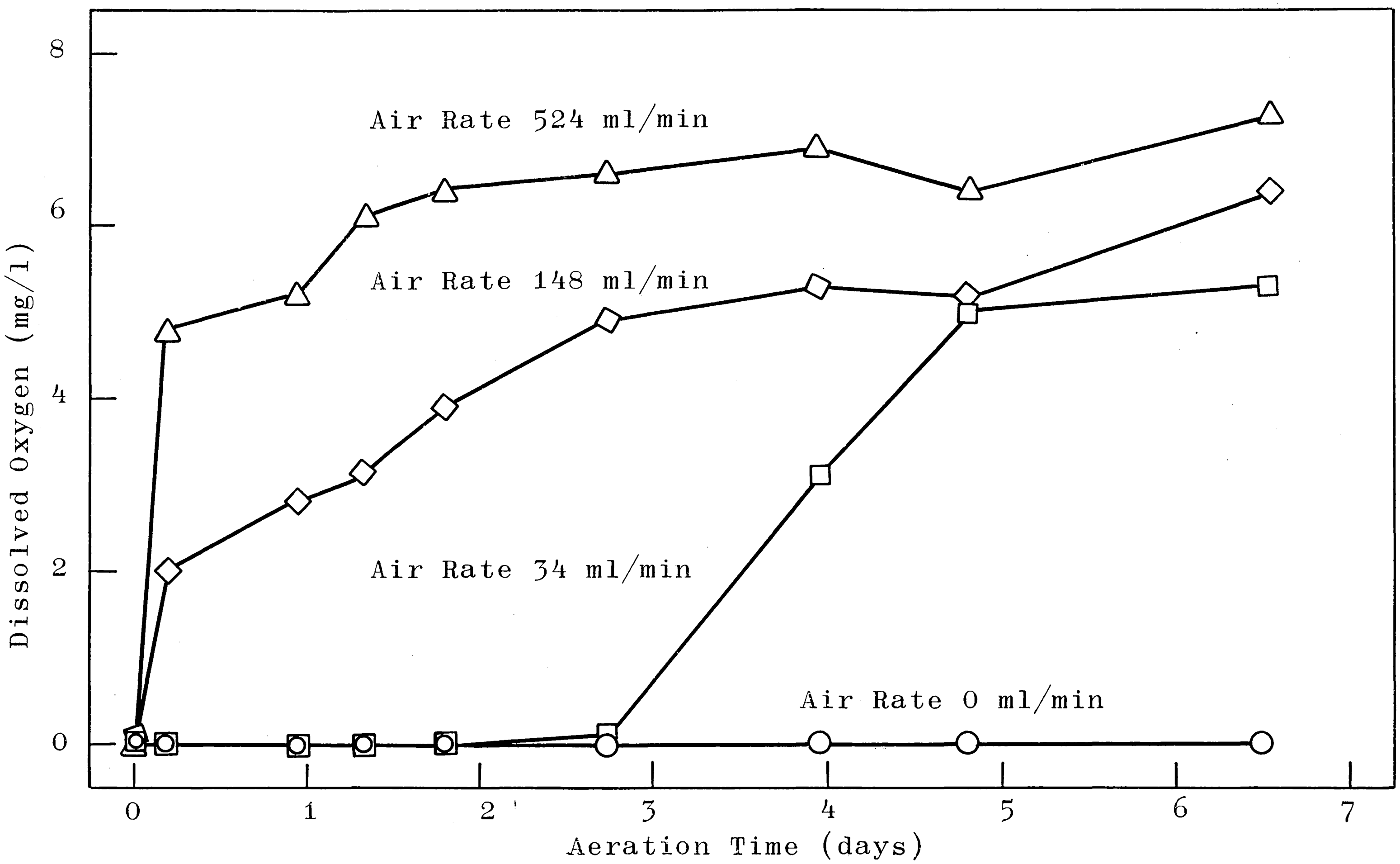

Figure 14. Variation in Dissolved Oxygen Concentration with Aeration Time for Different Air Flow Rates.

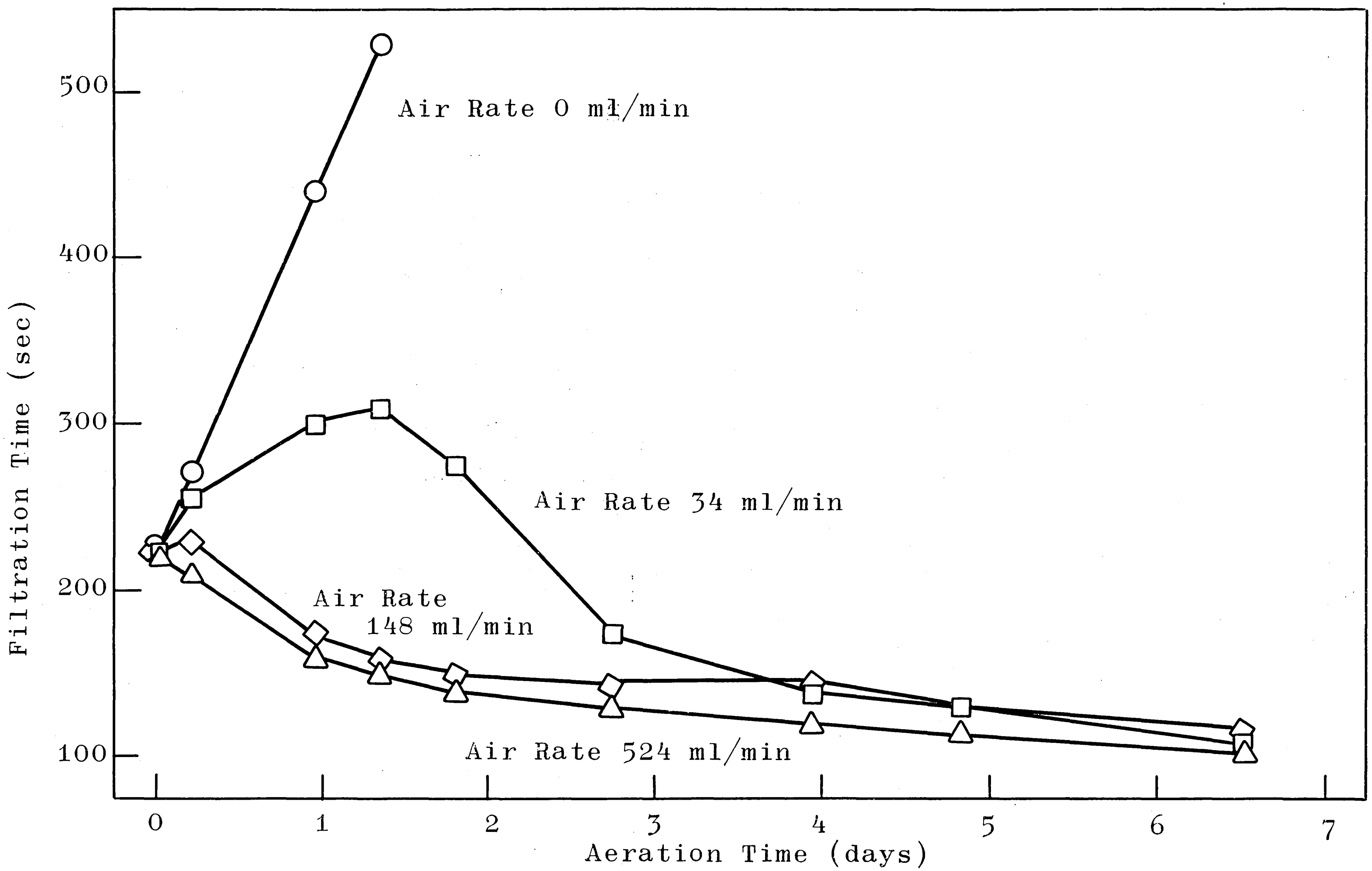

Figure 15. Variation in Filtration Time with Aeration Time for Different Air Flow Rates.

of aeration, filtration in all three aerated sludges was approximately the same. The one sludge with no aeration and no detectable D.O. showed a rapid degradation of filtration. In two days of anaerobic conditions, it took twice as long to filter as it took to filter the same volume of sludge initially.

Aerobic and Anaerobic Sludge

While studying the effect of aeration rate and dissolved oxygen level on sludge filtration, it was found that zero dissolved oxygen caused a drastic degradation in filterability. Tenney *et al*. (40) also reported an increase in coagulant demand in activated sludge when activated sludge was kept under anaerobic conditions for extended periods of time. From the results of the dissolved oxygen experiment, it was not clear whether the rapid mixing was causing the degradation in filtration by physically destroying the floc particles or whether the organisms themselves were reacting to the loss of oxygen in such a way as to cause the sludge to develop poor filtering characteristics.

In order to investigate the effects of zero dissolved oxygen further, another experiment was conducted. This time sludge was placed in two standard aeration tubes. One tube was aerated for one day and then aeration was stopped and no artificial mixing was provided. In this way, any degradation in filtering characteristics would be due to chemical and/or biological action and not to physical shearing forces caused by mixing. As a check on whether cellular material was staying intact, the total organic carbon concentration of the filtrate of each sludge was determined at the same time that the filtration tests were run.

Testing began when the aeration was stopped in the second tube. The results of the filtration determinations are shown in Figure 16. The filtering property of the anaerobic sludge again showed a tendency to degrade even though no mechanical mixing was provided. However, the rate of degradation in filtration for the unmixed sludge was only approximately 20 seconds per day as opposed to a rate of degradation of over 200 seconds per day for the mixed sludge.

The results of the TOC analysis are shown in Figure 17. Soluble organic carbon decreased slightly in the aerated sludge from 18 mg/l to approximately 12 mg/l. However, in the anaerobic sludge, TOC approximately doubled to 36 mg/l in two days time. Figure 18 shows the relationship between filtration and TOC concentration. It appears from the plot that the filtration time increases linearly as the total organic carbon in solution increases.

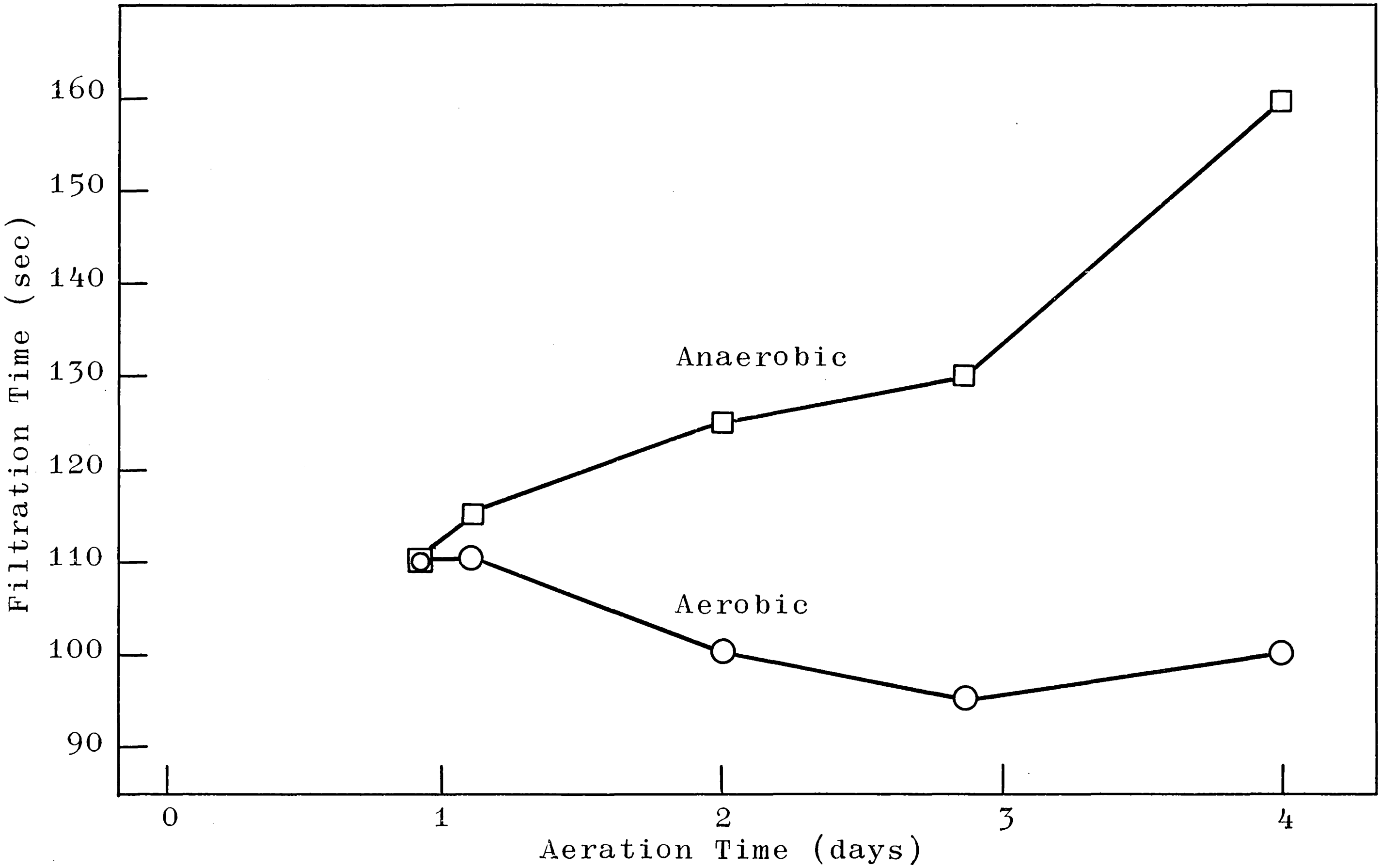

Figure 16. Variation in Filtration Time with Aeration Time for Aerobic and Anaerobic Sludge.

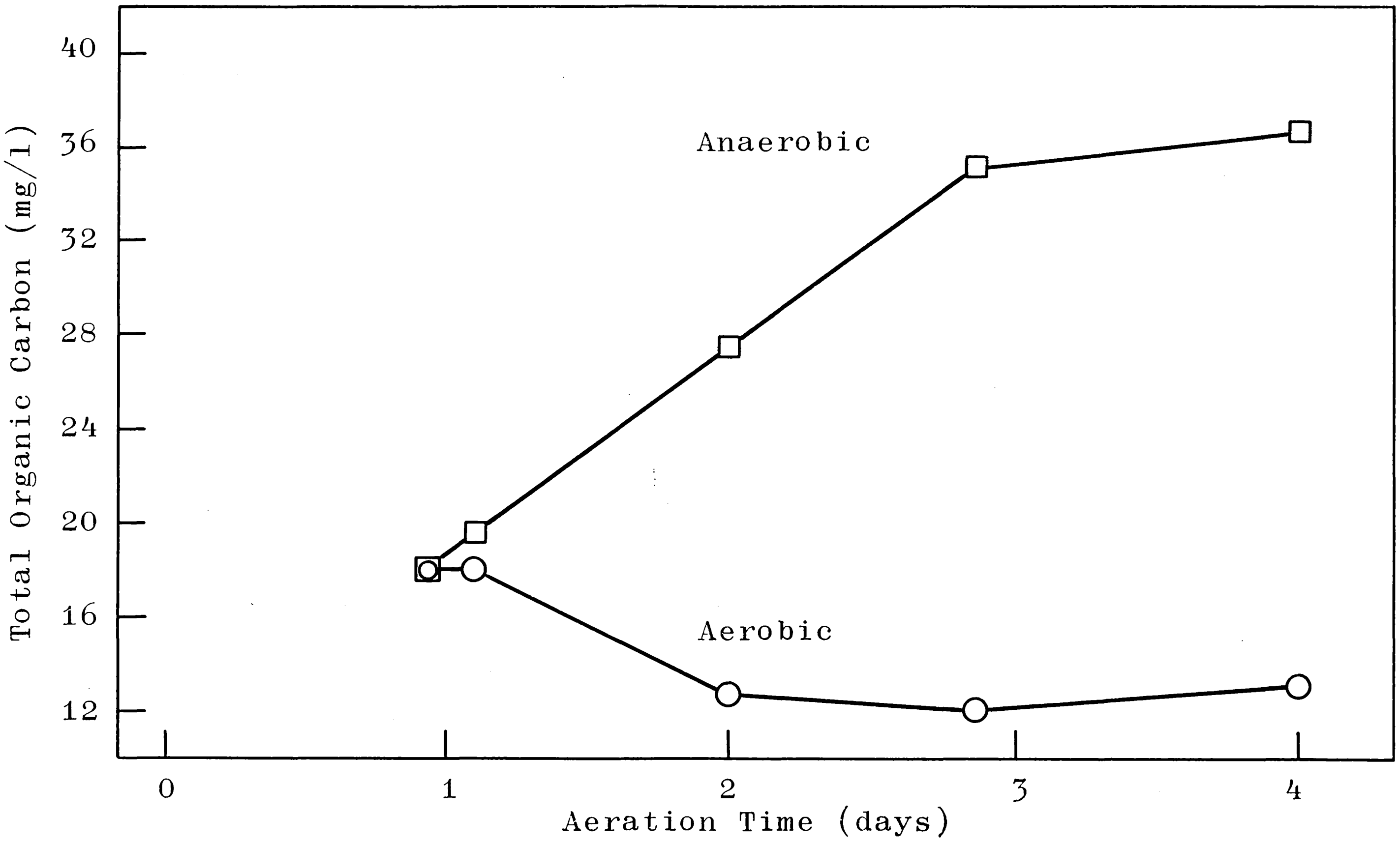

Figure 17. Variation in Total Organic Carbon Concentration for Aerobic and Anaerobic Sludge with Aeration Time.

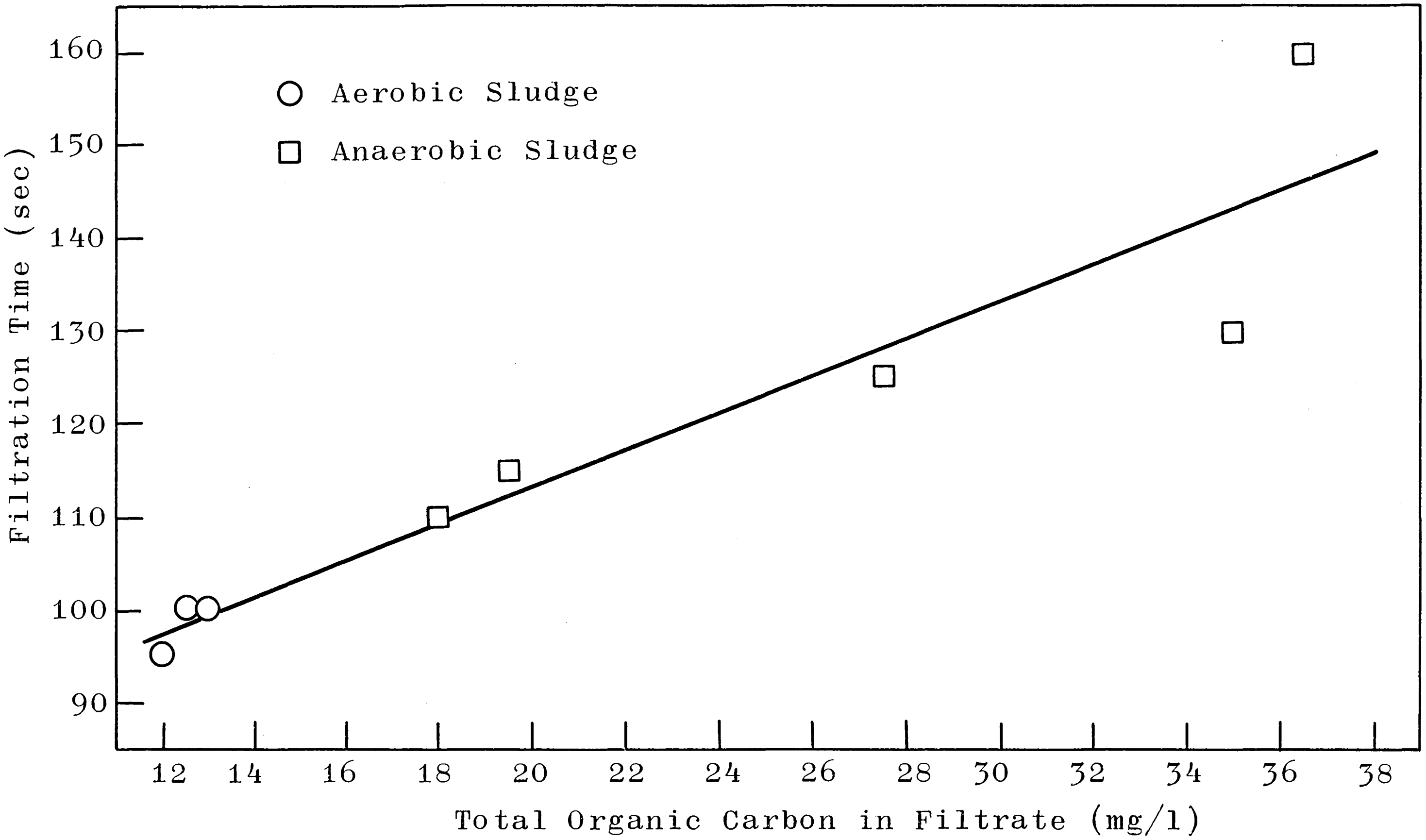

Figure 18. Variation in Filtration Time With Total Organic Carbon Concentration.

Aerobic Conditioning of Anaerobic Sludge

Sludge may often be subject to anaerobic conditions during normal operations in a sewage treatment plant. Such operations as pumping, settling and storage of sludge cause sludge to become septic. The effect of lack of oxygen on the filterability of activated sludge has already been demonstrated. In this experiment the effect of aeration on sludge which had been subject to anaerobic conditions was investigated.

Three standard aeration tubes were used in the study. Sludge was placed in all three tubes and one of the tubes was aerated. After two days had elapsed aeration was started in the second tube and after four days, aeration was started in the third tube. Figure 19 shows the results of filtration tests on the three sludges. The filtration time for 75 ml of sludge originally was 132 seconds; after two days of anaerobic conditions, filtration time was 162 seconds or 30 seconds longer; and after four days, filtration time was 189 seconds or 57 seconds above the original filtration time. The rate of decrease in filtration time was also a function of time under anaerobic conditions. Originally the filtration time decreased by 23 seconds within the first two days of aeration. The two day old anaerobic sludge had a two day decrease of 51 seconds, and the four day old anaerobic sludge had a 76 second decrease

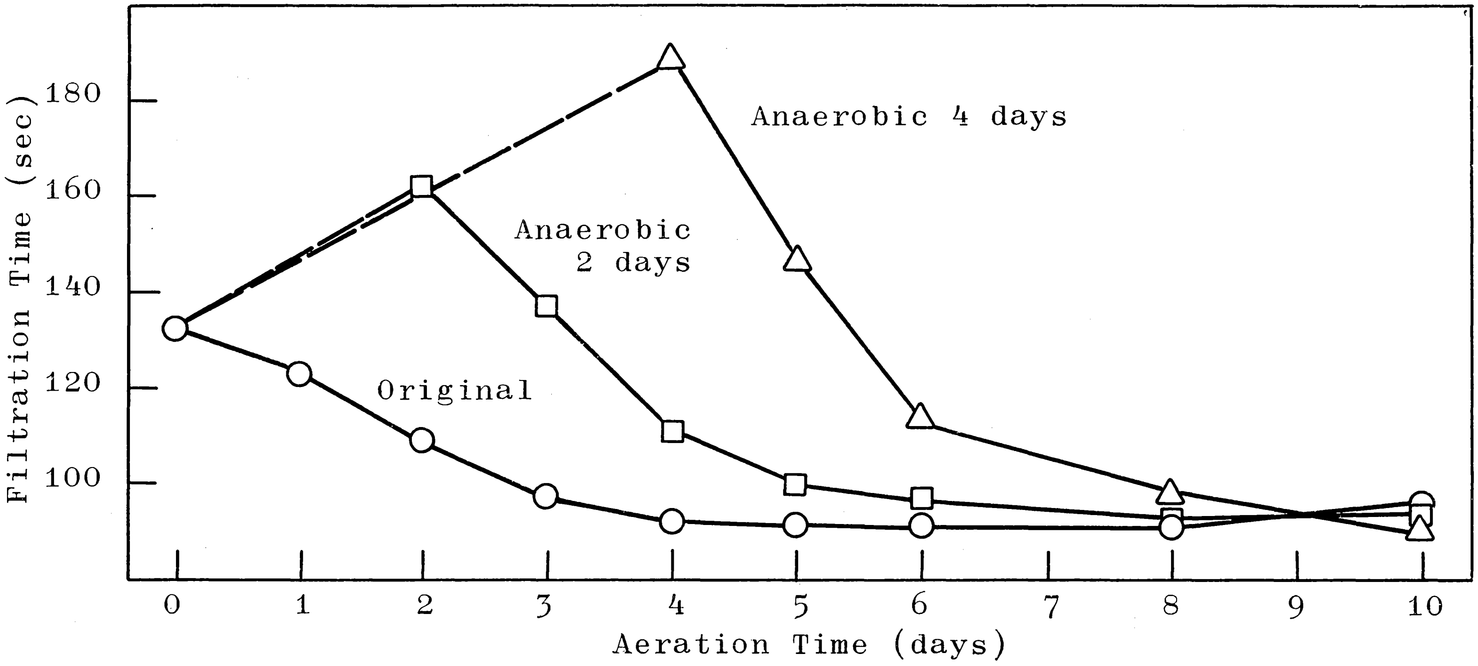

Figure 19. Variation in Filtration Time with Aeration Time for Sludge Subject to Different Periods of Anaerobic Conditions.

in filtration time in the first two days of aeration. Despite the difference in original filtration time, it took approximately the same aeration time (six days) to reach the maximum filtration rate.

Concentration

It is well known that suspended solids concentration has an effect on sewage sludge dewatering (6, 17, 27, 32, 36). There is also evidence that solids concentration has an effect on aerobic sludge digestion (15, 31). Randall *et al*. (31) reported on a laboratory study of aerobic digestion that the rate of solids destruction increased with the solids concentration, but that there were no significant differences in any of the measured parameters to account for the difference in solids destruction.

The purpose of this experiment was to determine the effect that suspended solids concentration has on the filtration rate of aerobically digested sewage sludge. Solids concentrations of 1.79, 1.59, 1.44, and 1.24 per cent suspended solids were used. These concentrations were obtained by diluting settled sludge with the required amount of its own supernatant. The four concentrations were aerated in aeration tubes for thirteen days. During aeration, the filtration rates and suspended solids concentrations were determined periodically.

Figure 20 shows how the filtration time for 75 ml varies with aeration time. The trend of the plots of all four concentrations are the same with a decrease in filtration time up to six days and as subsequent increase in filtration time from six to fourteen days. The similarity of the plots indicates that the improvement in filtration by aeration is independent of solids concentration within the limits of the test.

Suspended solids concentrations were determined for the four sludges on the sixth and fourteenth days of aeration. Figure 21 shows a plot of filtration time versus suspended solids concentration for each sludge initially, on the sixth day of aeration, and on the fourteenth day of aeration. The slopes of the three plots are similar, indicating that the increase in filtration time with increasing solids concentration is approximately the same for a particular sludge regardless of the stage of digestion. The rate for the sludge tested was approximately 62.5 seconds increase in filtration time for every one percentage increase in suspended solids.

Temperature

Temperature is a factor in all biological activity. Generally the rate of biological reaction increases with increasing temperature within certain temperature ranges. Eckenfelder (8) stated that the rate of aerobic biological

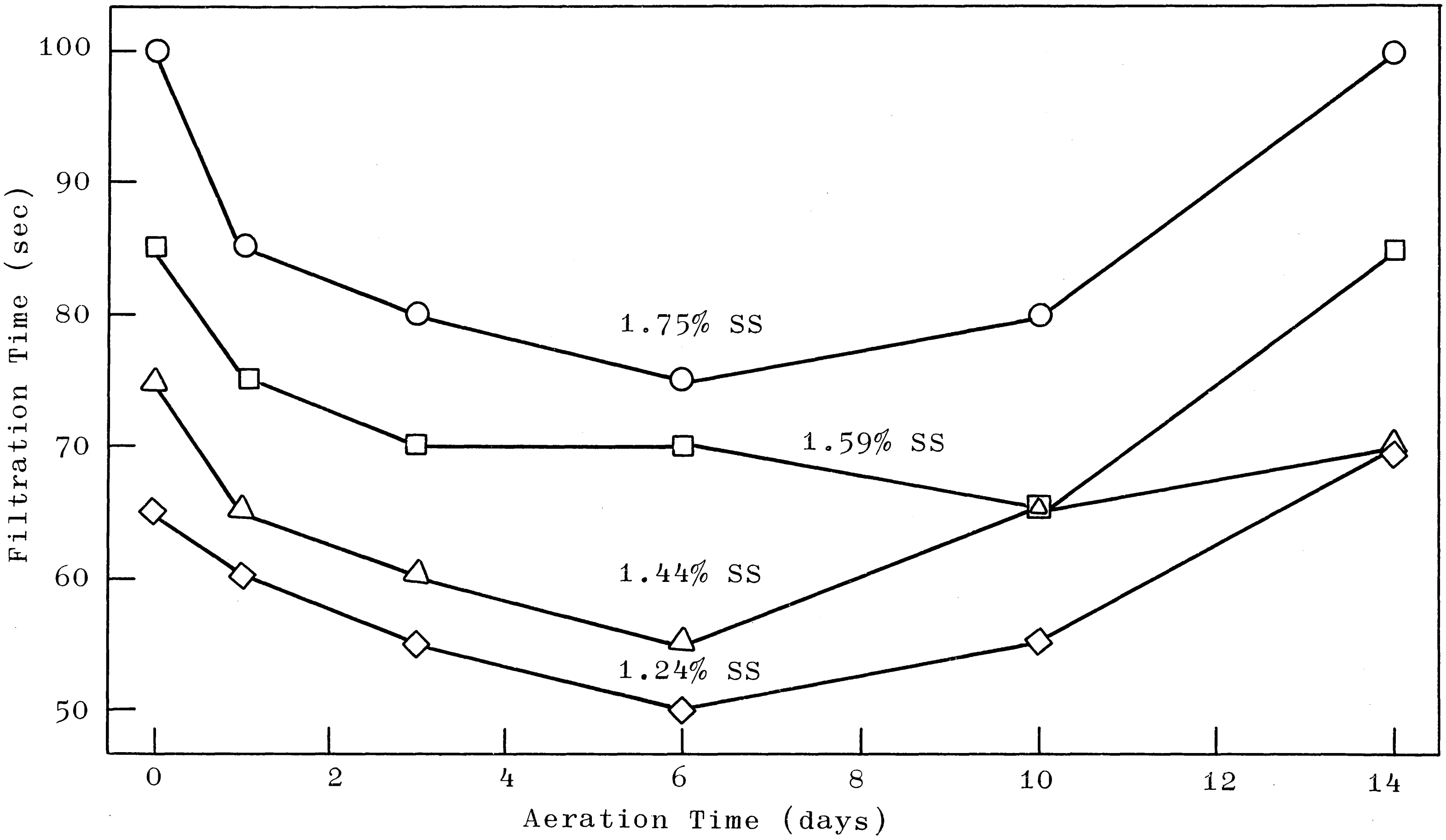

Figure 20. Variation in Filtration Time with Aeration Time for Different Suspended Solids Concentrations.

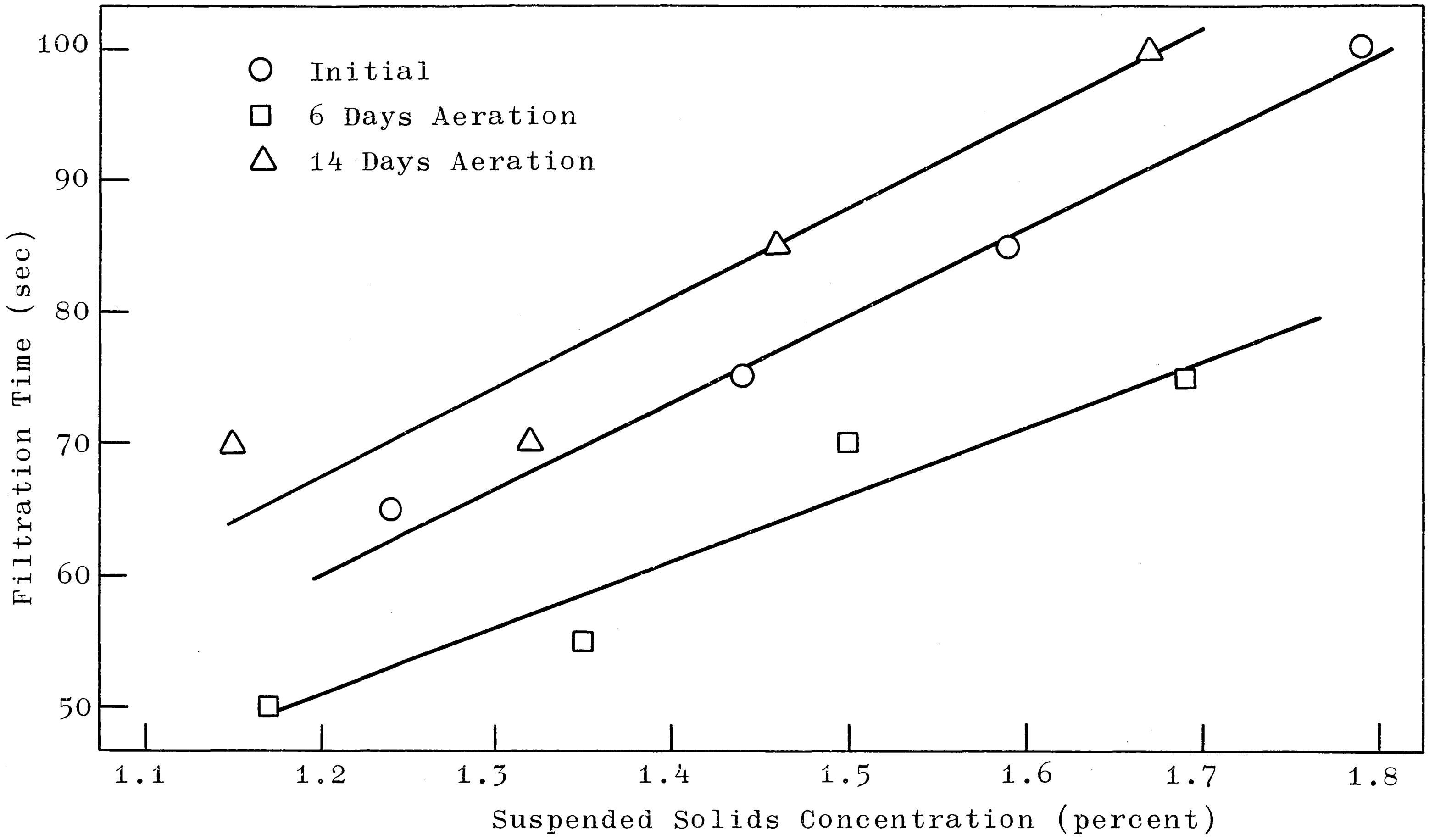

Figure 21. Variation in Filtration Time with Suspended Solids Concentration.

reactions will increase with temperature to an optimum value of 30° C, but further increases in temperature result in a decrease in the rate of mesophilic organisms. The magnitude of the temperature effect is, however, dependent on the nature of the process. Jarworski *et al.* (15) found that temperature had an effect on aerobic digestion. In batch studies, it was found that volatile solids reduction during six days of aeration was increased from 28 per cent at 15° C to 44 per cent at 25° C. To test the effect of temperature on dewatering, sludge from the same batch was aerated at different temperatures. Temperatures were controlled at 20°, 25°, 30°, and 35° C by the use of a constant temperature room and water baths. The results of filtration tests on the sludge are shown in Figure 22. The first series of filtration tests were conducted after the sludge was adjusted for the proper temperature, but before aeration was initiated. Due to the short time span between adjustment of temperature and filtration, the differing filtration times were assumed to be a result of non-biological phenomena. Figure 23 shows the relationship of temperature to filtration time for non-aerated sludge. In order to determine the effect of aeration on this effect of temperature on filtration time, the experiment was repeated on a batch of sludge which was a combination of the sludges aerated at 20° and

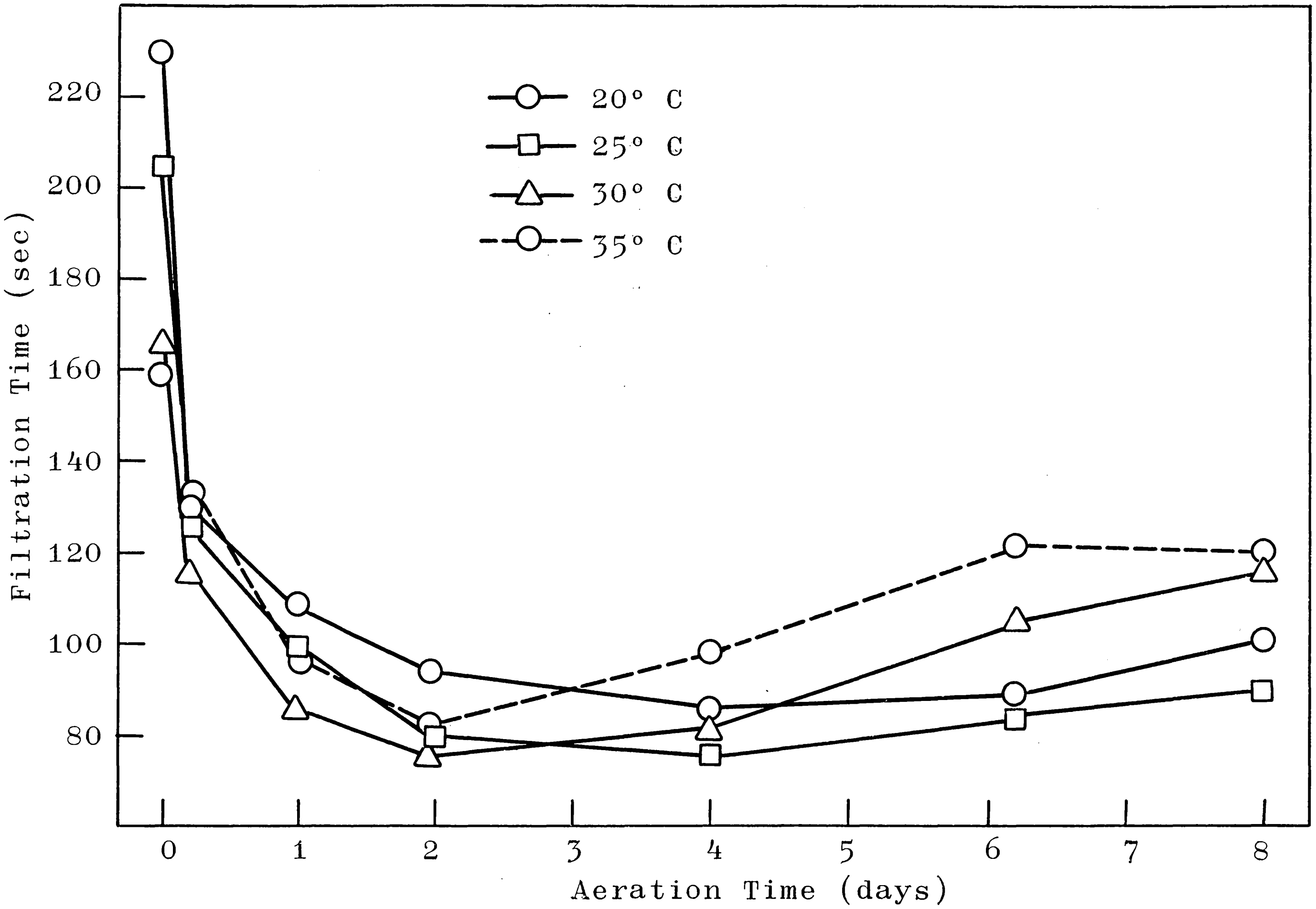

Figure 22. Variation in Filtration Time with Aeration Time with Digestion at 20° C through 35° C.

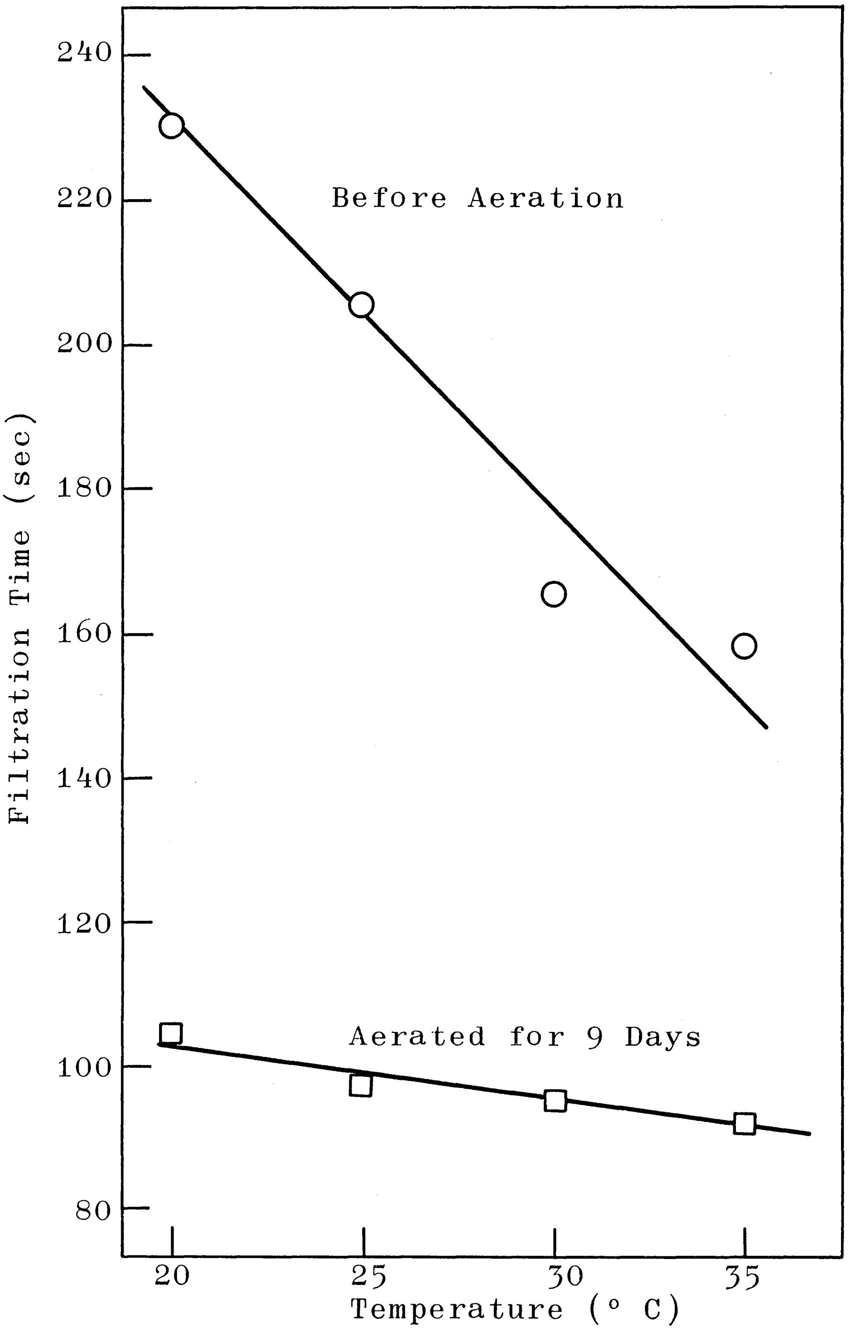

Figure 23. Variation in Filtration Time with Temperature at Two Stages of Digestion.

25° C for nine days. The results of this experiment are also shown in Figure 23. The effect of aeration for nine days seems to be a decrease in the drop in filtration time from approximately 5.8 seconds per degree centigrade to approximately 1.2 seconds per degree centigrade.

An investigation of Figure 22 shows that the simple relationship of increasing filter rates with increasing temperature does not necessarily hold true when biological activity is allowed to progress at different temperatures. After aeration for six hours, the sludge aerated at 35° C, the highest temperature studied, developed the poorest filtering rate of all the sludge aerated. It then improved its relative position for the next two days but finally ended up having the poorest filtration rate.

The overall improvement in filtration time appears to be a function of the temperature. The sludge aerated at 20° and 25° C both had an approximately 63 per cent improvement in filtration time, while the 30° and 35° sludge had a 54 and a 48 per cent improvement, respectively. The aeration time required to reach the minimum filtration time appears to be a function of temperature also. The two highest temperature sludges, 30° and 35° C, both reached their minimum filtration time in two days aeration, while the 20° and 25° C sludges took four days to reach minimum aeration time. The best filtering time was shown by the two middle temperature sludges, both taking only 76 seconds to filter 75 ml. The highest temperature sludge was next best with a filter time of 82 seconds, and finally, the poorest was the lowest temperature, taking 86 seconds.

Aeration at 6° C

The main purpose of aeration in aerobic sewage or sludge treatment is to provide oxygen to the aerobic organisms. This function generally is combined with the mixing of sludge. These operations can be combined in the form of subsurface diffused aeration, in which case the rising air causes the sludge to mix, or in the form of a surface aerator which uses mechanical mixing to provide aeration. However, this combination of aeration and mixing causes other effects which may or may not be valuable in a particular treatment process.

In the case of sludge digestion, the mixing of sludge is good from the standpoint of biological growth, but may be bad from the standpoint of excessive shear forces which may tend to break up floc formations in the sludge. Further aeration provides oxygen to the organisms, but it also may tend to affect chemical reactions or act as a scrubber removing certain gases from solution. This experiment was designed to determine what non-biological effect aeration has on sludge digestion.

Three standard aeration tubes were filled with sludge from the same batch. Tubes A and B were aerated at a temperature of 19° C, while tube C was placed in a cold water bath and aerated at a temperature of 6° C. Aeration was continued for 22 hours, at which time tube B was also placed in the cold water bath. Aeration was continued for approximately seven more days. Cooling was used to inhibit biological activity without affecting those chemical or physical characteristics other than that which are affected by temperatures. In this way biological activity could be separated from the other factors affecting digestion.

Filtration tests were run on the sludges initially, after placement of tube B in a cold water bath, and at other appropriate intervals throughout the experiment. Total organic carbon was also determined for the sludges at various intervals throughout the aeration period. The results of the filtration tests are shown in Figure 24. Initially the sludges all took the same time to filter. Sludge A, which was maintained at 19° C throughout the experiment, showed a rapid improvement in filtration for 36 hours, with a gradual improvement from there through four days of aeration. Sludge C, on the other hand, which was maintained at 6° C throughout the experiment, showed a reverse trend in filtration from that shown by sludge A. The first 36 hours of aeration showed a rapid increase in

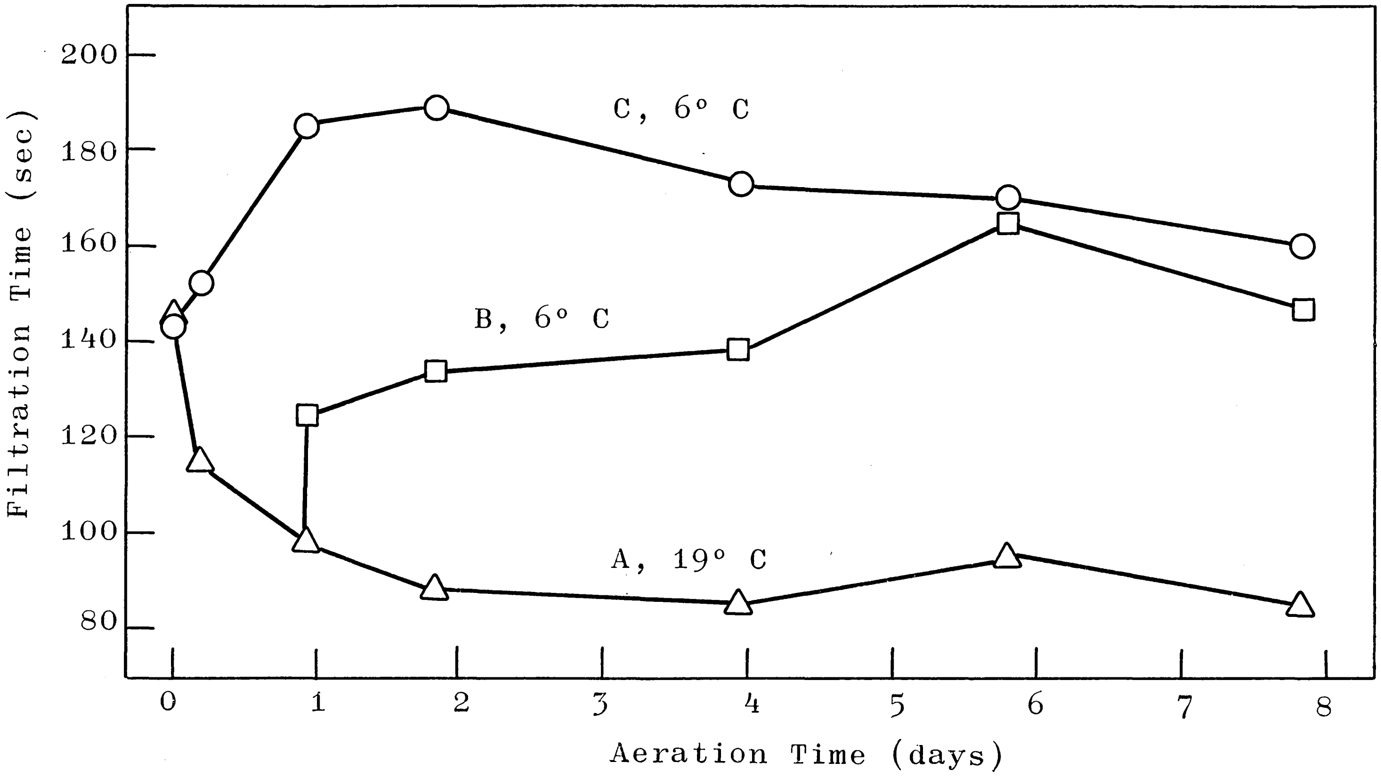

Figure 24. Variation in Filtration Time with Aeration Time for Digestion at 6° C and 19° C.

filtration time with a gradual improvement in filtration exhibited for the remainder of the test. Sludge B maintained the same filtering time as sludge A for the first 22 hours. When the temperature of sludge B was dropped to 6° C there was an immediate increase in filtration time, and as aeration continued, the filtration rate of B became gradually worse and approached the rate of sludge C.

The total organic carbon (TOC) of the filtrate was measured in order to detect any cell lysis or the release of any carbonaceous materials while the sludge was cooled. Figure 25 shows the results of the TOC determinations. The first test was conducted at the time that sludge B was lowered from 19° C to 6° C. Sludges B and C had approximately 6 mg/l more organic carbon in their filtrates than did the warmer sludge A. All sludge showed the same general decrease in organic carbon during the remainder of the aeration period with the final TOC of approximately 20 mg/l after eight days of aeration. A general decrease in inorganic carbon was also noted. Therefore, the total carbon showed the same general trend as the TOC only slightly more pronounced.

Mixing Rate

In order to further investigate the effects of mixing aerobic sludge on filtering, a mixing experiment was performed. Standard aeration tubes were used, but different

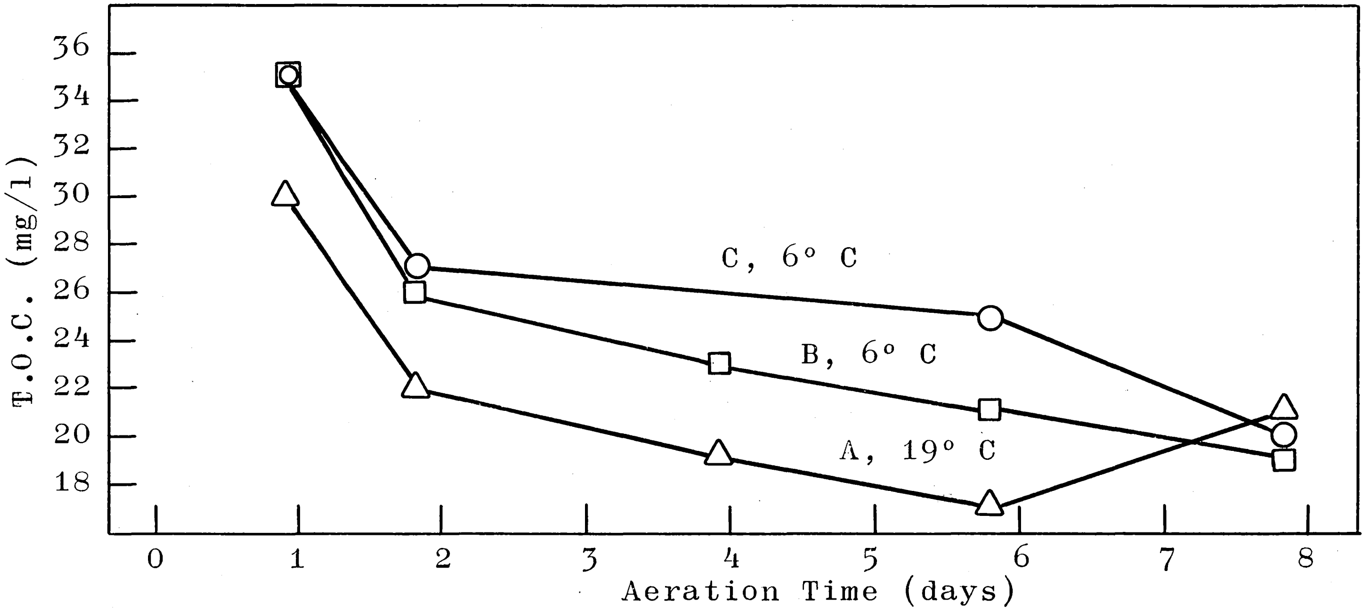

Figure 25. Variation in TOC with Aeration Time for Digestion at 6° C and 19° C.

air rates were employed to give different mixing characteristics. Rates of 2120, 1150, and 535 ml of air per minute were used. Dissolved oxygen checks were made periodically and the dissolved oxygen level in all tubes was above 3.0 mg/l.

The results of this experiment are shown in Figure 26. Of the three air rates used, the lowest rate consistently produced the better filtering sludge. The lowest air rate improved filtering for six days and then maintained the improved condition from six to fourteen days. The highest rate, on the other hand, yielded erratic results with a general worsening in filtering qualities.

pH

The effect of pH on aerobic digestion has been reported in the literature. Lawton and Norman (18) reported that a pH as low as 5.0 did not appear to significantly affect digestion efficiency, and Moore (25) reported that solids reduction was relatively unaffected at a pH of 3.5. Moore did, however, find that filtration and settling characteristics were improved when the pH was held between 4.5 and 3.5.

Two experiments were run in order to test the effects of pH control on sludge filtration. The first experiment consisted of holding the pH of one tube of sludge at approximately pH 7.0, and allowing another tube to seek its

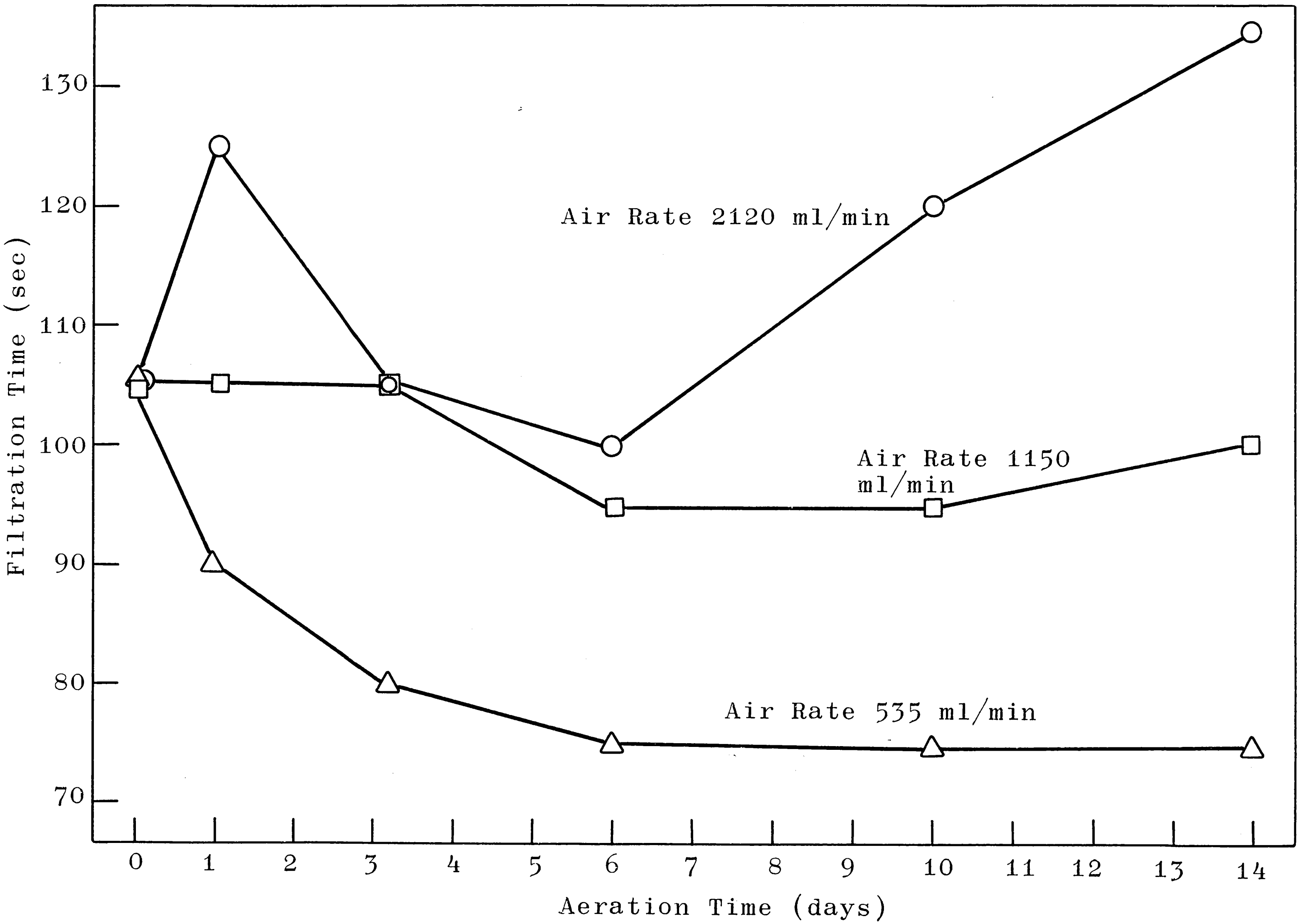

Figure 26. Variation in Filtration Time with Aeration Time for Different Air Flow Rates.

own pH level. The original sludge was at pH 6.9; after one day of aeration the pH rose to 7.4 and from then on, the pH fell steadily until it was 5.2 in fifteen days. The pH in the controlled sludge was allowed to rise originally, but was kept from falling below pH 7.0 by the addition of lime. The drainage rates of both controlled and uncontrolled sludge dropped from an original drainage time of over 650 seconds to a low of below 150 seconds, and throughout the aeration period the rates stayed essentially the same with no appreciable difference.

The second pH experiment was designed to investigate the findings of Moore (25) that sludge which was aerated at a low controlled pH would filter better than uncontrolled sludge. Samples of the same sludge were placed in three aeration tubes. One tube was uncontrolled, one tube was controlled at pH 4.5, and one tube was controlled at pH 3.5. The pH of each tube was checked daily and the pH was controlled by the addition of concentrated sulfuric acid. The results of the second experiment are shown in Figure 27. The uncontrolled sludge showed only a slight improvement in filtration rate throughout the aeration period due to the well conditioned nature of the original sludge. The pH of the uncontrolled sludge dropped slightly throughout the experiment to a low of pH 5.8.

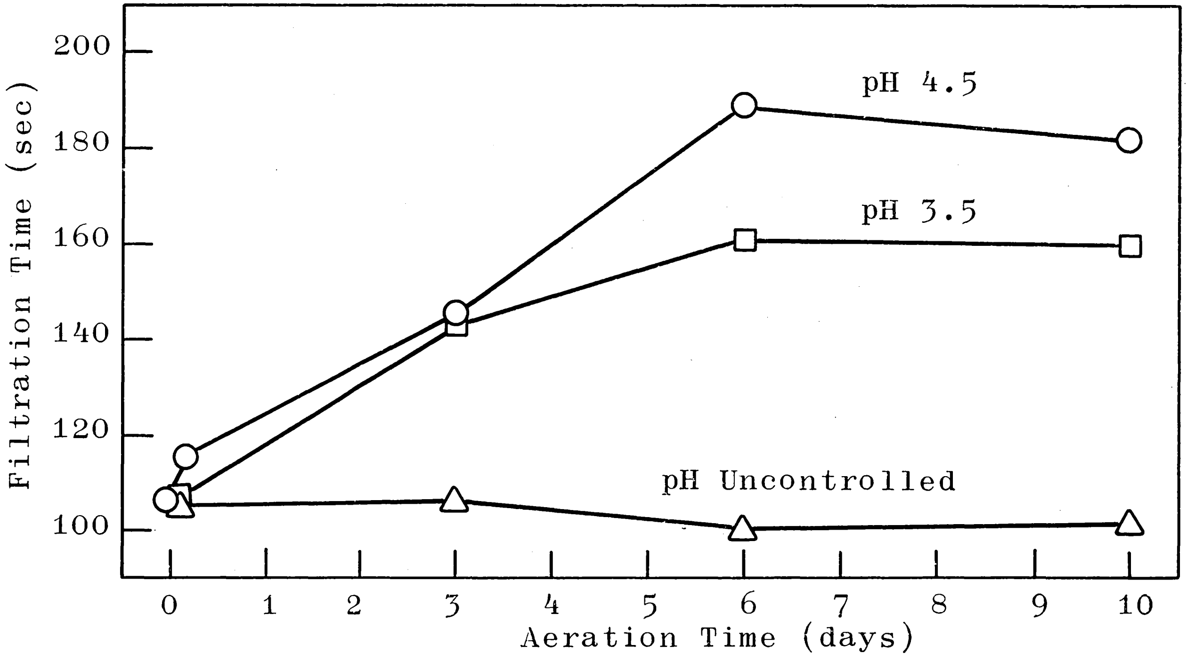

Figure 27. Variation in Filtration Time with Aeration Time at Controlled pH.

The controlled sludge showed a slight immediate increase in filtration time after the pH was originally adjusted and then a gradual increase in time for the first six days of aeration. Although both controlled sludges filtered at a slower rate than the uncontrolled sludge, the sludge with the most control showed a better filter rate than the sludge with the least control. That is, the sludge controlled to pH 3.5 consistently filtered at a faster rate than the sludge controlled to pH 4.5. In order to confirm the findings of this experiment, another experiment was conducted using the same procedures as the last experiment with sludge from a different batch. The results of the second experiment were essentially the same. That is, the uncontrolled sludge filtered best, the sludge controlled to pH 3.5 filtered next best, and the sludge controlled to 4.5 filtered worst.

Chlorine

Chlorine is used in sewage treatment for a variety of purposes. In addition to disinfection, chlorine is used in sludge handling to improve sludge thickening and sedimentation and to correct a sludge bulking problem. (24) Heukelekian (14) studied the effects of chlorine on sludge bulking and bound water. He concluded that chlorination resulted in an immediate decrease in sludge volume index and bound water, and that the action was physical rather than biological.

The effect of chlorine on aerobic sludge filtration was studied by introducing concentrations of 250 mg/l and 750 mg/l calcium hypochlorite (HTH) with 70 per cent available chlorine into two of three aeration tubes. After fifteen minutes, the filtration tests were performed and a residual of 0.07 mg/l chlorine could be detected in the filtrate of the sludge with the original 750 mg/l HTH. After eighteen hours, no chlorine could be detected in any of the three sludges.

Filtration tests were conducted on all sludges for a period of eight days. The results of these tests are shown in Figure 28. The addition of HTH caused a very rapid degradation of filtering quality. After fifteen minutes, the sludge with the concentration of 750 mg/l HTH went from a filter time of 250 seconds to 990 seconds. Continued aeration improved all the sludges. In twenty hours, the sludge with 250 mg/l HTH was back to its original filtering time. However, the 750 mg/l sludge took almost five days to recover to its original filtration time.

In an attempt to determine how chlorine was affecting the sludge, another experiment was conducted. This time 500 mg/l HTH was mixed with the sludge, and after fifteen minutes the filtrate of the sludge was collected and tested

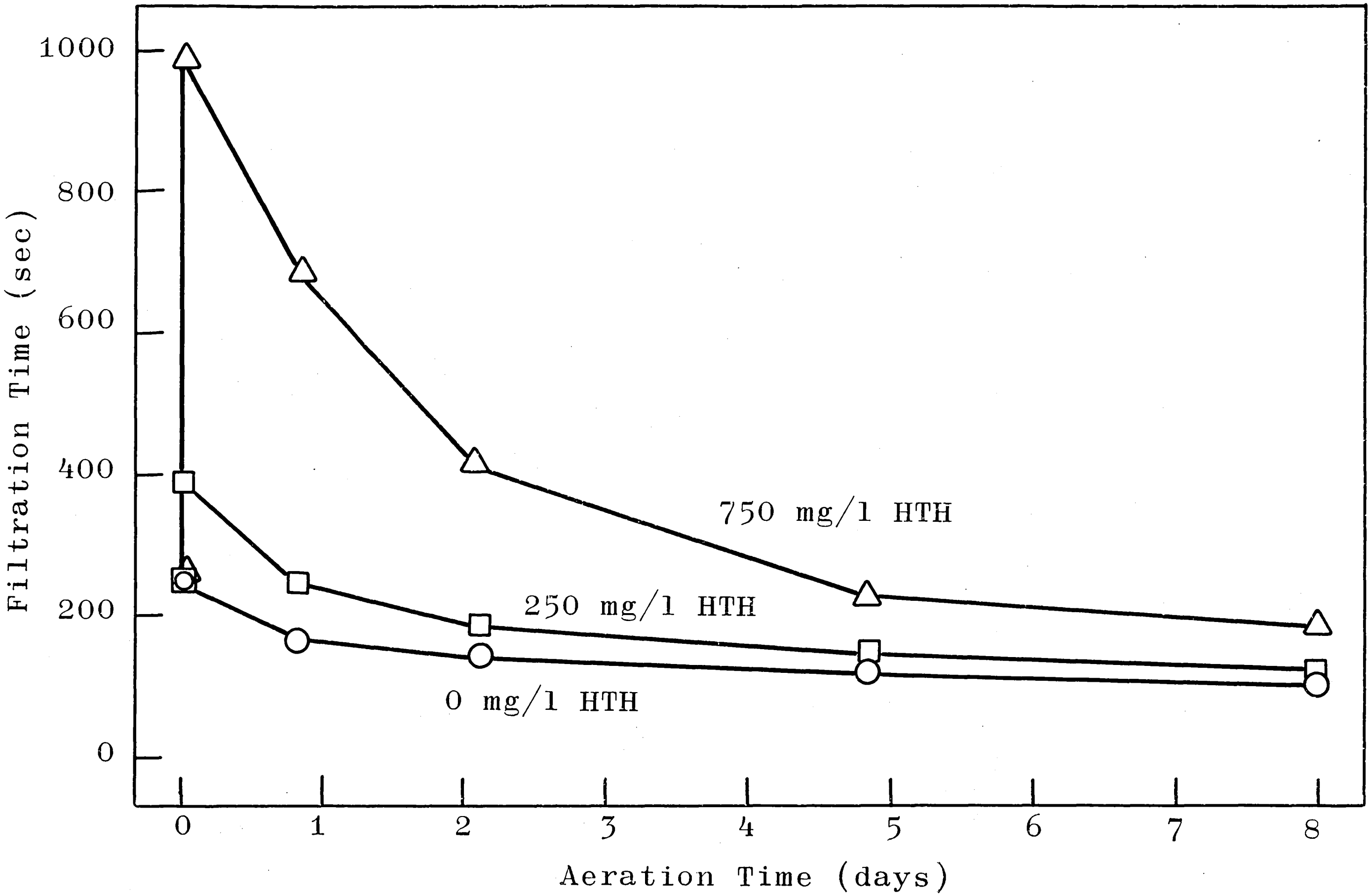

Figure 28. Variation in Filtration Time with Aeration Time for Different Chlorine Concentrations.

for total organic carbon. The total organic carbon for the chlorinated sludge was found to have increased from a non-chlorinated value of 11 mg/l to a value of 68.5 mg/l, indicating the release of considerable organic material to solution. The color of the filtrate was also observed to be yellow for the chlorinated sample as opposed to a clear liquid for the non-chlorinated filtrate.

Batch Versus Continuous Digestion

Aerobic digesters can be operated on either a batch or a continuous basis. Batch digestion involves placing sludge in a digester, aerating the sludge for a specified length of time, removing the digested sludge and then repeating the procedure with a fresh batch of sludge. Continuous digestion usually involves aerating a completely mixed tank of sludge in which portions of digested sludge are periodically withdrawn and replaced with fresh sludge. There is some indication that the method of operation has an effect on digestion solids reduction efficiency (15).

To determine the relative effect of batch and continuous digesters on filtration, a comparative study was made. A batch digester was operated as a standard aeration tube. Sludge was placed in the tube initially, aerated, and samples were removed. No new sludge was introduced during digestion. The continuous feed digesters were standard aeration tubes also, but once a day a portion of the sludge was removed and the same quantity of fresh sludge was used to replace the quantity removed. The quantity removed each day was determined by the detention time desired. Detention time was calculated by dividing the total volume of sludge in the tube by the quantity of sludge replaced each day. Detention times tested were three, five, and ten days. The sludge used throughout the experiment came from the same batch and was stored at 4° C until needed.

Figure 29 shows the results of filtration tests for the batch and continuous feed digesters. Batch and continuous digestion produced the same filtering rates at three days aeration, but there was a slight improvement in the filtration rate of the continuously digested sludge after five and ten days aeration. However, the maximum advantage of continuous digestion was only an improvement of approximately twelve per cent as measured by filtering time.

Dewatering by Sand Drying Bed

The most common method of sludge dewatering in small treatment plants is by sand drying beds. These beds employ two mechanisms of dewatering. First, water is drained from the sludge by gravity induced filtering using sand as the supporting and filtering media. Second, the remaining water is removed from the drained sludge by evaporation.

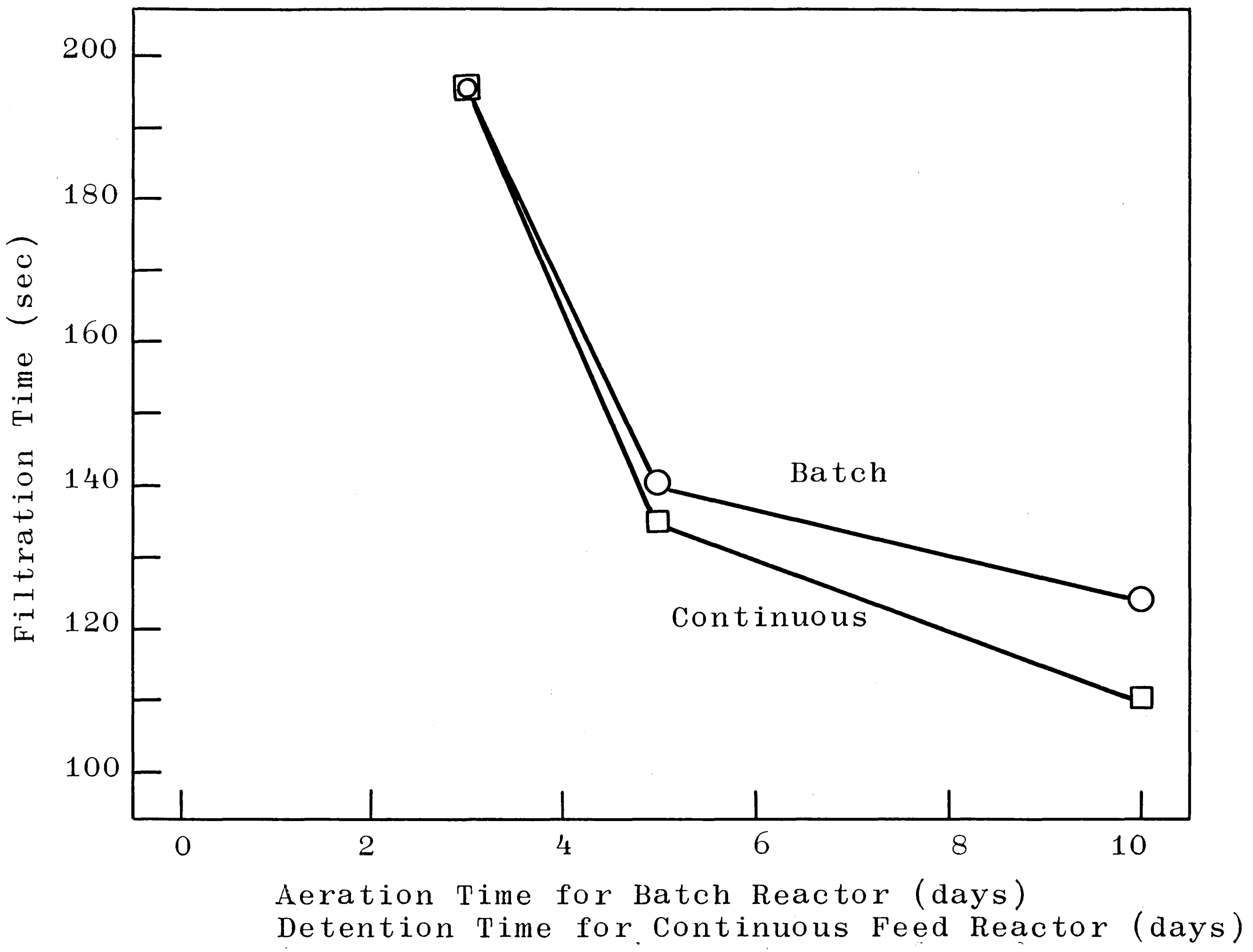

Figure 29. Variation in Filtration Time with Aeration Time or Residence Time for Batch and Continuous Digesters.

To measure the effect of aerobic digestion on sand bed sludge dewatering, a batch of aerated sludge was periodically dewatered by both the sand bed and vacuum filtration methods. To provide the large volumes of sludge required for the sand bed drainage test, a large plexiglass cylinder fitted with a perforated tube at the bottom to provide aeration was used as an aerobic digester. The vacuum filtration tests were conducted in accordance with the standard filtration procedures, but a special drainage cylinder was built to measure sand bed drainage.

Figure 30 shows the relationship between vacuum filtration, gravity drainage and total drainable water for an aerobically digested sludge. The sand drainage time is taken as that time required to drain 750 ml of fluid. The vacuum filtration and gravity drainage times both decrease throughout the six days of aeration. However, while the decrease in vacuum filtration time was about 32 per cent of the original, the decrease in the drainage time for 750 ml was about 73 per cent of the original. Another important factor in sand bed drainage is the total drainable water. Total drainage increased slightly during aeration with an initial increase of 5 ml during the first eighteen hours of aeration. There was another increase of 10 ml between the fourth and sixth day of aeration for a total increase of only two per cent of the original drainable water.

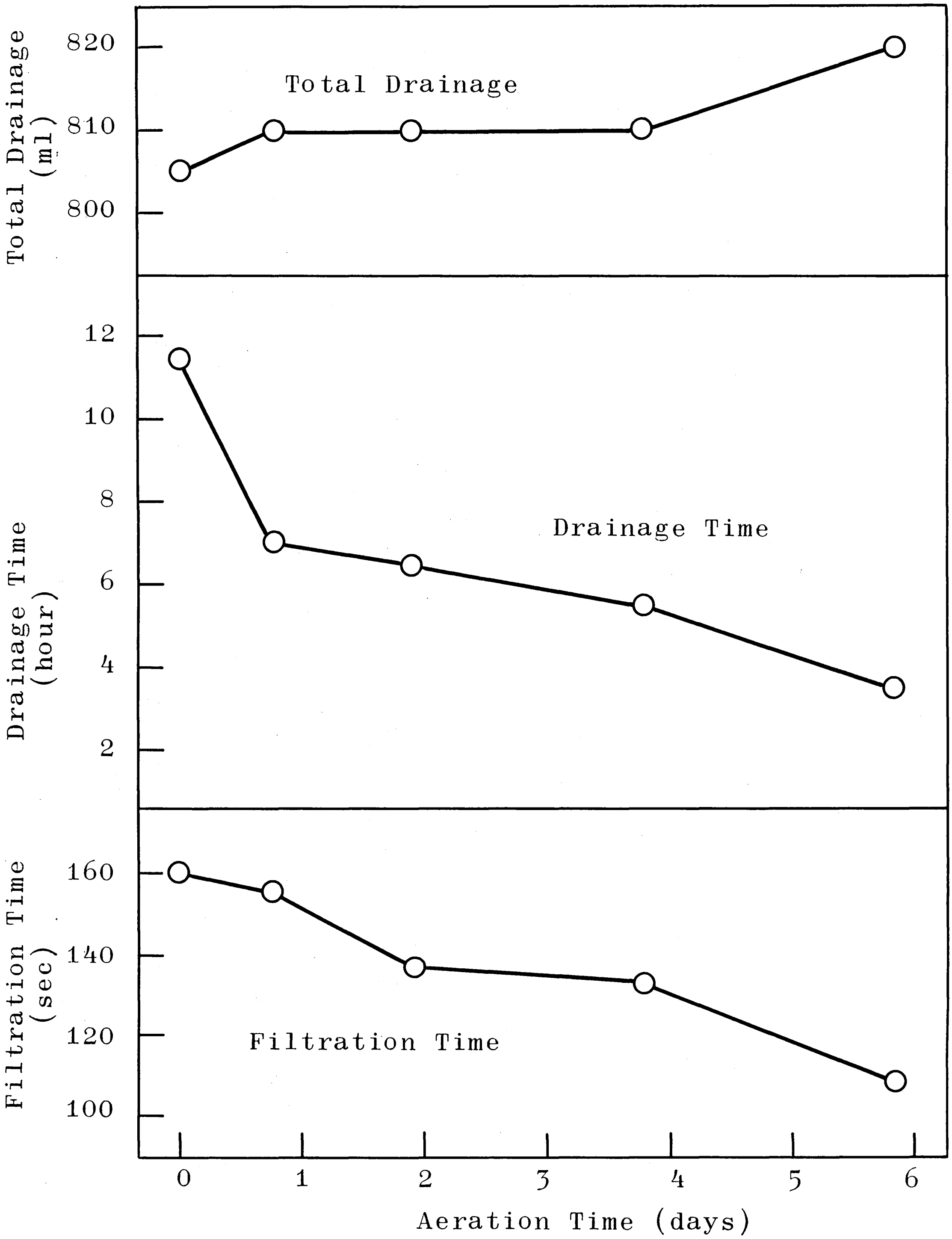

Figure 30. Variation in Total Drainage, Drainage Time and Filtration Time with Aeration Time.

DISCUSSION OF RESULTS

The sludge used in this investigation came from a sewage treatment plant using the extended aeration modification of activated sludge with no primary sedimentation. This modification employs a residence time of up to 24 hours in the aeration tank as compared to a residence time of only about six hours for conventional activated sludge. Such an extended time in the aeration tank allows the activated sludge organisms a longer time to assimilate and stabilize the solid and dissolved matter in the sewage being treated. Thus the sludge produced would be comparable to conventional activated sludge which had undergone a short period of aerobic digestion.

Sludge Characteristics

A characterization of the sludge used in this study indicated that it had undergone a partial stabilization during the treatment process. An indication of partial sludge stabilization was reduced biological activity as measured by oxygen uptake rate and dehydrogenase enzyme activity. The initial oxygen uptake rate was 21 mg/l/hr and the maximum dehydrogenase enzyme activity was 0.49 micromoles of TF produced. Both of these values are low when compared to an oxygen uptake rate of 110 mg/l/hr and an enzyme activity of 0.03 micromoles of TF/mg VSS for activated sludge as reported by Ford et al. (11). Yet the volatile solids content of the sludge, which is an indication of its biological content, was 68.6 per cent of the total suspended solids, a figure that is within the 68 to 70 per cent range given by Steel (39) for conventional activated sludge.

Complete stabilization had not occurred, however, as shown by the fact that the mixed liquor five day BOD, oxygen uptake rate, and dehydrogenase enzyme activity continued to decrease throughout the aeration period of the study. This leads to the conclusion that the fresh sludge used in the study was somewhat more stable than conventional activated sludge, but that it was still in a viable aerobic condition and was representative of sludge encountered at many installations where aerobic digestion is desirable.

As the aeration phase of the sludge characterization study progressed, one apparent non-typical characteristic of the sludge became obvious. Solids reduction for both volatile suspended solids and total suspended solids was poor throughout the aeration period. Most investigators have reported good solids reduction with ten days of aeration. Some studies have, however, indicated poor solids reduction with aerobic digestion. Murphy (26) reported poor volatile solids reduction up to six days of aeration;

and Turpin (43), reporting on aerobic digestion of waste from an extended aeration plant with characteristics similar to the plant used in this investigation, indicated solids reduction of less than 2 per cent for the first fifteen days of aeration. It appears from the literature that solids reduction with aerobic digestion may be almost as unpredictable as filterability. Since this study was concerned with filterability and not solids reduction, and furthermore, since solids were reduced steadily if slightly throughout the aeration period, the low rate of reduction was not considered to be detrimental to the investigation.

Filterability as a Function of Aerobic Digestion

Filtration tests on the sludge indicate that aerobic digestion does improve filterability. In the characterization study, filtration time for 75 ml of sludge went from an initial value of 132 seconds, to a high of 137 seconds after six hours of aeration, then decreased to a low of 91 seconds in five more days. After six days of aeration the filtration time tended to be somewhat erratic but showed a general tendency to increase. This aeration period is consistent with the finding of Randall and Koch (30) that the optimum conditioning period of activated sludge by aerobic digestion for sand bed dewatering occurs within five days. Preliminary and subsequent studies of aerobic digestion of the waste studied in this investigation confirmed the general trend of improved filtration for a given period with a subsequent degradation in filtering qualities with further aeration. However, the filtration rates and optimum digestion periods varied somewhat during the course of the investigation. In comparing sludges which were all aerated in standard aeration tubes at the same air rate and same temperature, the filtration time for 75 ml of fresh sludge varied from 65 to 160 seconds. The maximum improvement in filtration time varied from 23 per cent to 46 per cent improvement with the exception of one experiment in which the filtration time decreased by only six seconds. The aeration time required to reach the maximum improvement in filtration time varied from 4 to 6 days. Finally, most sludges showed a degradation in filtering characteristics after reaching the minimum filtration time, but the degree to which filtration time increased was not consistent from one sludge to another.

As indicated in the "Literature Review," the effect of aerobic digestion on dewatering does not seem to be consistent. Of six investigators who reported the effects of aerobic digestion on dewatering, two reported a general improvement (33, 43), one reported an improvement only under controlled low pH conditions (25), one reported poor filterability at five days with improvement after ten days (15), another reported an improvement in filterability for three days with a degradation from three to six days (26), and only one reported a general degradation in filterability at all stages of digestion (5). It must be remembered, however, that only two of these investigators were studying dewatering specifically and that both of these (26, 43) found improved filterability with aerobic digestion. Also, the waste treated in the investigations studied ranged from domestic to industrial and from primary sludges to activated sludges.

Explanation of Filtration Characteristics

To explain the variation in filtration during aerobic digestion, it is necessary to first look at biological flocculation. McKinney (22) theorized that biological suspensions are similar to colloidal suspensions and that the mechanisms of colloidal flocculation are also responsible for biological flocculations. Two conditions were thought to be necessary before bacteria would form flocs. The first condition was a low zeta potential for the microorganisms so that the repulsive forces would be small enough for the van der Waal's forces of attraction to predominate. A zeta potential level of ±20 to ± 30 millivolts or lower was felt to be necessary for this condition to occur. The second condition for bioflocculation was assumed to be a low food to microorganism ratio so that the motile forms of bacteria would not predominate. The zeta potential for the raw sludge used in this investigation was found to be -9.7 millivolts and only gradual decrease was noted during aeration. The highest zeta potential of -9.7 millivolts is well below the ±20 to ±30 millivolts minimum said to be necessary for flocculation.

The second condition of low food to microorganism ratio is somewhat harder to determine. Randall et al. (32) studied the dewatering of high concentrations of activated sludge and concluded that a mixed liquor BOD of approximately 600 mg/l was optimum for gravity dewatering. The BOD of the mixed liquor for the sludge used in this investigation was 2,600 mg/l for the fresh sludge and gradually decreased to a low of 1,360 mg/l after eight days of aeration. This extremely high BOD would seem to indicate a high food to microorganism ratio, but in fact, it was a measure of the cells themselves rather than available food in the form of substrate as envisioned by McKinney (22). Better measures of the food available to the organisms are the COD and the TOC of the filtrate. These tests would indicate the dissolved material available to the organisms. The COD of the filtrate of the fresh sludge was 73 mg/l but quickly decreased. In six hours of aeration it leveled off at between 20 and 30 mg/l and remained in this range for the remainder of the test. The TOC also started high at 42 mg/l, but it took approximately two days before it reached a stable condition at approximately 14 mg/l. Both the COD and TOC measurements indicate that after the second day the dissolved food to microorganism ratio was low and remained stable throughout the aeration period. Therefore, both of McKinney's (22) conditions for good flocculation were satisfied shortly after aeration started, indicating that full flocculation conditions should have existed after the second day of digestion.

Tenney and Stumm (41) felt that van der Waal's attractive forces alone were not of sufficient strength to account for biological flocculation. They postulated that polymers of biological origin were of major importance in flocculation and speculated that these polymers were such naturally occurring substances as complex polysaccharides and polyamino acids which are excreted or exposed at the surface of bacteria during the declining growth and endogenous-respiration phases of metabolism. The secreted polymeric molecules were thought to be of sufficient length to form bridges between microbial particles. Busch and Stumm (3) confirmed the concept that naturally occurring polymers are synthesized by bacteria, and they theorized that although polysaccharides and other polymers are produced during all growth phases, adequate concentrations of polymers per surface area of cells can accumulate only under conditions of declining growth or endogenous growth.

Dean (7) found that slimes and capsular material exuded by bacteria contained large quantities of flocculating materials such as polysaccharide gums and some polyamino acids. He also stated that the character of polymer flocculants is that they act as dispersants when present in an excess over the optimum dose, a factor which might account for the poor dewatering properties of some well stabilized activated sludges.

Since aerobic digestion maintains bacteria in the endogenous phase of respiration, it would seem likely that the production of extra-cellular polymer type substances would take place during digestion. Although the exact chemical nature of flocculant material produced by bacteria is not known, the most common reference is to a polysaccharide substance. The anthrone test is not a specific test for polysaccharides, but it is a test for carbohydrates and would indicate an increase in the level of polysaccharides. Figure 10 shows that the carbohydrate concentration of the sludge mixed liquor used in this investigation had an initial drop with a subsequent leveling off, but the carbohydrate content of the filtrate from a 0.45 micron filter had a steady and distinct increase from 6 mg/l initially to 20 mg/l in ten days. This steady increase in carbohydrate in the filtrate could indicate a steady leakage of polysaccharide material from the cells and a subsequent buildup in the filtrate. Another indication of leakage of cellular material was the concentration of protein in the filtrate. Figure 11 shows that the protein in the filtrate dropped the first day and then gradually increased for the remainder of the aeration period. After the initial drop, the protein concentration remained between 5 to 8 mg/l indicating a low level of cell protein leakage.

Another factor involved in the bioflocculation process is the presence of protozoa and rotifers. Many investigators (4, 22, 23, 44) have shown that protozoa and rotifers can contribute to mixed culture flocculation. This contribution is attributed to the feeding habits of these organisms and the fact that they not only remove debris and isolated cells from the mixed liquor, but that they also secrete a mucous substance during feeding which has been found to accumulate in the neighborhood of the feeding organism (44). No quantitative measurements were made of the numbers of higher animal life present in the aerobic sludge, but periodic microscopic examinations indicated that both rotifers and protozoa were present in the mixed liquor throughout the aeration period. These organisms probably contributed somewhat to the flocculation process of the aerobic sludge, but the extent of this contribution is not known.

In reviewing the discussion of the sludge characteristics and the flocculation mechanism, it can be concluded that the variation in sludge filterability during aerobic digestion depends upon a number of factors. The most important of these factors appears to be extracellular polymers produced by bacteria and other microorganisms. A build-up of such flocculating agents as polysaccharides and polyamino acids would account for the increase in carbohydrate and protein concentration observed in the filtrate. This gradual build-up of biologically produced polymers would tend to increase sludge flocculation and bridging between sludge particles and thus increase the sludge filterability. As the level of polymeric substances increased beyond the optimum flocculant dose, or the bacteria producing these substances reduced their activity to such a low level that the polymers were not being continually formed or secreted at the surface of the organisms, the filtration characteristics of the sludge would become worse.

In order for the mechanism of polymer induced flocculation to be effective in a digesting sludge, two conditions must be met. First, the food to microorganism ratio must be low enough for the bacteria in the sludge to be in the endogenous stage of respiration. At this stage the organisms produce the maximum amount of polymers per cell surface area. Second, the bacteria must be intact and active. Dead, inactive, or disrupted organisms would not produce sufficient biological polymers or provide adequate bridging sites to result in a well-flocculated system. If both these conditions are met, it is felt that the mechanism of biologically produced polymeric flocculation is the major influence in activated sludge filterability. If, on the other hand, the conditions are not met, the polymer mechanism can not function at maximum capacity and sludge filterability would suffer as a result.

Other factors affecting sludge flocculation could also play a part in determining filtration characteristics. The low zeta potential of the sludge means that the repulsive forces caused by surface charges are small enough so that they would not inhibit van der Waal's forces of attraction and other flocculating mechanisms. In this study the zeta potential remained relatively low throughout the aeration period indicating that its effect was fairly constant during digestion. The food to microorganism ratio (F/M) is important because a low F/M not only promotes endogenous growth which is favorable to production of extracellular polysaccharides but also favors non-motile bacteria. Most aerobic sludge would develop a low food to microorganism ratio shortly after aeration began because of the rapid uptake of any available food introduced into the digestion unit as shown by the uptake of TOC and COD in the experimental unit. Finally, the types of microorganisms present can play a part in the filtration characteristics of the sludge either by their feeding habits as illustrated by rotifers and protozoa or by their ability to produce extra-cellular biological polymers.

Variation of Operational Parameters

A study of the effects caused by varying operating parameters and environmental conditions of aerobically digesting sludge can be important in two ways. First, the relationships of the individual parameter to sludge filterability can be determined, and, second, the effect observed can be used to establish or confirm proposed mechanisms of sludge filterability and conditioning. It is believed that the mechanism of extra-cellular polymer production can be used to explain and interpret the results of the tests on operating parameters. Such information should prove useful for evaluating operating procedures on a rational basis for their sludge conditioning benefits.

Dissolved Oxygen

Experiments studying the effects of dissolved oxygen concentration on activated sludge filterability indicated that the lack of dissolved oxygen can be an important sludge conditioning factor. The filtering properties of activated sludge maintained in an anaerobic condition degenerated at the rate of approximately 18 per cent per day in terms of filtration time. This degeneration was also coupled with an increase of TOC in the filtrate indicating that cell disruption or at least cell leakage was taking place. A plot of TOC versus filtration time shows that the TOC, filtration time relationship was linear for the sludge tested. Mixing the sludge while it was in the anaerobic state simply increased the rate of filtration time increase, which indicates that not only were the individual cells leaking carbonaceous material, but also that the binding links between sludge particles were weakening.

The best dissolved oxygen level to maintain in aerobic sludge was not determined, but it was found that increasing the concentration above 2.0 mg/l during digestion did not significantly alter the filtration rates of the sludge. There was even some indication that the dissolved oxygen could be maintained below 2.0 mg/l and still produce the same filtration characteristics. After sludge had been subjected to anaerobic conditions and the filtration time had increased accordingly, the filtration characteristics of the sludge could be rejuvenated by aeration (Figure 19). In most cases, for anaerobiosis up to four days, the filtration time could be reduced just as rapidly and as much by aeration as the same sludge which had not been subjected to any extensive anaerobic period.

The studies of dissolved oxygen concentration and sludge aeration indicated that the organisms responsible for the improvement of filtration require oxygen to function. On the other hand, a sufficient number of these organisms were capable of surviving up to four days without oxygen and were still able to function adequately to improve filtration. These observations lead to the conclusion that facultative organisms are capable of improving the filtration rates of sludge and are possibly the primary organisms that are functioning in this role. On the other hand, it is also apparent that these organisms only perform this function when oxygen is present in the system and they are acting as aerobes.

Temperature

Temperature is a well-known factor in biological systems. Generally an increase in temperature is associated with an increase in biological activity within the limits of enzyme stability. These limits include the mesophilic range (25° to 40° C) and the thermophilic range (45° to 60° C) which are the two temperature ranges of primary interest in waste treatment.

The results of an aerobic digestion study at four different temperatures (20°, 25°, 30°, and 35° C) indicated that digestion temperature is a factor in conditioning aerobically digested sludge for dewatering. However, the overall effect of temperature seems to be relatively small.

The two sludges digested at the higher temperatures only took two days to reach their minimum filtration time while the two lower temperature sludges took four days, indicating that the rates of improvement at the higher temperatures were somewhat faster than at the lower temperatures. Although the two higher temperature sludges reached their minimum filtration time faster than the two lower temperature sludges, the best filtration time was exhibited by the two middle temperature sludges (25° and 30° C). The highest and lowest temperatures tested both exhibited the poorest minimum filtration times. These results indicate that the filtration behavior of aerobically digested activated sludge depends on the temperature of sludge digestion with an improvement in filtration qualities as the temperature is increased up to 30° C.

When activated sludge was digested at 6° C, the results showed that reduction in biological action caused by reducing the temperature produced a decrease in filtration characteristics. Two factors seemed to be responsible for this reaction. First, there was a slight cell disruption when the temperature was lowered, revealed by a slight increase in TOC in the filtrate. Second, there was a reduction in biological activity with a resulting decrease in the production of extra-cellular coagulants. This last factor was indicated by the general lack of recovery of filtration characteristics of the sludge with further aeration. Unlike other experiments where the organisms were stressed and originally lost some of their good filtering characteristics, the sludge digested at 6° C did not recover its original characteristics with a few days of additional aeration.

Mixing Rate

It has already been shown that mixing sludge in an anaerobic condition will cause an increase in the destruction rate of the sludge filtering qualities. Mixing rates can also play a part in aerobic sludge as illustrated in Figure 26. In this experiment, the dissolved oxygen in all digesters was maintained above 2 mg/l at all times, but the air flow rates in all three were different causing differing mixing rates. The results show that as long as sufficient oxygen is available (2 mg/l), additional aeration to provide mixing is detrimental to the sludge filtration rate. With sufficient oxygen, the organisms can produce polymers which cause coagulation and flocculation with gentle agitation, but as the aeration rate increases, the agitation in the fluid becomes greater, and forces which tend to break up floc formations increase. When agitation reaches a certain level, the fragile floc formations cannot withstand the forces and break up, thus causing a degradation in filtering properties.

Concentration

The suspended solids concentration of the aerobically digested sludge affects the dewatering properties of the sludge but does not seem to affect the digestion process. That is, an increase in suspended solids causes an increase in filtration time, but this relationship remains constant during aerobic digestion, indicating that the concentration does not affect the digestion process itself. This is probably due to the fact that the ratio of biologically produced polymers per surface area of sludge remains constant regardless of the solids concentration of the sludge.

pH Control

Controlling the pH of aerobically digesting sludge to improve the filtration characteristics proved unsuccessful. Maintaining the pH of the sludge at 7.0 produced a sludge which filtered at the same rate as uncontrolled sludge, and controlling the pH at 4.5 and 3.5 produced sludges with poorer filtration rates than the uncontrolled sludge. This poor filterability was probably due to a disruption in cell activity with a resulting decrease in polymer production. Thus it seems unnecessary from a sludge filtering standpoint to try to control the pH of aerobically digested sludge.

Chlorine

The chlorination of activated sludge proved to be quite harmful to sludge filtration. The addition of enough chlorine to produce a slight chlorine residual in the filtrate caused the filtration time to increase by 400 per cent and smaller concentrations of chlorine caused proportionally smaller increases in filtration time. This increase in filtration time was probably due to extensive cell disruption as indicated by a high TOC concentration in the filtrate after chlorination. Although the experiment using chlorine showed that chlorine is detrimental to sludge filtration, it also showed that aeration of sludge which has been subjected to chlorination can improve the filtering properties of the sludge, and as in the case in this experiment, the improvement can be almost as great as if the sludge had not been chlorinated at all. This knowledge could possibly be applied to a situation where sludge was chlorinated to control sludge bulking or to improve thickening and storage properties. Aeration could then be used to improve filtration characteristics before final dewatering.

Batch and Continuous Digestion

A comparison of digester performance when operated as either a batch unit or a continuous daily feed unit revealed that the continuous operation produced a slightly better dewatering sludge. This difference increased with the aeration or detention time of the sludge from no difference at three days to 12 per cent difference after ten days (Figure 29). This difference possibly was due to a build-up of extra-cellular polymers as a result of the long residence time of a portion of the sludge, and the ability of the sludge to stay active as new sludge was introduced daily. The filtering differences between the two operating procedures is relatively small and the decision of what procedure to use should not be based on this factor.

Sand Bed Drainage

The results of sand bed drainage experiments indicated that the mechanism of biological polymer production improves gravity dewatering as well as vacuum filtration. There does, moreover, seem to be a somewhat greater effect on gravity drainage, as shown by the larger percentage decrease in drainage time, than in filtration time. Another interesting observation of the sand bed dewatering experiments was the slight increase in total drainable water with aeration. A similar effect was noted by Randall and Koch (30). This could be due to either a reduction in suspended solids or a decrease in the sludge bound water. Both the gravity drainage rate and the total drainable water may be affected by the extra-cellular polymers produced by the sludge bacteria during aeration. However, without more information than is available from this investigation, the actual nature of the effect cannot be determined. Aerobic digestion does seem to improve the important gravity dewatering properties of sludge and therefore, should be of value for treating sludge which is to be dewatered on gravity sand beds.

Summary

The proposed mechanism of biological polymer induced flocculation seems to be adequate to explain the reaction of activated sludge filterability to different operating procedures. The reactions which support this conclusion are:

(1) When conditions for biological activity are good and when the food to microorganism ratio is low enough to promote endogenous growth, sludge filterability either improves or remains good.

(2) When biological activity is disrupted by chlorination, a quick change in pH or temperature, or lack of oxygen, the sludge filterability quickly degenerates.

(3) When biological activity is slowed down by cooling or by a long aeration period, filterability either stabilizes or becomes progressively worse.

CONCLUSIONS

1. Aerobic digestion can have a considerable effect on sludge filterability. Under the conditions of this test, the filterability of all sludges was improved with moderate aeration at 20° C. The degree of improvement depends on the nature of the fresh sludge, the rate of aeration during digestion, the temperature during digestion, and the time of digestion.

2. There is an optimum time of aerobic digestion for maximum filterability. Greater periods of aeration result in a worsening of filtration rate. In general, digestion time of four to six days is optimum for activated sludge from plants that do not use primary sedimentation.

3. The mechanism of filtration improvement during aerobic digestion appears to be biological in nature. Biologically produced extracellular polymeric substances are secreted by or exposed on the surface of bacteria during the endogenous phase of metabolism. These polymers cause coagulation and bridging between sludge particles thus affecting the filtering properties. This phenomenon occurs only when oxygen is present

in the system. However, the organisms responsible can survive up to four days without the artificial addition of oxygen.

4. It is necessary to maintain activated sludge in a viable, cellularly intact condition to achieve favorable filtration rates.

5. Anaerobic conditions are detrimental to the filtration characteristics of activated sludge. When the aeration of activated sludge is stopped, the organisms will quickly use up the available dissolved oxygen and then the filtration characteristics will start to degrade. This degradation has been observed to make filtration continually worse for up to four days.

6. Filtration characteristics degraded during anaerobic conditions can be recovered by subsequent aeration. The period of aeration required for recovery is similar to that required before anaerobiosis.

7. Differences in dissolved oxygen concentrations above 2 mg/l do not change the sludge filterability. Therefore it is not necessary to maintain the concentration of dissolved oxygen above this level to obtain improved filterability during aerobic digestion.

8. The rate at which sludge is mixed during aerobic digestion can influence the dewatering properties of the sludge. It appears that the more rapidly a sludge is mixed the greater the forces placed on the sludge floc particles and the poorer the filtration rate. Mixing is also detrimental to the dewatering of non-aerobic sludge. Mechanical mixing of sludge when dissolved oxygen is absent causes a more rapid degradation in sludge filtering properties than when the same sludge is not mixed.

9. Sludge filtration is a function of suspended solids concentration with an increase of 62.5 seconds in filtration time for 75 ml of sludge for each one per cent increase in suspended solids. The suspended solids concentration does not seem to affect the aerobic digestion process, however, because the 62.5 seconds per one per cent relationship holds true at different stages of digestion.

10. Chlorination of activated sludge reduces the filtering rate of the sludge. The filtering rate can, however, be restored after chlorination by aerating the sludge for a period of time.

11. Controlling the pH of aerobically digesting sludge does not necessarily improve the filtering properties

of the sludge. During this study, control of pH at 7.0 resulted in a sludge which filtered at the same rate as non-controlled sludge and controlling the pH at values lower than 7.0 resulted in a poorer filtering sludge.

12. Digestion temperature is a factor that affects sludge filtration. A given sludge when digested at a higher temperature will filter faster than the same sludge at a lower temperature. Temperature also affects aerobic digestion. Higher temperatures tend to speed up the effect of digestion and up to temperatures of 30° C tended to increase the maximum improvement in filtration rate during digestion.

13. Under the conditions of this investigation sludge digested in a daily feed continuous aerobic digester dewatered more readily than sludge digested in a batch aerobic digester.

14. Aerobic digestion affects the dewatering of sludge on sand drying beds. The time required to drain 750 ml from a one liter sample decreased by about 73 per cent after six days of aeration and there was an increase in the total drainable water of two per cent. Both of these effects would improve the overall dewatering of sludge on sand drying beds.

BIBLIOGRAPHY

1. Barnhart, E. L., "Application of Aerobic Digestion to Industrial Waste Treatment," Proceedings, 16th Industrial Waste Conference, Purdue University (1961).

2. Bhatla, M. N., "Relationship of Activated Sludge Bulking to Oxygen Tension," Water Pollution Control Federation Journal, 39 (Dec. 1967).

3. Busch, P. L. and Stumm, W., "Chemical Interaction in the Aggregation of Bacteria," Environmental Science and Technology, 2, 49 (1968).

4. Calaway, W. T., "Metazoa of Waste Treatment Process-Rotifers," Water Pollution Control Federation Journal, 11, 2 (Nov. 1968).

5. Carpenter, W. L. and Blesser, R. O., "Aerobic Decomposition of Secondary Papermill Sludges," Proceedings, 17th Industrial Waste Conference, Purdue University (1962).

6. Coakley, P. and Jones, B. R. S., "Vacuum Sludge Filtration-Interpretation of Results by the Concept of Specific Resistance," Sewage and Industrial Wastes, 28 (Aug. 1956).

7. Dean, R. B., "Colloids Complicate Treatment Processes," Environmental Science and Technology, 3, 9 (Sept. 1969).

8. Eckenfelder, W. W., Industrial Water Pollution Control. New York: McGraw-Hill Book Company, 1966.

9. Eckenfelder, W. W., "Studies on Oxidation Kinetics of Biological Sludges," Sewage and Industrial Waste, 28 (Aug. 1956).

10. Eckenfelder, W. W., and O'Connor, D. J., Biological Waste Treatment. New York: Macmillan Book Company, 1961.

11. Ford, D. L., Young, J. T., and Eckenfelder, W. W., "Dehydrogenase Enzyme as a Parameter of Activated Sludge Activities," Proceedings, 21st Industrial Waste Conference, Purdue University (1966).

12. Genter, Albert, "Conditioning and Vacuum Filtration of Sludge," Sewage and Industrial Wastes, 28, No. 7 (July 1956).

13. Hamlin, M. J., and El-Hattab, I., "Factors Affecting the Dewatering of Sludge," Journal Institute of Public Health Engineering (Brit.), 66 (1967).

14. Heukelekian, H., and Weisberg, E., "Bound Water and Activated Sludge Bulking," Sewage and Industrial Wastes, 28 (April 1956).

15. Jaworski, N., Lawton, G. W., and Rohlich, G. A., "Aerobic Sludge Digestion," Conference on Biological Waste Treatment, Manhattan College, New York (April 20-22, 1960).

16. Jeffrey, E. A., "Laboratory Study of Dewatering Rates for Digested Sludges in Lagoons," Proceedings, 14th Industrial Waste Conference, Purdue University (1959).

17. Jones, B. R. S., "Vacuum Sludge Filtration, Prediction of Filter Performance," Sewage and Industrial Wastes, 28, 9 (Sept. 1956).

18. Lawton, G. W., and Norman, J., "Aerobic Sludge Digestion Studies," Water Pollution Control Federation Journal, 36, 4 (April 1964).

19. Logsdon, G. S., and Jeffrey, E. A., "Estimating Gravity Dewatering Rates of Sludge by Vacuum Filtration," Water Pollution Control Federation Journal, 38, 2 (February 1966).

20. McCarty, Perry L., "Anaerobic Waste Treatment Fundamentals," Public Works (September 1964).

21. McCarty, Perry L., "Sludge Concentration--Needs, Accomplishments and Future Goals," Water Pollution Control Federation Journal, 38, 4 (April 1966).

22. McKinney, R. E., "Biological Flocculation," Biological Treatment of Sewage and Industrial Waste, I. New York: Reinhold (1966).

23. McKinney, R. E., and Gram, A., "Protozoa and Activated Sludge," Sewage and Industrial Wastes, 28, 10 (Oct. 1956).

24. *Manual of Instruction for Sewage Treatment Plant Operators*. Albany, New York: New York State Health Education Service.

25. Moore, H. R., "The Effects of pH on Aerobic Sludge Digestion," Unpublished Master's Thesis, Virginia Polytechnic Institute (1970).

26. Murphy, K. L., "Sludge Conditioning by Aeration," Unpublished Master's Thesis, University of Wisconsin (1959).

27. Nebiker, J. H., Sanders, T. G., and Adrian, D. D., "An Investigation of Sludge Dewatering Rates," *Water Pollution Control Federation Journal* (Aug. 1969).

28. Quon, J. E., and Johnson, G. M., "Drainage Characteristics of Digested Sludge," *Journal Sanitary Engineering Division, ASCE 92*, 2 (April 1966).

29. Ramanathan, M., Guady, A. F., Jr., and Cook, E. E., "Selected Analytical Methods for Research in Water Pollution Control," Center for Water Research in Engineering, Oklahoma State University, Stillwater, Oklahoma.

30. Randall, C. W. and Koch, C. T., "Dewatering Characteristics of Aerobically Digested Sludge," *Water Pollution Control Federation Journal*, *41* (May 1969).

31. Randall, C. W., Saunders, F. M., and King, P. H., "Biological and Chemical Changes in Activated Sludge During Aerobic Digestion," Paper presented at the 18th Southern Water Resources and Pollution Control Conference, Raleigh, North Carolina (April 1969).

32. Randall, C. W., Turpin, J. K., King, P. H., "Activated Sludge Dewatering: Factors Affecting Drainability," paper presented at the 42nd Annual Conference of the Water Pollution Control Federation, Dallas, Texas (Oct. 1969).

33. Reynolds, T. D., "Aerobic Digestion of Waste Activated Sludge," *Water and Sewage Works*, *114* (Feb. 1967).

34. Ritter, Lewis E., "Design and Operating Experience Using Diffused Aeration for Sludge Digestion," *Water Pollution Control Federation Journal*, *42* (Oct. 1970).

35. Saunders, F. M., "Aerobic Digestion of Waste Activated Sludge," Unpublished Master's Thesis, Virginia Polytechnic Institute (1968).

36. Schepman, B. A. and Cornell, C. F., "Fundamental Operating Variables in Sewage Filtration," Sewage and Industrial Waste, 28 (Dec. 1956).

37. Simplified Laboratory Procedures for Wastewater Examination, W.P.C.F. Publication No. 18, Water Pollution Control Federation, Washington, D. C.

38. Standard Methods for the Examination of Water and Wastewater, 12th Edition, New York: American Public Health Association (1965).

39. Steel, E. W., Water Supply and Sewage. New York: McGraw-Hill Book Company (1960).

40. Tenney, M. W., Echelberger, W. F., Jr., Coffey, J. J., and McAloon, T. J., "Chemical Conditioning of Biological Sludges for Vacuum Filtration," Water Pollution Control Federation Journal, 42 (Feb. 1970).

41. Tenney, M. W. and Stumm, W., "Chemical Flocculation of Microorganisms in Biological Waste Treatment," Water Pollution Control Federation Journal, 37 (1965).

42. Trubnick, E. H. and Mueller, P. V., "Vacuum Filtration Principles and Their Application to Sewage Dewatering," Conference on Biological Waste Treatment, Manhattan College (April 1957).

43. Turpin, J. K., "The Relation of Cellular Parameters to Activated Sludge Drainability During Aerobic Digestion," Unpublished Master's Thesis, Virginia Polytechnic Institute (1969).

44. Watson, J. W., "Mechanism of Bacterial Flocculation Caused by Protozoa," Nature, 155 (1945).

FACTORS AFFECTING THE FILTRATION CHARACTERISTICS OF AEROBICALLY DIGESTED SLUDGE

by

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Abstract

The cost of handling and disposal of sewage sludge is a major expense in sewage treatment. Often half of the treatment plant expense is in the purchase and maintenance of sludge handling equipment. The sludge problem becomes particularly acute with activated sludge processes because of the large volumes of waste activated sludge produced and the nature of the activated sludge itself. The object of this investigation was to conduct laboratory scale investigations of the effects of aerobic digestion on activated sludge dewatering and to attempt to determine the chemical and biological mechanisms affecting sludge filterability.

The results of this investigation showed that aerobic digestion can have a considerable effect on sludge filterability. The filterability of all sludges was improved with moderate aeration at 20° C. The degree of improvement depends on the nature of the fresh sludge, the rate of aeration during digestion, the temperature during digestion, and the time of digestion with the optimum time of digestion between four to six days.

The mechanism of filtration improvement during aerobic digestion appears to be biological in nature. Biologically produced extracellular polymeric substances are secreted by or exposed on the surface of bacteria during the endogenous phase of metabolism. These polymers cause coagulation and bridging between sludge particles, thus affecting the filtering properties. This phenomenon occurs only when oxygen is present in the system. However, the organisms responsible can survive up to four days without the artificial addition of oxygen.

A study of various operating parameters in aerobic digestion leads to some further conclusions regarding sludge filtration. Factors which have a detrimental effect on filtration are: lack of dissolved oxygen, excessive mixing, low temperature during digestion, and chlorination of sludge before filtering. Factors which do not appear to have a significant effect on filtration are: differences in dissolved oxygen concentrations above two mg per liter, and the maintenance of a neutral pH in the digester.