THE EFFECTS OF AEROBIC DIGESTION ON CENTRIFUGATION

by

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I. INTRODUCTION

The earth, is generally considered to be billions of years old, and it has undergone considerable changes during this period of time. However, the earth has never changed quite so rapidly as it has with the arrival of civilized man with his creative ability to instigate projects which are continually causing a renovation of "mother earth."

In the past, man very seldom considered the effects of his works on the environment, but, with the growing public interest in ecological factors, more and more emphasis is being placed on cleaning up and maintaining a healthy environment.

One area that is receiving considerable attention is that of municipal and industrial sewage treatment plants. The news media, engineers and regulatory agencies have stressed the importance of acceptable effluent quality (preferably one that is low in suspended solids, BOD, inorganic nutrient concentrations, and deleterious refractory organic matter). For this reason municipalities and industries are in most cases having to upgrade present facilities and/or construct new ones.

One of the major expenses incurred in the operation of a wastewater facility is the treatment and disposal of sewage solids and subsequently produced biological sludges. Although the actual volume of solids in the influent sewage is less than one percent, it has been shown that the city of Chicago utilizes 46 percent of the annual maintenance and operation budget on sludge handling (3). Nebiker, et al. (30), reported that somewhere between 25 to 65 percent of the total capital and operating costs of primary and secondary treatment plants was for sludge handling.

Two processes that are used for solids disposal are sludge digestion, or stabilization, and sludge dewatering. The objectives of these two processes are the reduction in sludge volume, the decomposition of highly putrescible organic matter to stable or inert organic material, and the reduction in volume and moisture content of the sludges. Although both these processes can be adopted to utilize any type sludge, it is generally conceded that secondary or biological sludge is the most difficult and costly of the domestic sludges to dewater because of its unique chemical, physical, and biological characteristics.

Sludge stabilization has traditionally been accomplished by anaerobic organisms, in the absence of oxygen. This digestion process, because of economics, is followed by a dewatering process which in most instances is a gravity-type sand drying bed. Nebiker, et al. (30), report that 72 percent of the treatment plants in the United States utilize sludge drying beds despite a variety of mechanical methods available for sludge volume reduction. However, with the expansion of available technology as well as more stringent effluent standards, other types of solids disposal techniques, have been developed, one of which is the aerobic digestion process.

Aerobic digestion is a process by which the sludge is continually aerated to keep aerobic organisms in the endogenous phase of respiration. During the endogenous phase cellular material is destroyed, and thus, solids are reduced and stabilized. This process can be used to stabilize primary or biological sludges or mixturers. However, activated sludge is more amenable to aerobic digestion because the required aerobic organisms are already developed and the dewatering problems commonly associated with anaerobically digested sludge do not develop (34).

Dewatering, as previously mentioned, presents a major problem in sludge handling. Many processes have been developed, but their degree of effectiveness generally depends on the characteristics of the particular sludge in question. Centrifuging is one such technique. The purpose of this investigation was to study the effects of aerobic digestion on subsequent sludge dewatering by centrifugal means with particular emphasis on the degree of digestion desired before centrifugation. Hopefully, the results of this study will show the practicality of centrifugation as a method of waste activated sludge dewatering following aerobic digestion.

II. LITERATURE REVIEW

Biological Aspects of Aerobic Digestion

Aerobic digestion as defined by Ritter (38) is aeration of waste activated sludge and primary sludge in a separate tank for a period of 15 to 30 days to oxidize organic matter. The general aerobic biological process can best be described by the basic equation (12):

$$\text{Organic Matter} + O_2 + NH_3 = \text{Sludge Cells} + CO_2 + H_2O$$

When there is just enough available food to keep the microorganisms alive, a so-called endogenous phase exists. As the oxidation of the organic load proceeds, food substrate is eventually depleted forcing the aerobic microorganisms to consume their own protoplasm to obtain the necessary energy for cell maintenance.

Cellular material has been characterized by the formula $C_5H_7O_2N$ (16). Using this formula as a base, Eckenfelder (13) reported the following biochemical reaction as one which exemplifies the endogenous oxidation of cell tissue:

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 - \Delta H$$

It should be pointed out, however, that only 75 to 80 percent of the cell tissue can be oxidized. The remaining 20 to 25 percent is composed of inert compounds and organic compounds that are not normally biodegradable (27).

Because aerobic digestion is such a relatively new method in the processing of sludge it has been used primarily in small plants, particularly extended aeration and contact stabilization units. However, as more reliable information on process kenetics and economics is developed, this process will probably gain widespread usage. Metcalf & Eddy Inc. (27) indicate there are many advantages for aerobic digestion as compared to anaerobic digestion. These are: (1) volatile-solids reduction approximately equal to that obtained anaerobically, (2) low BOD concentrations in supernatant liquor, (3) production of an odorless, humus-like, biologically stable end product that can be disposed of easily, (4) production of a sludge with excellent dewatering characteristics, (5) recovery of more of the basic fertilizer values in sludge, (6) fewer operational problems, and (7) lower capital cost. There are, however, two major disadvantages: (1) high power cost associated with supplying the required oxygen, and (2) methane (CH_4), a useful product, is not recovered as in anaerobic digestion.

Hopefully with more investigation of the aerobic stabilization process, it will become as acceptable as the anaerobic process. As yet, the design and operating parameters of the aerobic process are poorly understood and have not been investigated nearly as thoroughly as the anaerobic process. In addition, extremely little research has been compiled for aerobic digestion followed by dewatering by centrifugation. Following is a review of the available literature which will attempt to define the scope of the aerobic digestion process. Also included will be the results of other work in the area which may be pertinent to the methods used and results obtained from this investigation.

Aerobic Digestion and Dewatering of Waste Activated Sludge

Aerobic stabilization was first used by Randolphs and Heukelekian (40) as early as 1932, in a comparative study of the destruction of concentrated primary sludges by both anaerobic and aerobic means. Their results showed that under properly seeded conditions the rate of decomposition of volatile matter, fats, proteins, and biochemical oxygen demand (BOD_5) were similar for both stabilization processes. For unseeded material, the results were quite different. The rate of destruction was found to be much greater under aerobic conditions. After 35 days of operation, reductions in total nitrogen, volatile solids, and fats were found to be 30, 50 and 99 + percent respectively. They concluded that in the same period of time, the aerobic process gives a more thorough decomposition of organic matter than does the anaerobic process.

In 1950 Coackley (7) investigated the extent of aerobic stabilization possible for sludges previously subjected to anaerobic digestion. The sludges were aerated for periods up to 70 days and at temperatures ranging from 18°C to 37°C. No significant reduction in volatile solids or drainability was reported for the 18°C trial. However, the sludge that was aerobically digested at 37°C showed a significant volatile solids reduction (63 percent at 47 days) and good drainability beyond that obtained during anaerobic digestion.

The stability of the aerobically digested sludge was demonstrated by the fact that anaerobic digestion could not be initiated in the aerobically digested sludge. It was concluded that the elevated temperature allowed greater biological activity to take place.

Jepson and Klein (18) supported Coackley's findings by showing that both settling rates and final densities of mixed sludges could be improved by increasing the digestion temperature up to 21°C.

In 1956 Eckenfelder (14) reported on the oxidation of sludges originating from a variety of wastes. In his study, waste activated sludge that was aerated for seven days at 25°C showed a 48 percent decrease in the mixed liquor COD, a 38 percent decrease in the suspended solids, and a decrease of 13 percent in the volatile content of the sludge. Eckenfelder also reported the auto-oxidation rate of waste activated sludge at 25°C to be 10 to 12 percent per day of the volatile solids. He further concluded that after five days of aeration, first order kinetics were no longer approximated and the auto-oxidation rate decreased rapidly with increased aeration.

Murphy (29) in 1959 studied the effects of aeration on the filterability and settleability of sewage sludges. He used primary and waste activated sludges, mixed at a ratio of 1:1 by volume, and aerated the sludges for different periods of time at a temperature of 15°C. He concluded that the reduction of volatile solids with digestion time up to six days was not appreciable. He also found that excessively vigorous aeration caused a reduction in both filterability and settleability.

Kehr (23) studied the possibility of using aerobic digestion as an alternative to the anaerobic process. His results showed an incredible 77 percent reduction of the total matter when using biological sludge. Primary sludges aerobically digested led to a reduction of between 60 to 70 percent of the organic matter. Kehr concluded from this study that stabilization of bacterial sludge could occur within a three to five day period under batch-type aerobic conditions. From these results, Kehr recommended that the aerobic digestion process was more suitable for smaller communities serving a population of 5,000 to 10,000 because of the low cost of construction and simple operation.

Jaworski, Lawton, and Rohlich (19) also studied the aerobic digestion process using a mixture of primary and waste activated sludge. Their work was carried out over a period of 60 days with temperatures ranging from 15 to 25°C. They concluded that the reduction of volatile solids was a function of detention time and that, in general, greater reductions in volatile solids were obtained at higher temperatures of digestion. Their results showed a 21, 32, 41, and 46 percent reduction in volatile solids content of the sludge after 5, 10, 30, and 60 days detention time, respectively, when the digestion temperature was 15°C, and 24, 41, 44, and 46 percent reductions after 5, 10, 30, and 60 days detention, respectively, at a temperature of 35°C.

Barnhart (4) studied the application of aerobic digestion to industrial waste treatment. He concluded that the solids reductions obtained were comparable to anaerobic digestion performance. He also reported that temperatures below 20°C were significantly retardant to digestion and that the rate of solids degradation varied widely with different type sludges, but that 15 days of detention time was sufficient to accomplish acceptable digestion in all cases.

Lawton and Norman (24) in a three year study investigated aerobic digestion of waste activated sludge produced from a domestic waste comprised of one-third pretreated meat packing waste and two-thirds domestic sewage. They reported that the reduction of volatile solids was extremely good, (34-36 percent and 39-53 percent at 15 and 30 days, respectively, at a temperature of 20°C) as the detention time is extended up to and past 12 days. Their data indicated better volatile solids reduction at higher solids loading rates, and showed that increased temperatures of digestion result in increased volatile solids reduction within certain limits. They also observed that the drainability of the sludges digested for short period of times (5 days) was poorer than non-digested samples, but for digestion periods greater than 10 days, the drainability of the sludge was improved.

Malina and Burton's (25) data indicated that a greater breakdown of organic solids took place at higher loading rates. This is quite the opposite of the results of Jaworski, et al, (19) and Lawton and Norman (24) who indicated that the ideal loading rate for maximum solids reduction was 0.10 pounds V.S/day/ft^3. For loading rates of 0.10 lb V.S./day/ft^3 and 0.14 lb V.S./day/ft^3 the reduction of volatile solids was 33.3 and 43.2 percent respectively. These studies were conducted with waste activated sludge in units with a theoretical detention time of 15 days and at a temperature of 35°C. They further noted a 70-82 percent reduction of the supernatant chemical oxygen demand (COD) and a 45-48 percent reduction of the sludge.

Carpenter and Blasser (9) evaluated the aerobic digestion of waste activated sludge from a news and chip boardmill operation. Their results indicated that volatile solids reduction is influenced by temperature and also that the addition of nitrogen and phosphorous to nutrient deficient sludge such as boardmill waste sludge significantly increased the volatile solids reduction.

Viraraghavan (48) in his work with primary sludges concluded that no significant reduction of volatile matter occurred beyond 15 days. Four series of experiments for periods of 5, 10, 15, and 20 days were performed with reductions of 25, 31.7, 37.5 and 38.5 percent in volatile matter respectfully.

Irgen and Halvorson (17) reported that treatment by the aerobic process produced a near nutrient free supernatant. Supernatant BOD_5 and COD reductions ranging from 83 to 87 percent and 45 to 69 percent respectively, were noted. The overall process was accomplished in a detention time not exceeding 20 days, and at temperatures ranging between 23° to 30°C.

Randall, Saunders, and King (37) reported good suspended solids reduction during aerobic digestion with increased detention time. However, unlike previous results they obtained considerable solids reduction after 15 days of aeration. They further concluded that, although it may do so, aerobic digestion does not necessarily improve the drainage characteristics of waste activated sludge. Drainage may be retarded by large amounts of fibrous material and some types of microorganisms. Drainability of aerobically digested sludge was found to be closely related to sludge activity as measured by oxygen utilization.

Randall and Koch (36), using six different sludges from contact stabilization facilities, did extensive research in the area of sludge dewatering. Their results indicated that sludges obtained from digesters where the dissolved oxygen (DO) concentration was maintained at less than 1.0 mg/l dewatered poorly. The results further showed that a successful technique for improving the drainability of aerobically digested activated sludge is to extend the aeration period. This was true only when the sludge was poorly conditioned initially.

Turpin (43) studied three different activated sludge wastes to relate process parameters and cellular parameters to sludge drainability. His results 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 can be accomplished over a wide pH range and that higher solids reductions occur with sludges having a higher percent of volatile solids. However, the percent of volatile matter showed little change during aerobic digestion. Detention times of up to 30 days continued to show significant solids reductions.

Parker, Randall, and King (35) reported that the filtration characteristics of an aerobically stabilized biological sludge are a function of the degree of flocculation of that sludge. They further concluded that the filtration improvement which they obtained was the result of biologically induced flocculation. When conditions for biological activity were good and the food to microorganism ratio (F:M) was low enough to promote endogenous respiration, the sludge filterability improved. They also reported that filterability can be adversely affected by anaerobic storage, excessive mixing, chlorination, and rapid changes in temperature.

Rivera-Cordero (39) investigated the effects of aerobic digestion on activated sludge dewatering and attempted to define which factors are responsible for changes in dewatering characteristics. Three different types of sludges were used to obtain results that would be applicable in as many actual cases as possible. The sludges were digested in a batch reactor at 20°C. He concluded that aerobic digestion affects both the specific resistance and the compressibility factor. Also that the specific resistance decreased with aeration time, reaching a minimum value after one to five days and then increasing with further aeration to values exceeding that of the original sludge. He further showed that the filtration characteristics of activated sludge are affected by biological, chemical, and physical changes during aerobic digestion. Changes in exocellular polymer concentration and in pH were found to be the most important factors affecting the filtration characteristics.

Centrifugation

With our nation growing so rapidly, land has become a scarce item, particularly in metropolitan areas. It is for this reason that the sanitary engineer must provide other alternatives, aside from sand drying beds, for the dewatering of wastewater treatment plant sludges. One method that is gaining considerable acceptance is that of centrifugation.

The first use of the centrifuge for sludge handling (1) was reported in Cologne, Germany in 1902. In 1907 the centrifuge was being used in several more European countries, and in 1920 it made its American debut in Milwaukee, Wisconsin. These early centrifuges were all perforated basket type centrifuges, and they proved to be very inadequate for the dewatering of domestic sewage. Not until 1954 with the development of a solid-bowl conveyor centrifuge did centrifugation gain acceptance as a technique for the dewatering of wastewater sludges.

Basically there are three different types of centrifuges: the basket centrifuge (perforated and imperforated), the disc centrifuge, and the solid-bowl conveyor centrifuge (conical, cylindrical, and conical and cylindrical) (1). Each of the different types has its own application and in most instances is used accordingly.

The perforated basket centrifuge has its main application in handling uniform coarse solids at high slurry concentrations. It is usually employed where the treatment requires a washed and/or dry product. For this reason and the fact that it is dependent on filtration for separation it is very seldom used for sewage sludges. The imperforate basket is used most often when working with dilute concentrations of fines because of its ability to produce good clarification of fine solids (20). The separation of solids in this type model is brought about by sedimentation against an imperforated surface, under the influence of a centrifugal field, generally in the range of 1,000 to 6,000 times the force of gravity. With the imperforated basket centrifuge clarification takes place in a quiescent zone, undisturbed by moving elements such as a conveyor, and, in general, recovery is good for all types and sizes of particles. The major disadvantage in using the basket model is that it does not have facilities for continuous discharge of the collected cake, and for this reason interruption of the feed for cake discharge is essential (22).

The disc centrifuge, more commonly referred to as the disc nozzle, has a wide variety of applications. Units of this design often are used to make liquid-solid, liquid-liquid, and liquid-liquid-solid separations. The design of this centrifuge permits it to capture and to polish slurries containing very fine solids. The high G force available makes this an excellent clarifying unit. However, the disc centrifuge is not a good dewatering unit. Clarification, thickening, emulsion breaking and some washing and fines classification are all prime functions of this type of centrifuge. Because of its design characteristics, the disc centrifuge is used primarily for the thickening of wastewater sludges (1).

The third type is the solid-bowl conveyor centrifuge, which is a good compromise of the best features of the other types of centrifuge. It can be an excellent classifier and dewatering unit or a good clarifier, despite its lower centrifugal force. Just as important, it is a continuous unit requiring very little operator attendance (2).

In evaluating the performance of a centrifuge there are two major items the engineer evaluates, the solid concentration of the cake, usually expressed as a percent, and the percent recovery obtained by the centrifuge. Percent recovery (n) can be calculated from the following equation (53):

$$n = \frac{Cs\ (Ci - Cf)}{Ci\ (Cs - Cf)}$$

Cs = Dry solids concentration in the cake

Ci = Dry solids concentration in the feed

Cf = Dry solids concentration in the centrate

These two items indicate to the operator how the centrifuge is performing.

In tests run by Albertson and Guidi (1) using all three basic models they concluded; (1) While the perforated basket was very good for dewatering, poor clarification and substantial loss of solids occurred, (2) the imperforated basket could not produce dry cakes, although good clarification could be used, and (3) the disc machine when used primarily for thickening activated sludge, created serious objections because of continued plugging problems. Since the objective of a centrifugal dewatering unit is to produce a well dewatered cake and a clarified liquor, Albertson and Guidi concluded that both the basket and disc machine had obvious disadvantages.

Most of the literature dealing with centrifugation of wastewater treatment sludges is in reference to solid-bowl conveyor centrifuges. When trying to optimize the dewatering performance of a centrifuge two types of variables must be considered. They are machine and process variables. The machine variables can be classified as: (1) bowl design (length to diameter ratio, and bowl angle), (2) bowl speed, (3) pool volume (distance from liquid surface to bowl wall) (26), and (4) conveyor speed. The process variables can be classified as: (1) feed rate, (2) solids characteristics (particle size and density), (3) feed consistency, (4) temperature, and (5) chemical aids. Investigations by Vesilind (45), however, indicate that the above list can be reduced considerably. In fact, Vesilind's work indicates that for basic information only one process and one machine variable are necessary. They are the feed rate and bowl speed, respectively. All the other variables, according to Vesilind, are "fine tuning" variables that must be considered in the final selection, but from the approach of trying to predict results from a prototype or laboratory model the above mentioned variables are the only two required. This simplifies matters considerably and Vesilind's (46) results indicate that the difference between predicted and actual performance is within plus or minus 10 percent.

In Mill Valley, Claifornia (5), population 14,000, a solid-bowl centrifuge is being used to dewater 10,000 gallons of domestic sewage weekly. The unit operates 5 hours weekly, at a rate of 32 gallons per minute (gpm), and produces 5 cubic yards of cake with 23 percent solids concentration. A four run test showed that the centrifuge produced 920 pounds of dry solids per hour, recovering up to 98 percent of the suspended solids when using a flocculant. The feed concentration averages 5 to 6 percent and centrate solids 0.1 to 0.2 percent. The sludge cake is taken to a landfill, and the centrate is discharged to a drying bed and stored as a soil conditioner.

In a study for Charmin Paper Products Company, Woodruff, et al. (51), demonstrated the effectiveness of using two different model centrifuges in series. Since thickening of sludge by a gravity thickener proved to be inadequate, a disk-type nozzle centrifuge followed by a solids-bowl centrifuge was tried. Both machines were first operated independently, with the disk-nozzle model obtaining between 4 and 10 percent suspended solids concentration and the solid-bowl centrifuge producing a very wet and unacceptable cake. However, using the two models in series, with the disk-nozzle centrifuge being used for thickening and the solid bowl being used for dewatering, a cake containing 22 percent solids was obtained. Woodruff and his colleagues concluded that using the two stage operation would reduce the required throughput and would significantly increase the solids removal efficiency.

Zeper and Pepping's (52) investigation also involved the use of two centrifuges operated in series. Like Woodruff, et al. (51), a disk nozzle centrifuge, primarily used for thickening, followed by a solid bowl centrifuge used for dewatering, was used during the testing. Sludge for this investigation was obtained from an oxidation ditch process, with results showing a 35 percent recovery. Additional tests using a flocculation agent (3 gr./kg. dry feed solids) showed a remarkable improvement in the percent recovery, with 70 percent recovery being obtained.

Secondary effects of the centrifuges on the wastewater system were also determined and found to be insignificant in comparison to the influent load. The BOD_5 load of the centrate was only one percent of the organic load of the wastewater treatment plant. Zeper and Pepping concluded that the dewatering of solids from an oxidation ditch process was feasible by centrifugation. The optimum rates obtained during the testing period showed a feed rate of approximately 22 gpm with an influent feed of four percent dry solids content and a flocculant dosage of 5 gr./kg. of dry feed solids. With these rates and dosages they were able to obtain 90 percent recovery.

Moffett (26), in working with pharmaceutical waste found centrifugation to be an acceptable method of dewatering digested sludge. Sludge was withdrawn from two thickeners following anaerobic digestion and was fed to a solid-bowl conveyor centrifuge at a rate of 20 gpm. A cake with 7 percent solids and having the consistency of peanut butter was obtained.

Wheatland (49), using a disc-nozzle centrifuge attempted to separate activated sludge from mixed liquor for recycle to an aeration tank. His results showed that this was not a very feasible method. The centrate had both a higher turbidity and a higher BOD_5 than supernatant liquid obtained by settlement. Furthermore, the condition of the separated activated sludge was very different from that obtained by settlement. Wheatland postulated that this change had been induced by the intense shearing forces and that the sludge appeared to have become homogenized. If sludge in this condition were returned to an aeration tank it seems likely that a steady deterioration of the system would be imminent.

Vaughn and Reitwiesner (44) also investigated the possibility of thickening sludge using a disc-nozzle centrifuge. Their results indicated that the centrifuge was capable of thickening dilue waste streams to concentrations of four to six percent total solids (TS) with satisfactory solids recoveries. One interesting fact pointed out in Vaughn's and Reitwiesner's work is that sludges from an aerobic digester and from a water treatment plant using chemical coagulation, were the hardest to dewater.

In 1967, Albertson and Sherwood (2) tested the new long-bowl centrifuge (same as solid-bowl conveyor model, with the exception of a larger length to diameter ratio) which provides a greater pool capacity, giving more clarification capacity. They tested two different types of sludges, primary, and primary and waste activated sludge mixed, and obtained good results. With the primary they obtained a cake with 28 to 35 percent total solids and obtained 85 to 90 and 95+ percent recovery without and with flocculant addition, respectively. The primary and waste activated sludge mixture provided a cake with 18 to 24 percent total solids and a percent recovery of 60 to 80 and 95+ without and with flocculant addition, respectively. In another series of tests conducted at over 70 locations throughout the United States, Albertson and Guidi (1) investigated the optimum machine performance on four basic type sludges. The sludges used were: (1) raw primary and secondary sludges, (2) digested primary and secondary sludges, (3) pulp and paper wastes, and, (4) water-softening sludges. Their investigation revealed good cake solids ranging in concentration from 18 to 35 percent. Good recovery was also obtained, and it increased markedly with the addition of chemical flocculants. One result worth noting is that both the cake solids concentration and the percent recovery were less when digested sludges were used instead of raw sludges.

As is evident from the literature, solid-bowl conveyor centrifuges are used more, by far, than any other model. Vesilind (45) feels that there are five distinct processes that occur in the solid-bowl centrifuge which would explain its superiority. The first process is one in which the solids settle at a constant rate and exhibit zone settling characteristics. In the second process the sludge-liquid interface begins to slow down and compression of the sludge occurs. The third phase is simply horizontal movement of the material in the cylinder, followed by the fourth process which is horizontal movement of the material in the cone. The last process is the most important and it determines the degree of moisture in the sludge cake, it is drainage of the sludge on the beach (unsubmerged part of the machine through which the separated solids move to the discharge end). If in fact all processes do occur, which is probably the case, then the engineer must describe in detail what is occurring in each process and develop each phase more thoroughly to provide better dewatering of sludges by the solid-bowl conveyor centrifuge.

Keith and Little (21), however, report that the basket centrifuge, particularly the imperforated basket, offers a suitable alternative to the solid-bowl model. As mentioned earlier, as solids accumulate in the basket, clarification is impeded and the effluent becomes dirty. It is then necessary to stop the feed and remove the cake from the bowl. If the solids are soft and plastic in nature, the majority will flow up the bowl wall where a skimming device can remove them at full speed. When the solids are coarse and abrasive, it is customary to slow down the bowl and cut out the solids with a knife, dropping them through the open bottom of the basket. The basket unit with skimmer and knife is particularly adaptable to changes in the quality of feed solids including both the soft solids and silty heel produced by most activated sludge processes.

While the basket centrifuge also has a tendency to break flocs, its slower speed reduces this effect so recoveries are generally very good with no coagulant. Since there is minimum disturbance during deposition, Keith and Little's investigations showed that it is usual for the cake discharge by skimmer from the basket centrifuge to have a higher average concentration than that achieved in the conveyor centrifuge at equivalent recoveries.

O'Donnell and Keith (33) have demonstrated, even with difficult sludges such as waste activated sludge or water treatment alum sludge, that 90 and frequently 95 percent recovery are possible without a coagulant.

As can be seen from the literature, centrifugation is gaining acceptance as a technique for thickening and dewatering wastewater sludges. Small space requirements, high capacities, rapid processing, and in most instances a continuous operation, make centrifugation a desirable alternative in handling wastewater sludges.

III. METHODS AND MATERIALS

In an effort to show that centrifugation followed by aerobic digestion is a suitable method of sludge handling, two runs with two individual batch-fed digesters, followed by sludge centrifugation at selected intervals, were completed. Approximately 40 and 45 gallons of sludge was subjected to aeration in the first and second runs, respectively. Two sludges were used, both being waste activated, and they were digested for 15 days and 14 days respectively. The effect of aerobic digestion of the waste activated sludges on subsequent centrifugation was the primary concern of this investigation.

The digestion process was conducted in a room temperature environment with temperatures ranging from 23°C to 27°C. No attempt was made to control any digestion parameters. However, additions of tap water to the units were required to compensate for losses in digester volume due to evaporation. The only restrictions placed upon the air supply were (1) a minimum of 2.0 mg/l dissolved oxygen and (2) suspension of all solids in the digester at all times. No chemical additions to adjust pH or improve centrifugation or sludge filterability were made.

Experimental Apparatus

Two separate aeration chambers were used during this investigation. Both were metal barrels, 22.5 inches in diameter and 34 inches high. Although the capacity of each digester was 55 gallons

(208 liters), only a maximum of 45 gallons (170 liters) of sludge was digested in order to allow some freeboard. None of the aeration chambers were equipped with sampling spouts, therefore, all samples were obtained either by dipping with a bucket, for centrifugation tests, or a laddle comprised of a 100 ml flask attached to a piece of copper tubing for all other tests.

Air was dispersed into the digestion unit through a perforated ring of copper tubing positioned approximately one inch above the bottom of the aeration unit. A sketch of the digestion unit is shown in Figure 1.

Centrifugation of the aerobically digested sludge was accomplished through the use of a Sharples Mark III/Fletcher SludgePack centrifuge (a prototype model). The centrifuge basket had a volume of 0.535 cubic feet and was capable of obtaining a speed of 3000 revolutions per minute (rpm), thereby simulating a force of 1500 G's. Photographs of the centrifuge are shown in Figures 2 and 3.

Procurement and Handling of Sludge

Two different waste activated sludges were used in this investigation. One sludge came from the Roanoke, Virginia sewage treatment plant which uses the conventional activated sludge process. This plant has a designed flow of 22.0 million gallons per day (MGD) and treats a mixture of domestic and industrial wastes. The sludge samples collected for both runs were collected at a sampling valve on the line running from the thickener to the primary digesters. Each

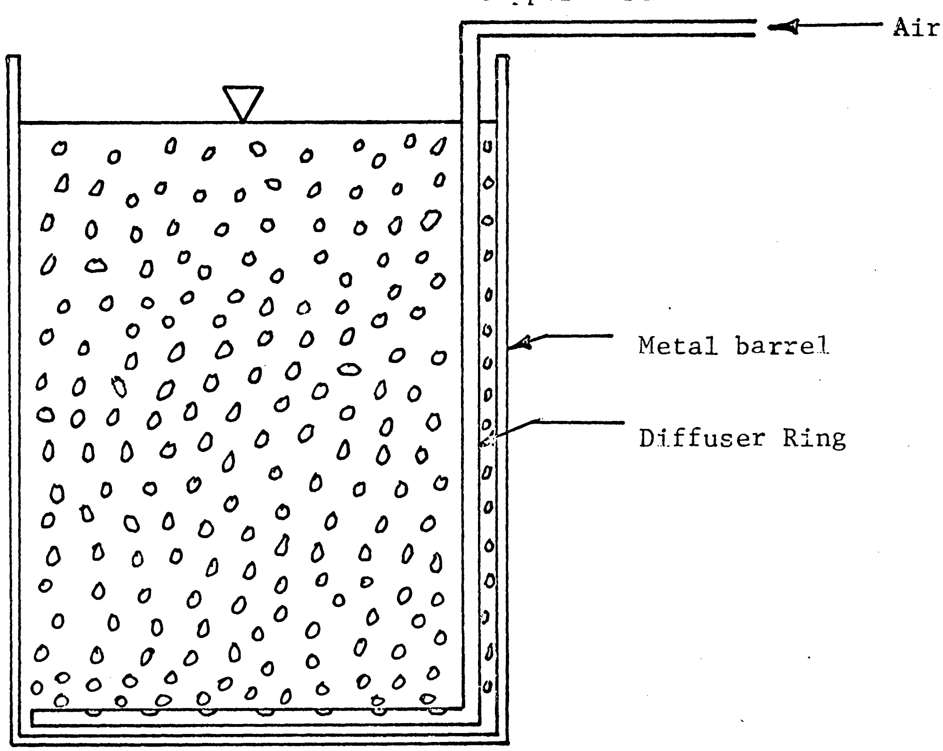

FIGURE 1. AEROBIC DIGESTION APPARATUS

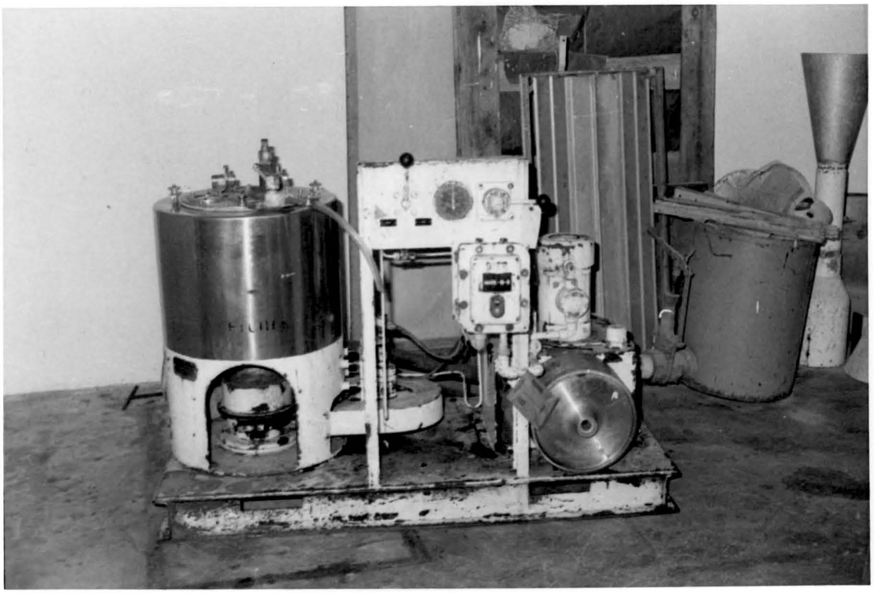

FIGURE 2. PHOTOGRAPH OF MARK III/FLETCHER SLUDGEPACK CENTRIFUGE

FIGURE 3. PHOTOGRAPH OF THE BASKET OF THE SLUDGEPACK CENTRIFUGE

of the two samples consisted of a mixture of primary and waste activated sludges. The other sludge was obtained from a small extended aeration plant located at the Blacksburg Corning Glass Plant. This plant treats a domestic waste flow of approximately 12,000 gallons per day. The plant has a comminuter but no primary settling. Aeration is by means of four diffused aerators and the sludge is recycled to the aeration tank from the final settling tank by two air lift pumps. The sludge samples were collected at the outlet of the return sludge line. This plant is normally operated as to maintain a pH of about 7.0 in the aeration tank. For this purpose, about five pounds of hydrated lime are added every five days to the aeration tank.

The Corning sludge for both runs was allowed to settle and supernatant was decanted to increase solids concentrations. The Roanoke sludge had such high solids concentration that for the first run no alteration of the solids concentration was necessary. In the second run, it was decided to operate at a lower solids concentration, therefore, the Roanoke thickened sludge was diluted by adding tap water at approximately a three to one ratio. After concentration or dilution, each of the sludges was thoroughly mixed prior to aeration. In no instance did the elapsed time between procurement of the sample and the start of aeration exceed six hours. The initial solids concentrations and percent volatility for each sludge is shown in Table 1.

Sampling Procedure

On days of sludge analysis, aeration was discontinued,

TABLE I

INITIAL SOLIDS CONCENTRATIONS AND VOLATILITY

Run No.	Type of Sludge Digested	Total Suspended Solids (mg/l)	Percent Volatility
1	Corning	15,965	65.2
1	Roanoke	27,600	71.0
2	Corning	11,887	67.4
2	Roanoke	10,813	65.8

the digester walls were scraped, and water added to compensate for any evaporation losses. Aeration was restarted to thoroughly mix the digester contents and samples were taken. The first sample was of sufficient volume (5 gallons from each digester) to perform the centrifugation test. The second sample was obtained to perform all the required analytical tests. After completion of the analytical tests all unused sludge was returned to the digester and the new digester volume was marked.

A sampling and testing schedule for sludge analysis was established with testing being done on days 1, 3, 5, 7, 10, 12, and 15 of digestion for run number one, and days 0, 1, 2, 3, 5, 7, 10, 12, and 14 of digestion for run number two.

Analytical Procedure

The following methods were used to analyze the mixed liquor and supernatant samples from the aerobic digesters, and the centrate from the centrifuge.

1. Suspended Solids

Total and volatile suspended solids were determined using Gooch crucibles with glass fiber filters (Reeves-Angel, 2.1 cm). The filters were placed in the crucible rough side up and seated with distilled water over a vacuum. Crucibles and filters were then dried at 103°C for a minimum of 20 minutes, fired in a muffle furnace at 600°C for thirty minutes, cooled in a desiccator for a minimum of one hour, following which the tare weights were recorded. 10 ml. of sample were poured into each crucible, filtration being aided by a vacuum pump. After filtration the crucibles and samples were dried at 103°C for 24 hours, cooled and desiccated for a minimum of one hour and weighed. They were then ignited at 600°C in a muffle furnace for 20 to 30 minutes, cooled and desiccated for approximately two hours, and the final weights recorded. All solids determinates were run in triplicates to insure the validity of the results obtained. An average of the results from these three samples was considered to be the actual solids concentration. However, if one sample differed considerably from the others, it was rejected and the average value was calculated from the remaining data.

2. Total Solids

Total solids concentrations were determined for the sludge cake obtained from the centrifuge. Evaporating dishes were dried at 103°C for a minimum of one hour, cooled in a desiccator for one hour, following which the tare weights were recorded. An unknown amount of sample was placed in the dish and the weight was recorded. All solids determinations, like the suspended solids test, were run in triplicate to insure the validity of the results obtained. Following the weighing the dish plus sample were then dried at 103°C for a minimum of 24 hours, cooled and desiccated for a minimum of one hour and weighed. The solids concentrations were then determined as a percentage by using the formula:

$$\%\text{solids} = \frac{\text{total weight} - \text{dry weight}}{\text{total weight}} \times 100$$

and then converted to a weight per volume form (mg/l).

3. pH

Mixed liquor and both supernatant and centrate pH values were determined for both runs. A Fisher model 120 pH meter was used to obtain this data. Prior to each determination, the pH meter was calibrated with a standard buffer solution.

4. BOD_5

BOD_5 was measured on the centrate and supernatant from the filterability test for both runs in accordance with the procedures outlined in Standard Methods (42). BOD_5 dilutions changed throughout each run for both sludges. Dissolved oxygen determinations for this analysis were made using a Yellow Springs Instrument Model 54 Dissolved Oxygen Meter equipped with a Clark type membrane covered polargraphic probe.

5. COD

COD was measured on the centrate and the supernatant obtained from the filterability test. The COD determination was performed according to the procedures outlined in Standard Methods (42). Sample sizes varied from 1 ml to 20 ml depending on the solids content.

6. Oxygen Uptake

The oxygen uptake rates were measured for the sludges in both runs. A 400 ml sample was taken from the digester, placed in a 1500 ml beaker, and sparged with air for approximately five minutes. After this procedure a standard BOD bottle was filled with sludge and fitted with the dissolved oxygen metering equipment previously described. After the oxygen meter was allowed to stabilize, an initial dissolved oxygen content was noted. The oxygen content of the sludge was then periodically noted, with the frequency of observation being a function of the relative rate of oxygen utilization. The slope of the best straight-line fit for the plot of oxygen utilization versus time was considered to be the oxygen uptake rate for that particular sample.

7. Sludge Settleability

Sludge settleability was measured by filling a 100 ml graduated cylinder to the 100 ml mark with mixed liquor from each digester and recording the supernatant appearing at 5, 10, 15, 20, 30, and 60 minutes. The reasons the test was performed in this manner were that sludge volume index (SVI) is not useful for digested sludges since it measures settling after 30 minute settling time, which is much too short for thick sludges and because only a relative comparison of settleability during digestion was desired. When sufficient data had been collected, the sludge samples were returned to their respective digesters. Settleability readings were plotted as ml of supernatant appearing per 100 ml of mixed liquor.

8. Filterability

The filterability of the digested sludges was evaluated using the concept of specific resistance developed by Coackley and Jones (8). The filtration apparatus consisted of a 7.0 cm diameter Buchner funnel fitted with a 7 cm piece of #4 ashless, Whatman filter paper. The stem of the funnel extended through a rubber stopper into the top of a 100 ml plastic graduated cylinder. Through this stopper was also placed a piece of metal tubing which connected to a length of rubber tubing leading to a mercury manometer and a vacuum pump. A pinch clamp was used to seal the vacuum system ahead of the funnel apparatus (52). Manipulation of an adjustable hose clamp was used to produce the desired filtration pressure differential, as observed from the mercury manometer.

The filtration test was conducted in the following manner:

(1) The vacuum pressure was adjusted to the desired level. For this investigation a 12.0 inch mercury differential was used.

(2) A 20 ml volume of distilled water was filtered through the apparatus to insure proper setting of the filter paper.

(3) The vacuum was again checked.

(4) 100 ml of sample was placed in the funnel.

(5) The pinch clamp was slowly opened thus applying a vacuum.

(6) The time intervals in which a specified volume of filtrate was obtained were recorded. For this investigation the time it took to collect 50 ml of filtrate at 5 ml intervals was recorded.

Substituting the data obtained into Coakley and Jones' equation (8), the specific resistance of the sludge to filtration was calculated.

The equation is

$$r = \frac{2PA^2n}{u\ c}$$

where: r = specific resistance, cm/gr x 100 = m/kg

P = applied filter pressure, g (force)/cm^2

A = filter area, cm^2

u = viscosity of filtrate, poises

c = suspended solids concentration, g/ml

n = slope of the plot T/V vs. V, sec/ml^2

During the testing, the viscosity of the filtrate was assumed to be equal to that of water at the same temperature, which was room temperature (approximately 30°C). The slope of the plot of T/V (time/filtrate volume) vs. V (filtrate volume) was determined from the best straight-line fit of the plot.

9. Centrifugation

As previously mentioned a Mark III/Fletcher SludgePack imperforated basket centrifuge was used for this test. It was the intention of this investigation to see how aerobic digestion influenced centrifugation. During the testing all variables that might alter the centrifugation results, were kept constant. These included bowl speed, 2650 rpm, feed rate, approximately 1.25 gpm, and detention time, 5 minutes over all.

The centrifugation test was conducted in the following manner:

(1) The machine was turned on and set at a speed of

2650 rpm and allowed to reach this rate.

(2) A 5 gallon sample of sludge was taken from the aeration unit.

(3) The machine speed was checked to insure the proper setting.

(4) The sample was fed to the centrifuge at a rate of approximately 1.25 gpm.

(5) The centrate was collected in a galvanized tub, and the cake in the centrifuge basket.

After obtaining solids data for the feed, cake, and centrate, the percent recovery was calculated from an equation previously cited. A review of this equation shows that

$$n = \frac{Cs(Ci - Cf)}{Ci(Cs - Cf)}$$

where: n = percent recovery

Cs = Dry solids concentration in the cake

Ci = Dry solids concentration in the feed

Cf = Dry solids concentration in the centrate

During this investigation in the calculation of percent recovery, total suspended solids were used for both the feed and the centrate with total solids being used for the sludge cake. Tests showed, however, that very little (less than 0.1 percent) dissolved solids were present in both the feed and centrate, so very little error, if any, occurred from this calculation expedience.

IV. EXPERIMENTAL RESULTS

The experimental results obtained during the course of this study are presented and briefly discussed in this chapter. The data is presented primarily in graphical form. Each of the parameters studied is discussed individually with regard to observations during the two digestion runs. It should be noted that no initial sample data was obtained for run #1.

Suspended Solids

Total and volatile suspended solids variations observed during the two digestion runs are shown in Figures 4 through 7, respectively. The rate of solids destruction for run #1 is quite similar for the two sludges, although they have different solids concentrations. For run #2 the rate of solids destruction is somewhat erratic with the solids concentration decreasing at first and then increasing and decreasing at an unpredictable rate. However, there was a good overall rate of destruction. The overall behavior of the solids for run #2, has been experienced before, but never to such an extensive degree, (28,32). The volatile suspended solids followed the same pattern for both runs indicating that the percent volatility is fairly constant for batch digested waste activated sludges, verifying the results of Randall and Koch (36). The large variation in both the total suspended and volatile solids for digestion run #2 has been explained by Moore (28) to be due to the unstabilized nature of the sludge at the time of sampling. The author feels that due to the consistency of the variation that

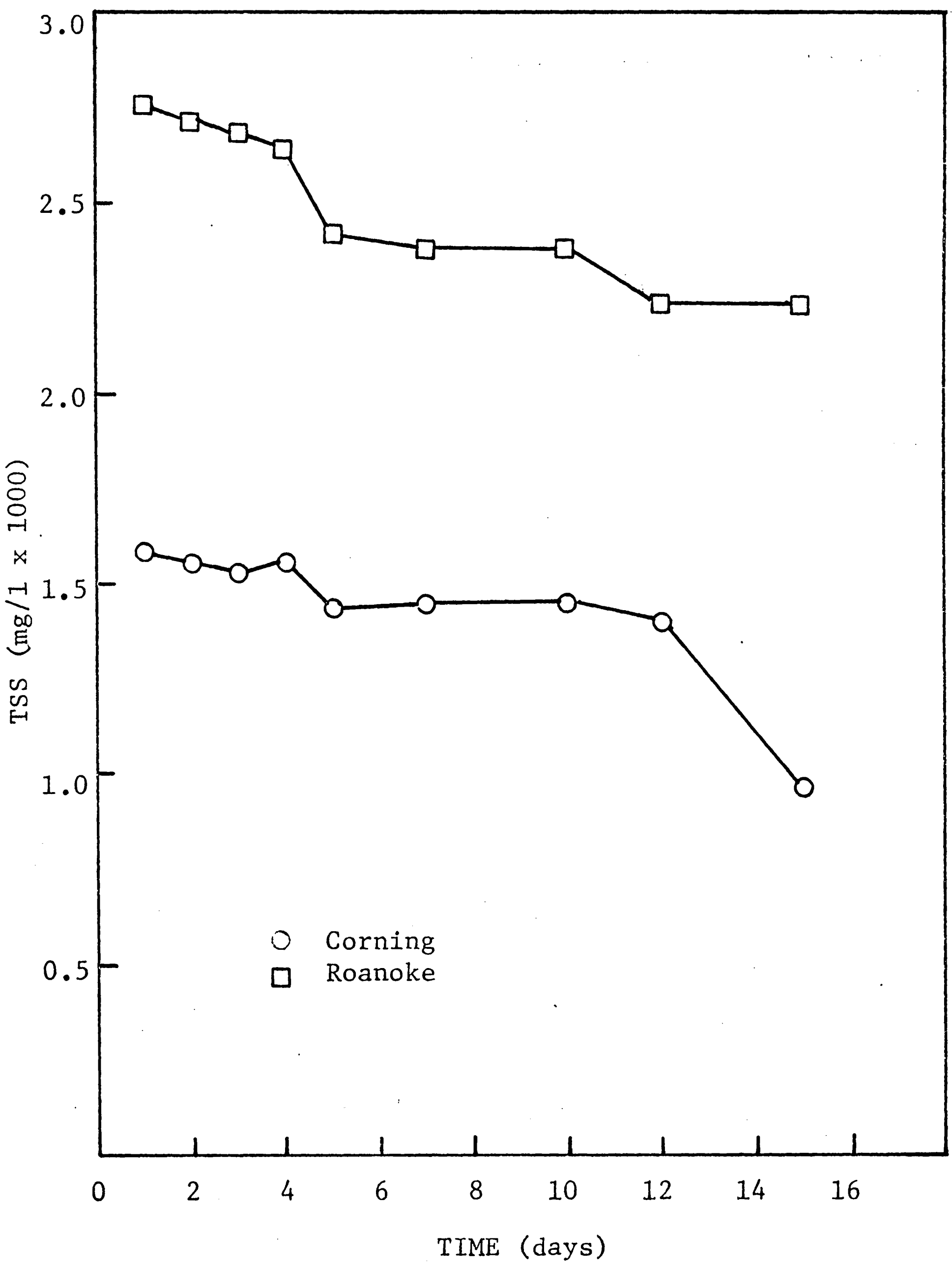

FIGURE 4. TOTAL SUSPENDED SOLIDS VARIATION FOR DIGESTION RUN 1

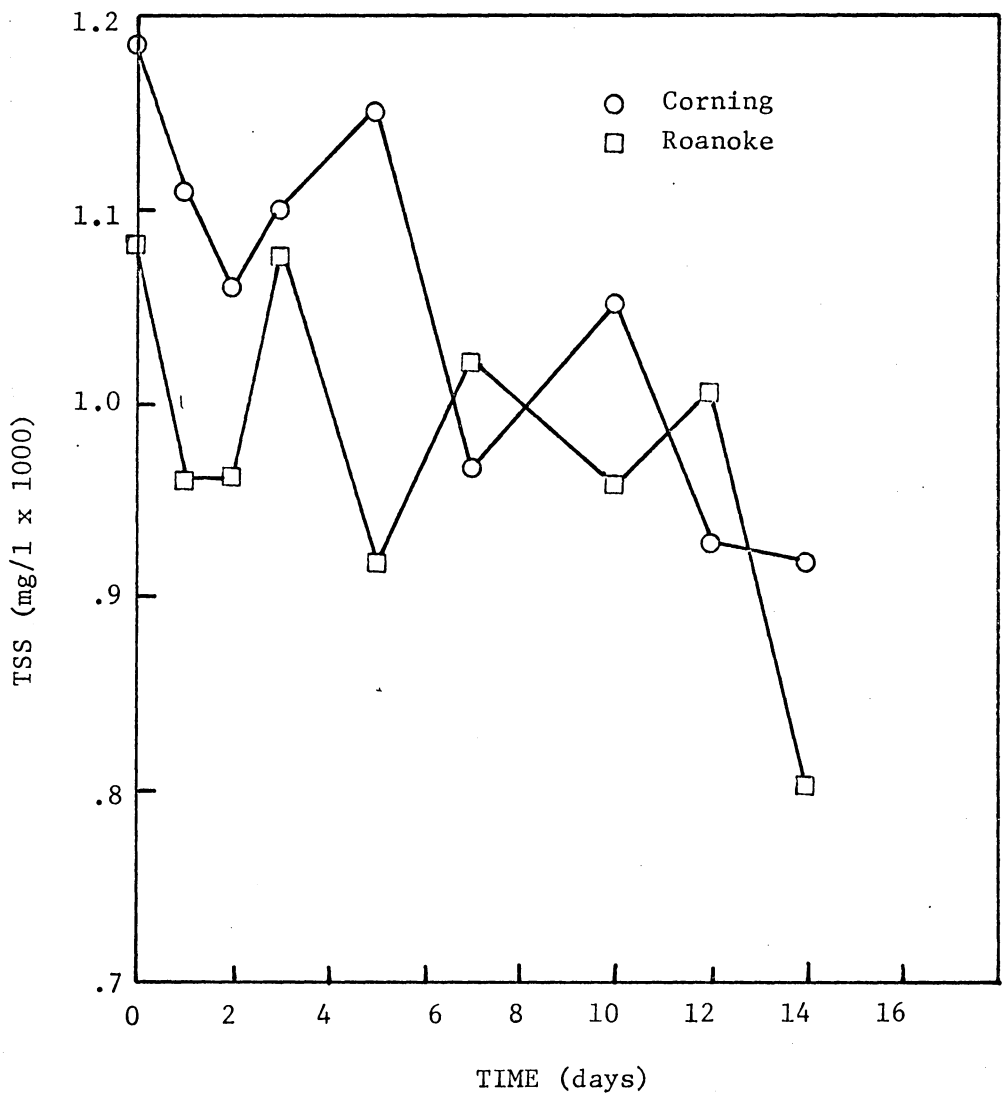

FIGURE 5. TOTAL SUSPENDED SOLIDS VARIATION FOR DIGESTION RUN 2.

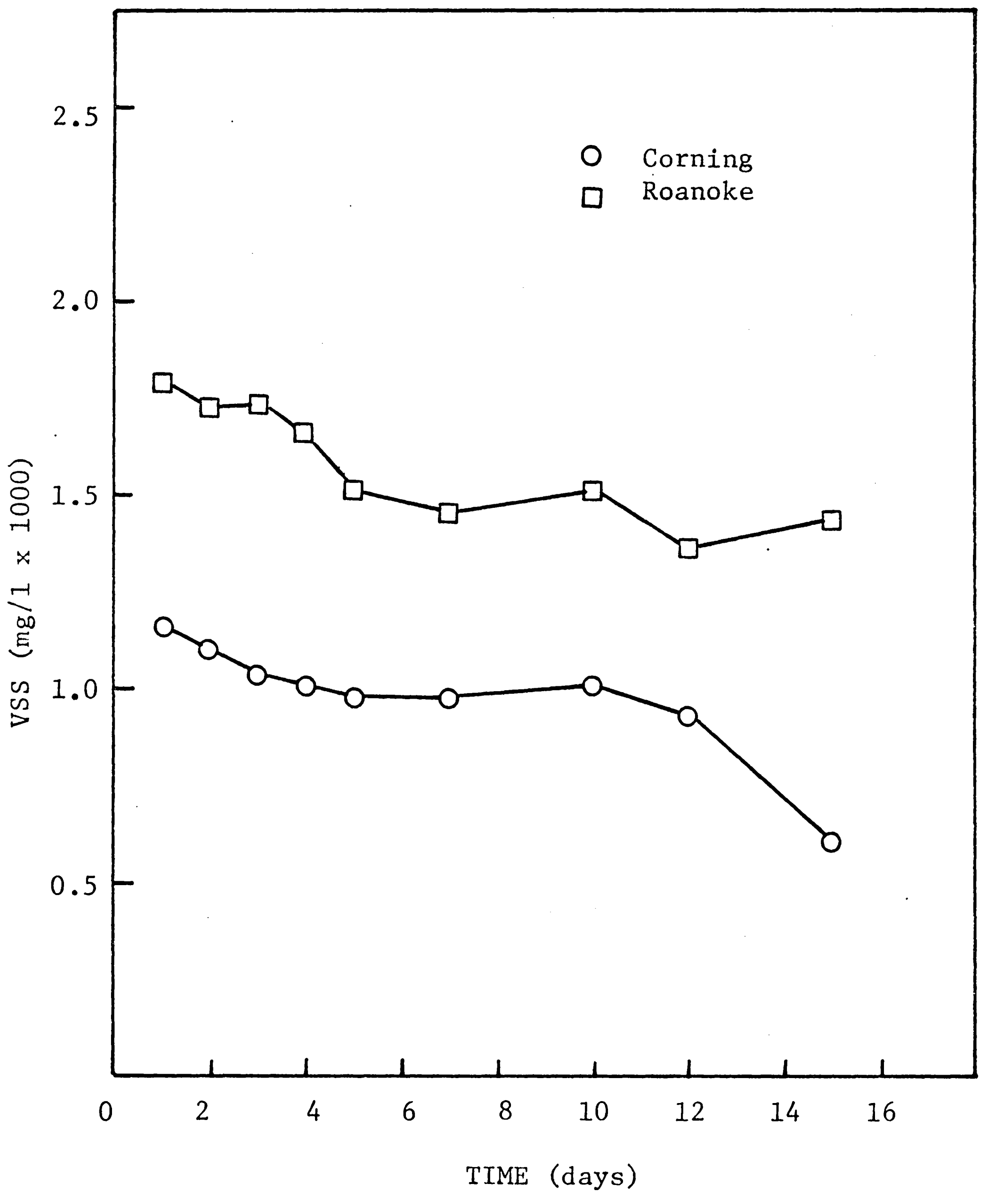

FIGURE 6. VOLATILE SUSPENDED SOLIDS VARIATION FOR DIGESTION RUN 1

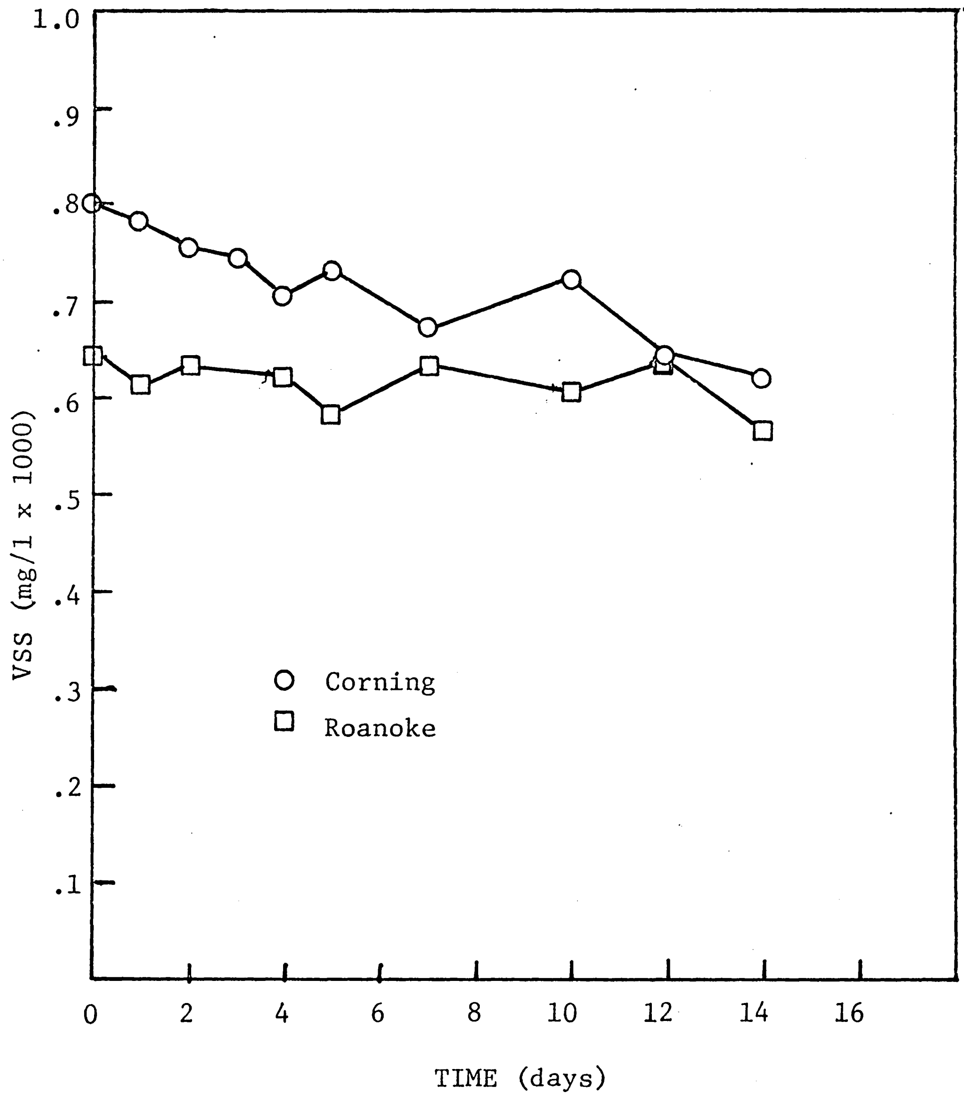

FIGURE 7. VOLATILE SUSPENDED SOLIDS VARIATION FOR DIGESTION RUN 2.

experimental error is not an acceptable explanation.

The percentage of both total suspended and volatile solids reductions are presented in Figure 8 through 11 respectively. Again as in solids destruction, the curves are very similar with the greatest reductions occurring after the tenth day of digestion. Total suspended solids reductions of 19 and 35 percent with corresponding volatile suspended solids reductions of 20 and 46 percent for the Roanoke and Corning sludge, respectively, were obtained during run #1. During run #2, which was run at a lower solids concentration, a total suspended solids reductions of 22.5 and 23 percent with volatile suspended solids reductions of 24 and 21 percent for the, Roanoke and Corning, sludges, respectively, were recorded. A possible trend that might be concluded from the percent reduction data, is that the percent reduction of both total suspended and volatile suspended solids is almost identical when the initial solids concentrations are similar and that the higher the initial solids concentration the greater the percent reduction.

pH

The variations in mixed liquor, supernatant, and centrate pH observed during the two runs are shown in Figures 12 and 13. The data indicate that the difference between the mixed liquor, supernatant, and centrate pH were minimal throughout the digestion period. As might be expected from previous investigator reports, an initial increase in pH was observed for all sludges upon aeration. The magnitudes varied from 0.2 to 0.9 pH units,

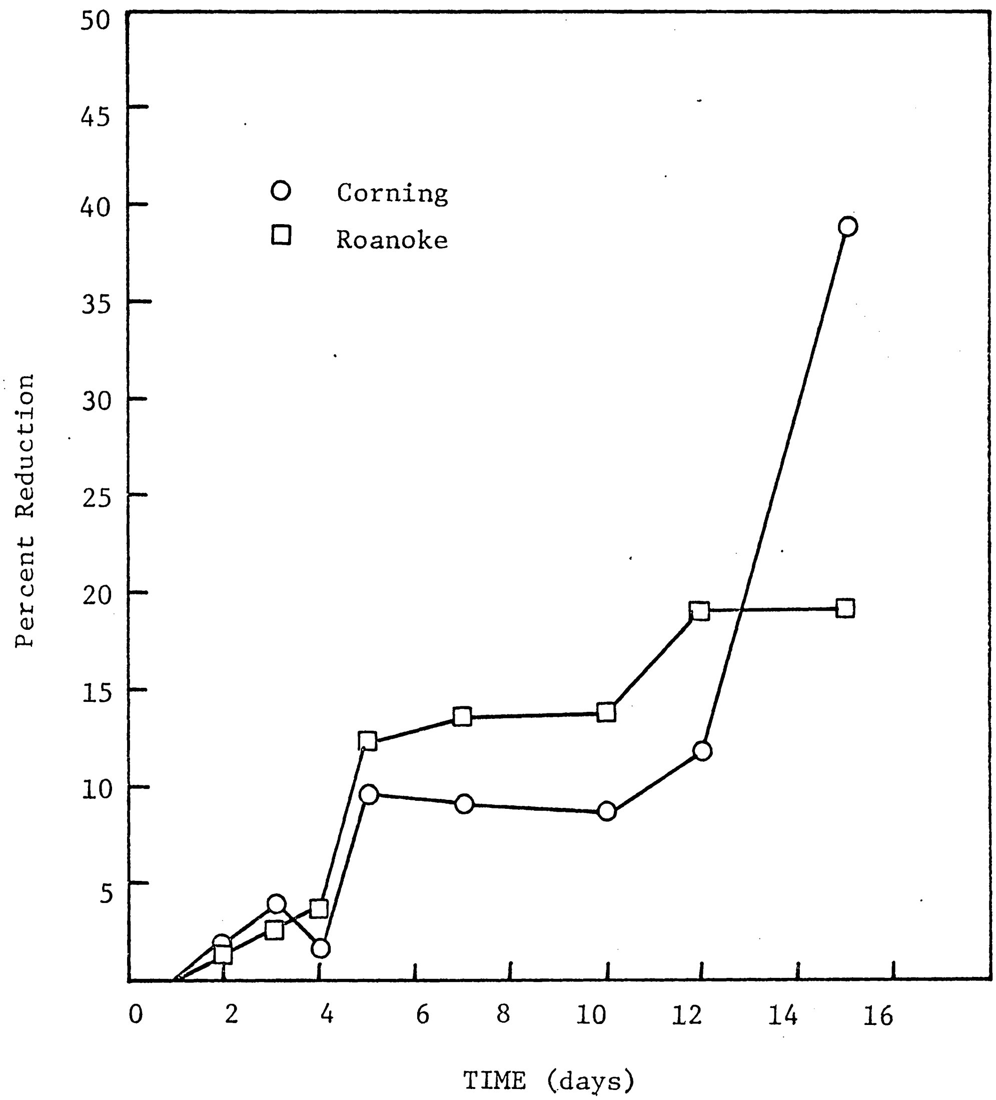

FIGURE 8. PERCENT SUSPENDED SOLIDS REDUCTION FOR DIGESTION RUN 1.

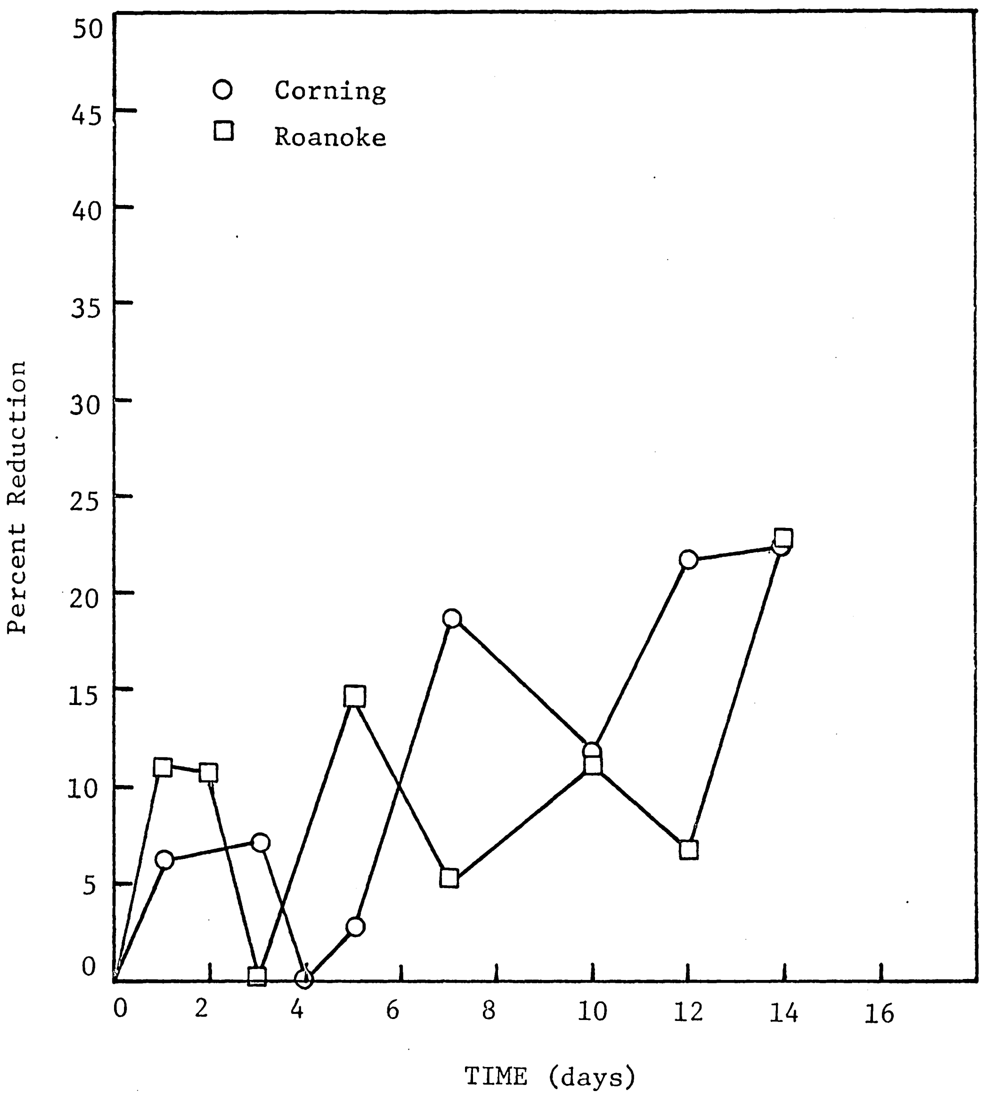

FIGURE 9. PERCENT SUSPENDED SOLIDS REDUCTION FOR DIGESTION RUN 2.

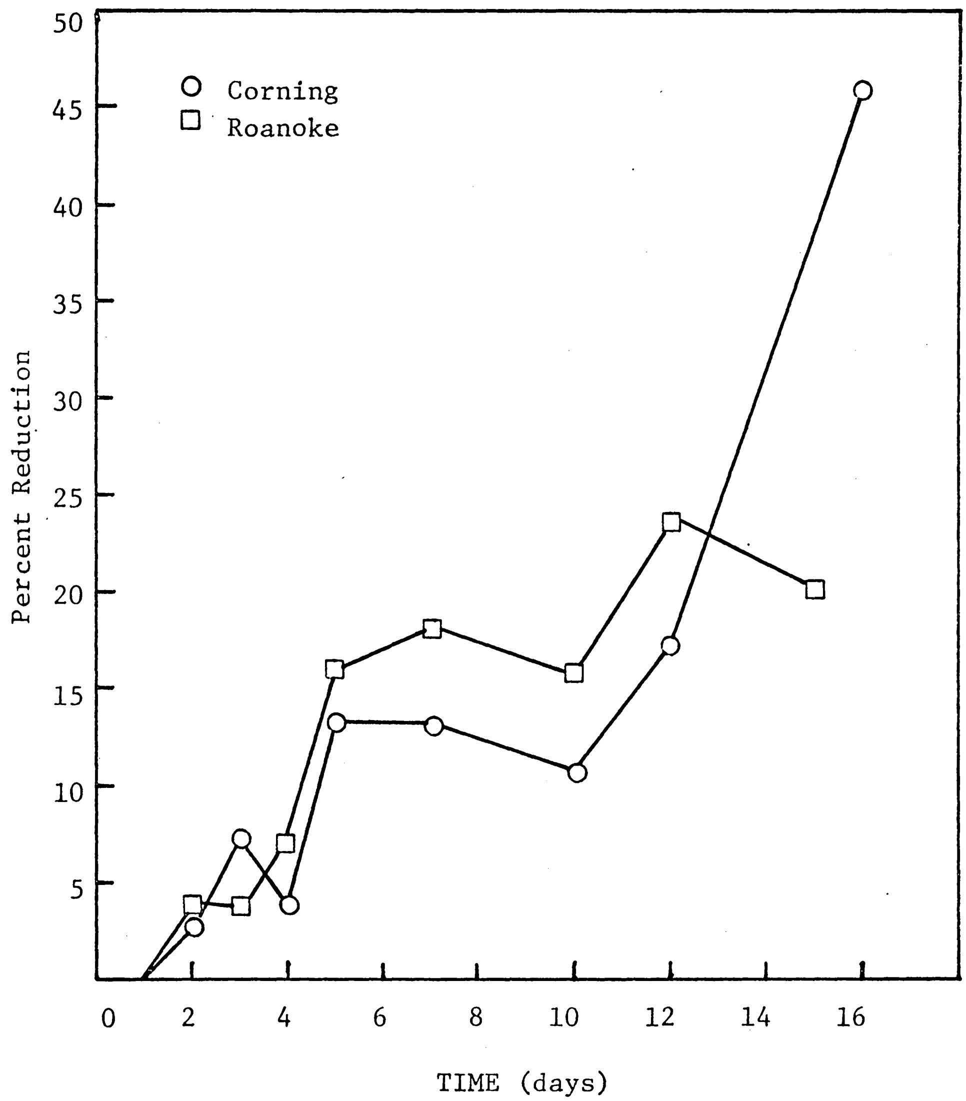

FIGURE 10. PERCENT VOLATILE SUSPENDED SOLIDS REDUCTION FOR RUN 1.

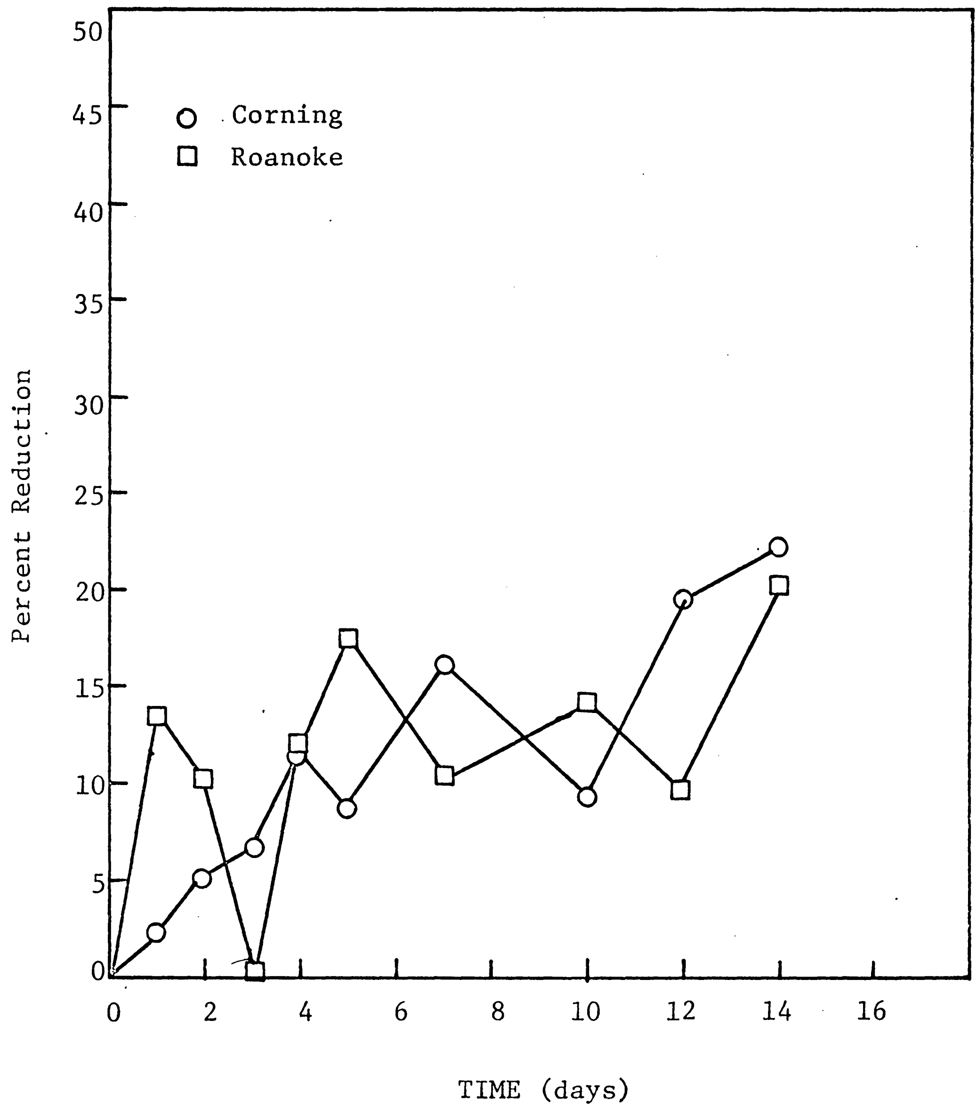

FIGURE 11. PERCENT VOLATILE SUSPENDED SOLIDS REDUCTION FOR RUN 2.

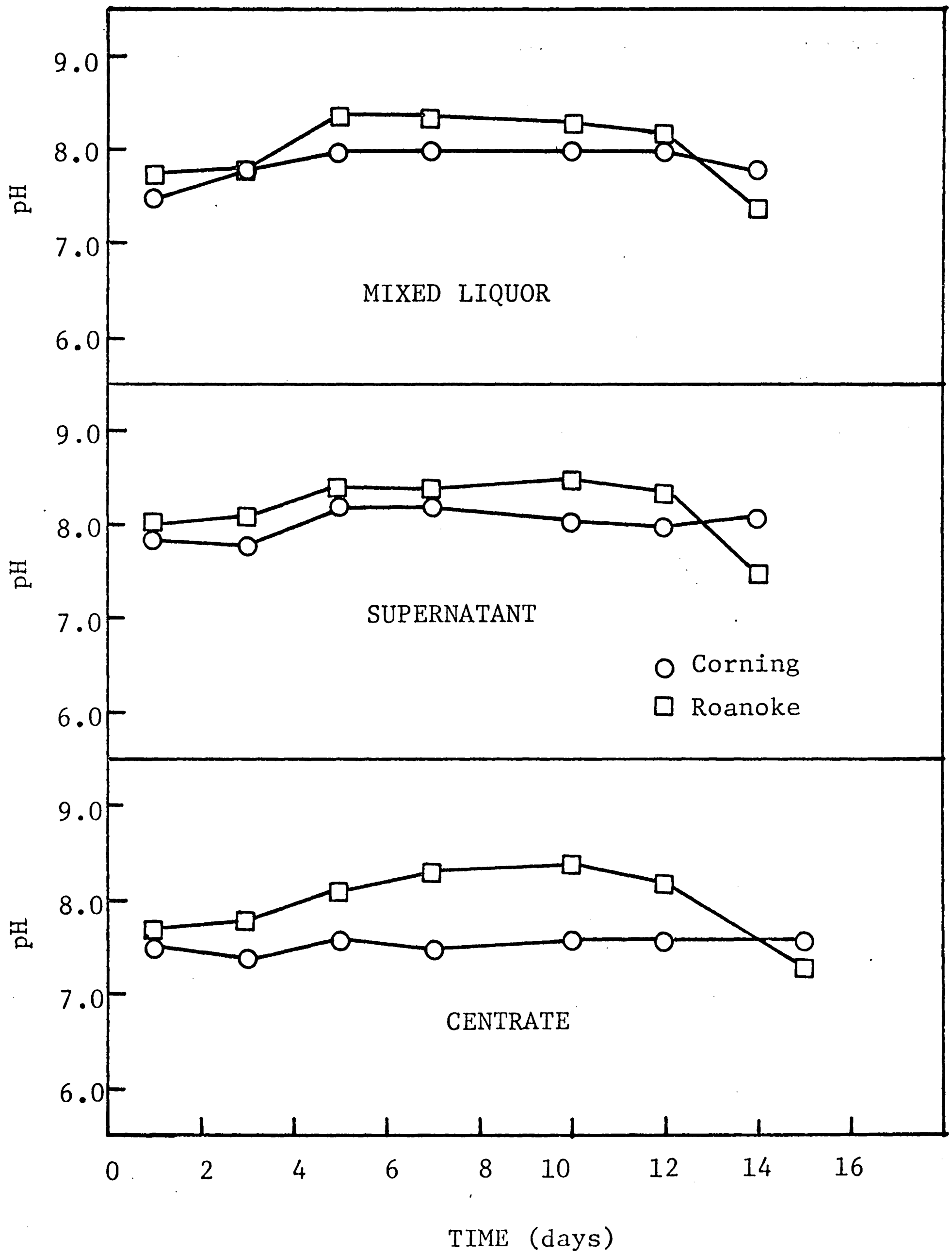

FIGURE 12. pH VARIATION FOR DIGESTION RUN 1 FOR MIXED LIQUOR, SUPERNATANT, AND CENTRATE

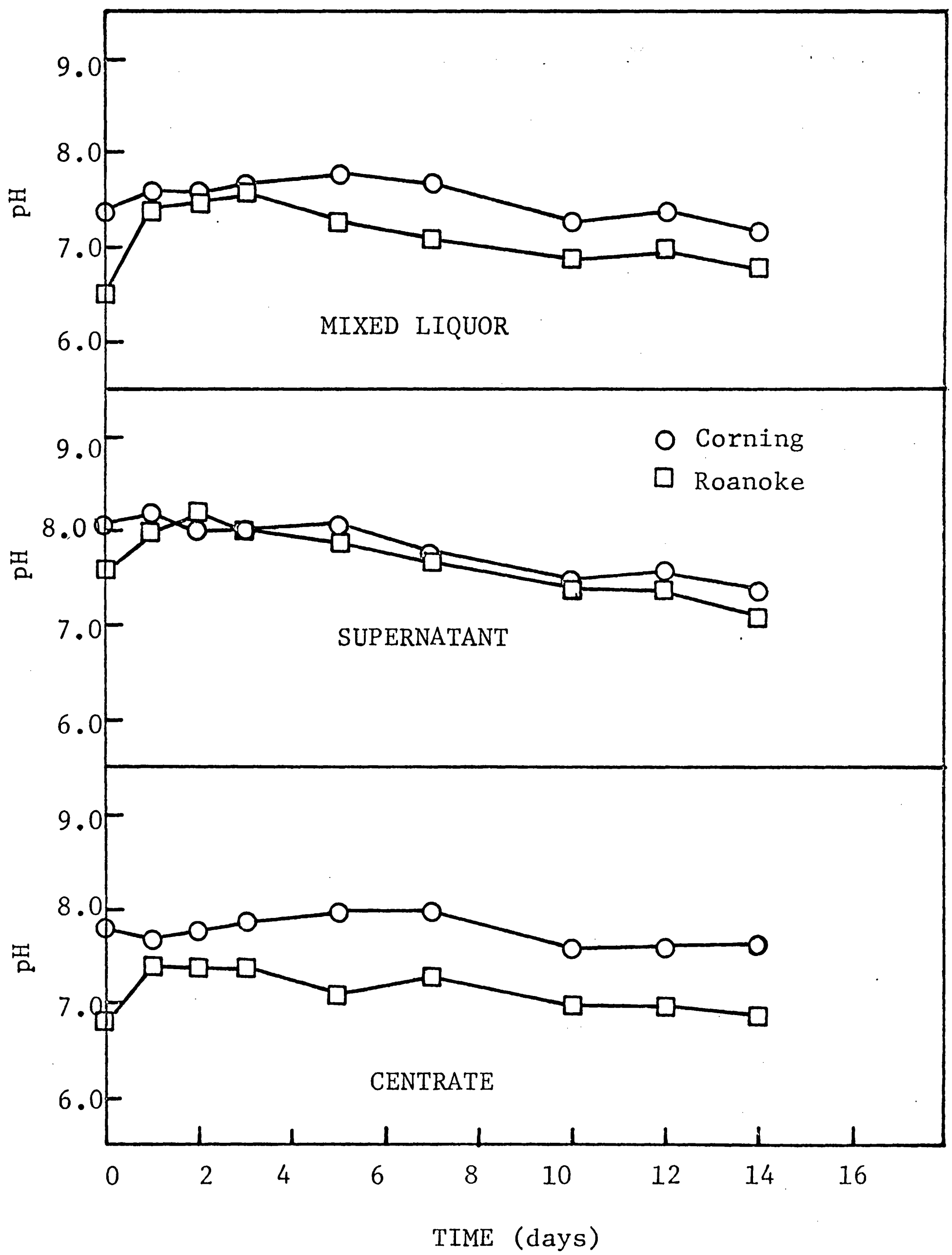

FIGURE 13. pH VARIATION FOR DIGESTION RUN 2 FOR MIXED LIQUOR, SUPERNATANT, AND CENTRATE

respectively, for Corning and Roanoke sludges during run #2. No initial pH reading was obtained in run #1, but there was an increase in pH from day 1 to day 3 in both the Corning and Roanoke sludges. The peak mixed liquor pH occurred on day 5 of both runs, after which it decreased slightly. Unlike previous studies, which observed a decline as much as 3 and 4 pH units after 12 to 15 days of aeration, very little decline in the pH occurred in either run. Supernatant and centrate pH's were rather similar during both runs, varying between 0.2 and 0.3 pH units throughout the experiments.

COD

The chemical oxygen demand of both the supernatant and centrate was measured throughout the duration of the experiments. The data is presented in Figures 14 and 15. For run #1 both the supernatant and centrate COD for the Roanoke sludge decreased up until day 5 or 7 and then rose sharply. The Corning sludge CODs remained fairly constant throughout the entire first run. In run #2 the Roanoke sludge CODs dropped off sharply with the start of aeration and then remained fairly constant. The Corning sludge CODs showed no immediate improvement with aeration, but stayed rather constant throughout the digestion period except for a sharp jump in the centrate COD after 3 days in run #2.

Oxygen Uptake

The rate of oxygen uptake, or oxygen utilization, has been plotted against digestion time and is presented in Figure 16. Oxygen uptake by itself is not a decisive digestion parameter, however,

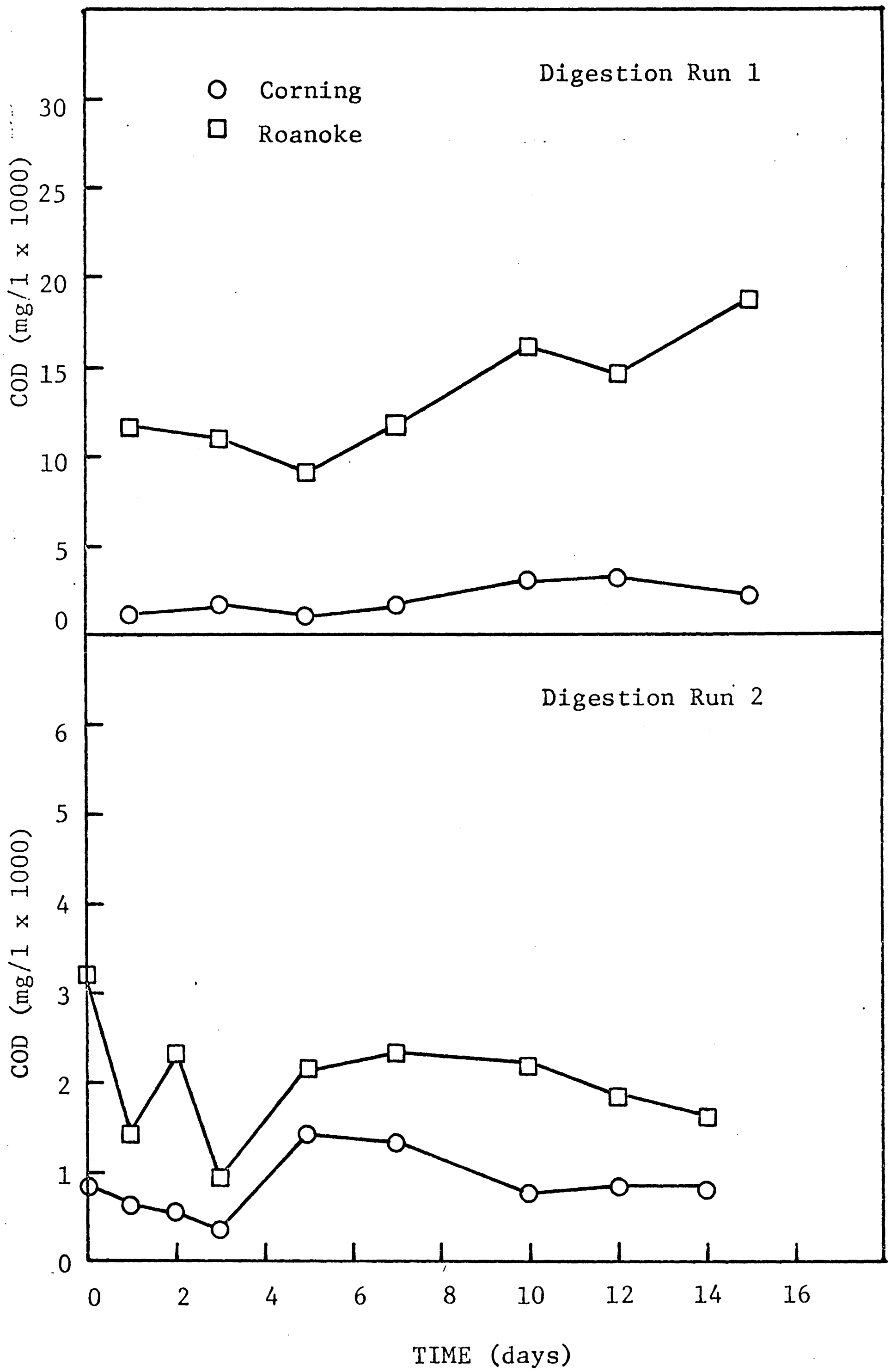

FIGURE 14. CENTRATE COD DATA

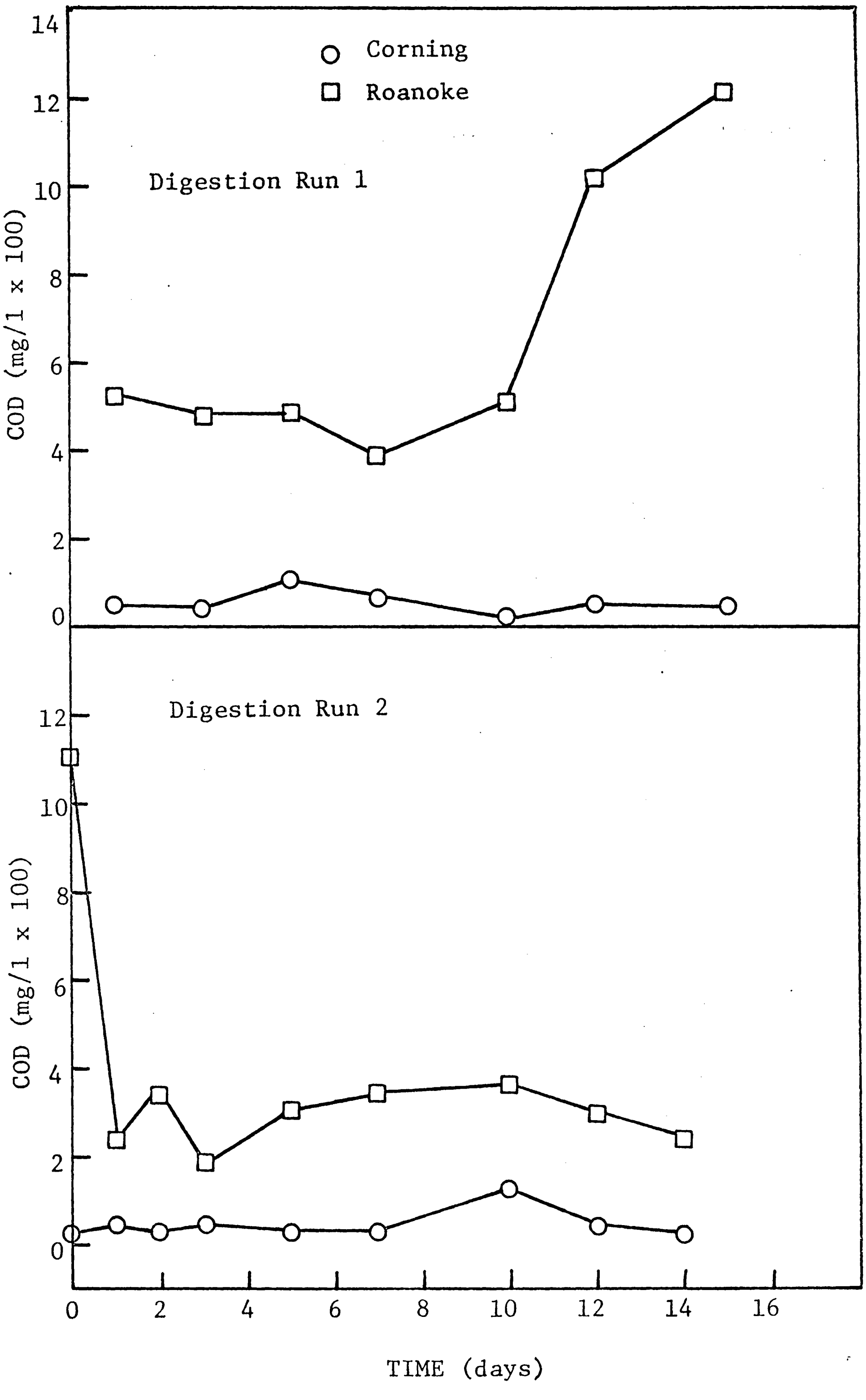

FIGURE 15. SUPERNATANT COD DATA

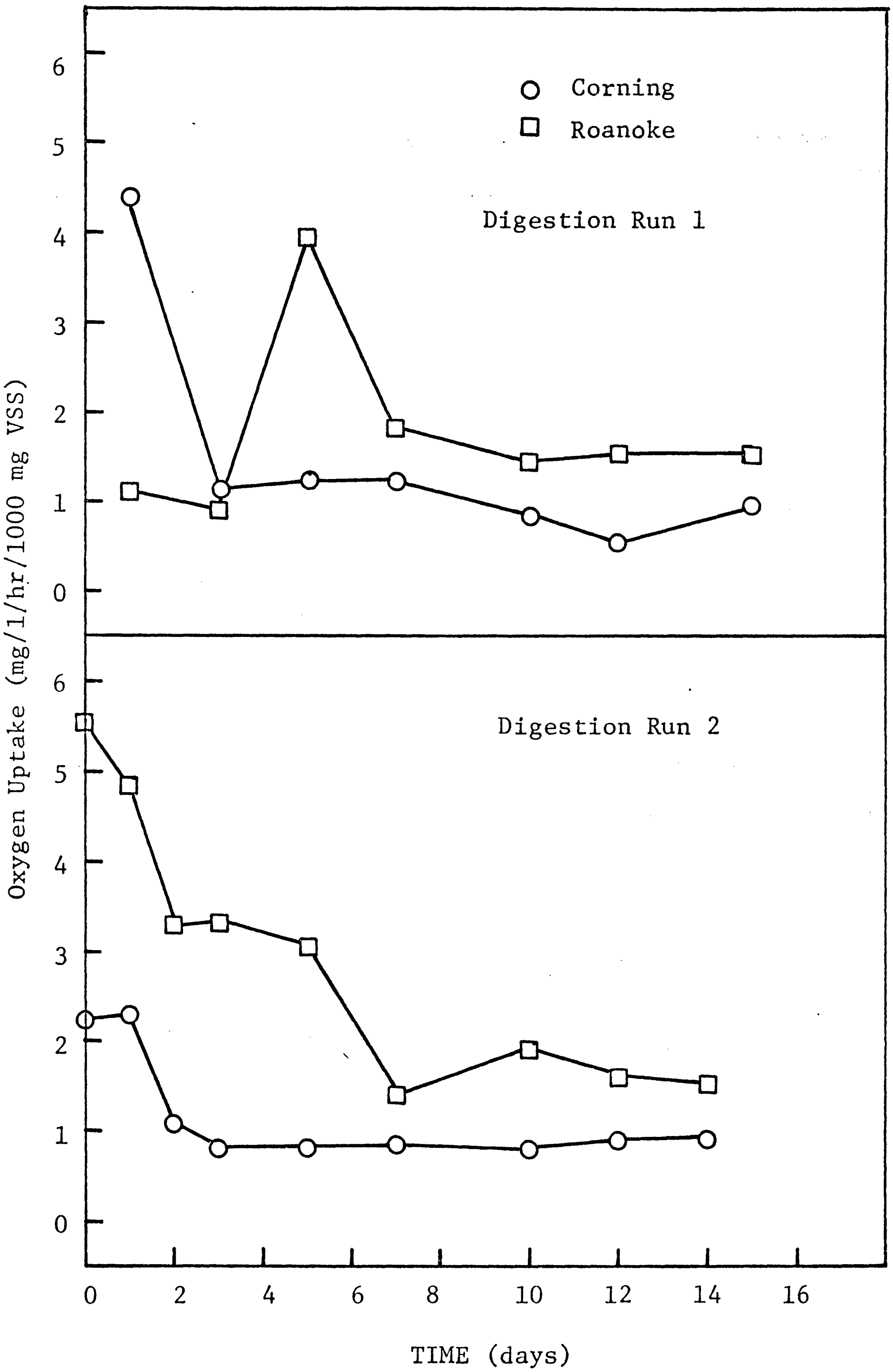

FIGURE 16. OXYGEN UPTAKE DATA

when correlated with other parameters (e.g. solids reductions, filterability, drainability, etc.) it can be of valuable assistance in determining the causes of various responses in these other parameters.

It is obvious that both sludges for both runs reach the state of endogenous respiration upon prolonged aeration. However, it is strange that the Roanoke sludge for run #1 did not peak until five days of digestion and that endogenous respiration was not reached until seven days. Although the exact reason for the phenomenon is unknown, it may possibly be related to the condition of the sludge at the time the sample was obtained. The Roanoke sludge for run #2 did not exhibit a peak but instead declined gradually until endogenous respiration was reached at approximately day seven.

The Corning sludge in both runs reached endogenous respiration at a relatively early time in digestion, in comparison to the Roanoke sludge. Like the Roanoke sludge of run #2, the Corning sludge in both runs also did not exhibit a peak, but instead gradually declined to the endogenous state at approximately day three.

$\underline{BOD_5}$

The actual BOD_5 values of both the supernatant and centrate for the Corning and Roanoke sludges are presented in Table II. Due to the high BOD_5 of the Roanoke centrate, its value could not be experimentally obtained using the prescribed sample dilution,

TABLE II

BOD$_5$ DATA FOR DIGESTION RUNS

Run No.	Sample Description	Digestion Period (days) 0	1	5	10	14	15
1	Corning Centrate	–	217	118	280	–	254
1	Roanoke Centrate	–	> 7,700	5,808	3,090	–	3,300
1	Corning Supernatant	–	47	24	5	–	30
1	Roanoke Supernatant	–	468	222	108	–	900
2	Corning Centrate	210	–	90	35	52	–
2	Roanoke Centrate	1,350	–	375	120	250	–
2	Corning Supernatant	210	–	20	18	8	–
2	Roanoke Supernatant	310	–	28	23	16	–

therefore a value for which the BOD_5 is greater than was substituted to indicate its magnitude. Little BOD_5 data was obtained because it was being used mainly as a guideline to check the effects of aerobic digestion on centrifugation. As the percent recovery (see Chapter III) decreased, this led to an increase in solids, thereby causing the BOD_5 to increase with time, which did happen. The higher values for days 0, 1, and 5 can be explained in that the sludge had not been digested sufficiently enough to cause a decrease in the BOD_5. The supernatant values decreased steadily because of the good removal of solids provided by the vacuum filtration apparatus. The high value of the Roanoke supernatant for 15 days of aeration can possibly be attributed to experimental error.

Filterability

Specific resistance values for both sludges were determined during the digestion periods and are shown in Figures 17 and 18. The actual experimental data which was collected and utilized to compute the specific resistance is given in the appendix.

From Figure 17 it can be seen that for run #1 the specific resistance of the Corning sludge increased initially, then decreased through 7 days of aeration, after which it rose again to a peak and then tappered off. The Roanoke sludge, on the other hand, rose continually from day 1 and did not level out until 10 days of digestion, after which it decreased slightly. This shows that the filterability of that sludge worsened with increased digestion.

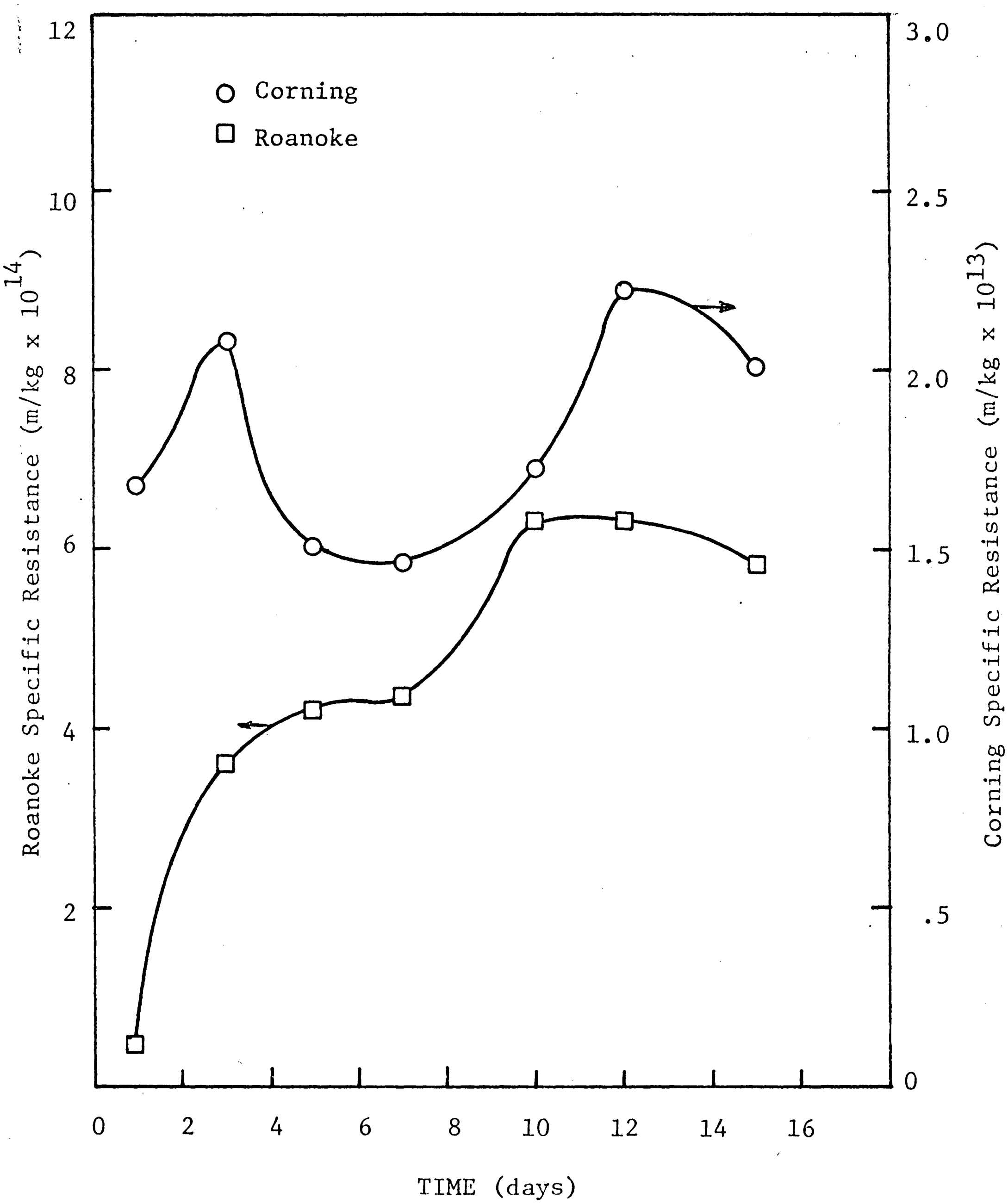

FIGURE 17. VARIATION OF SPECIFIC RESISTANCE FOR DIGESTION RUN 1.

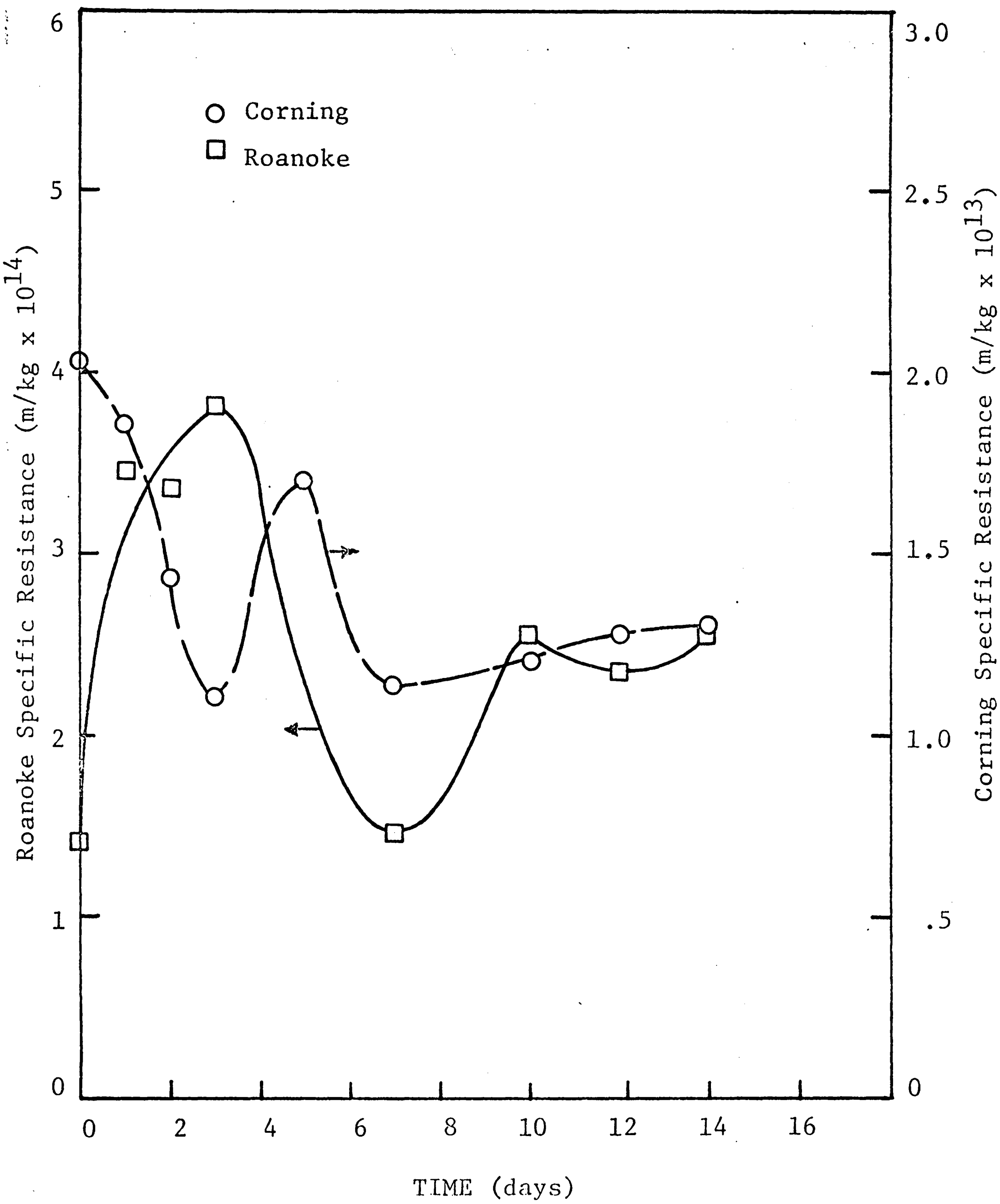

FIGURE 18. VARIATION OF SPECIFIC RESISTANCE FOR DIGESTION RUN 2.

For run #2 the sludges behaved quite differently from that of run #1. As Figure 18 illustrates, the Roanoke sludge specific resistance increased through 3 days of digestion, then decreased through day 7 and then increased once again. The Corning sludge, however, decreased initially continuing through day 7 after which it rose through day 15.

It should be noted that the relative filterability of the sludges previously described was poor, as indicated by the very large units of specific resistance (m/kg x 10^{13} and m/kg x 10^{14}), however, both the Roanoke and Corning sludges in run #2 exhibited better filterability qualities than those in run #1, possibly due to the lower solids concentrations.

Centrifugation

The effectiveness of a centrifuge is measured in terms of cake concentration and centrate clarity. When considering centrifugation as an alternative method of sludge dewatering, optimization of solids capture is the most essential parameter to consider. The remaining portion (centrate) in most instances is recycled back to the head of the sewage treatment plants and as little added load as possible is desired.

Figures 19 through 22 show how both cake and centrate solids were affected by digestion.

Run #1 shows that cake solids for the Corning sludge increased overall while that from Roanoke decreased slightly although a large fluctuation occurred during the digestion period. In run #2

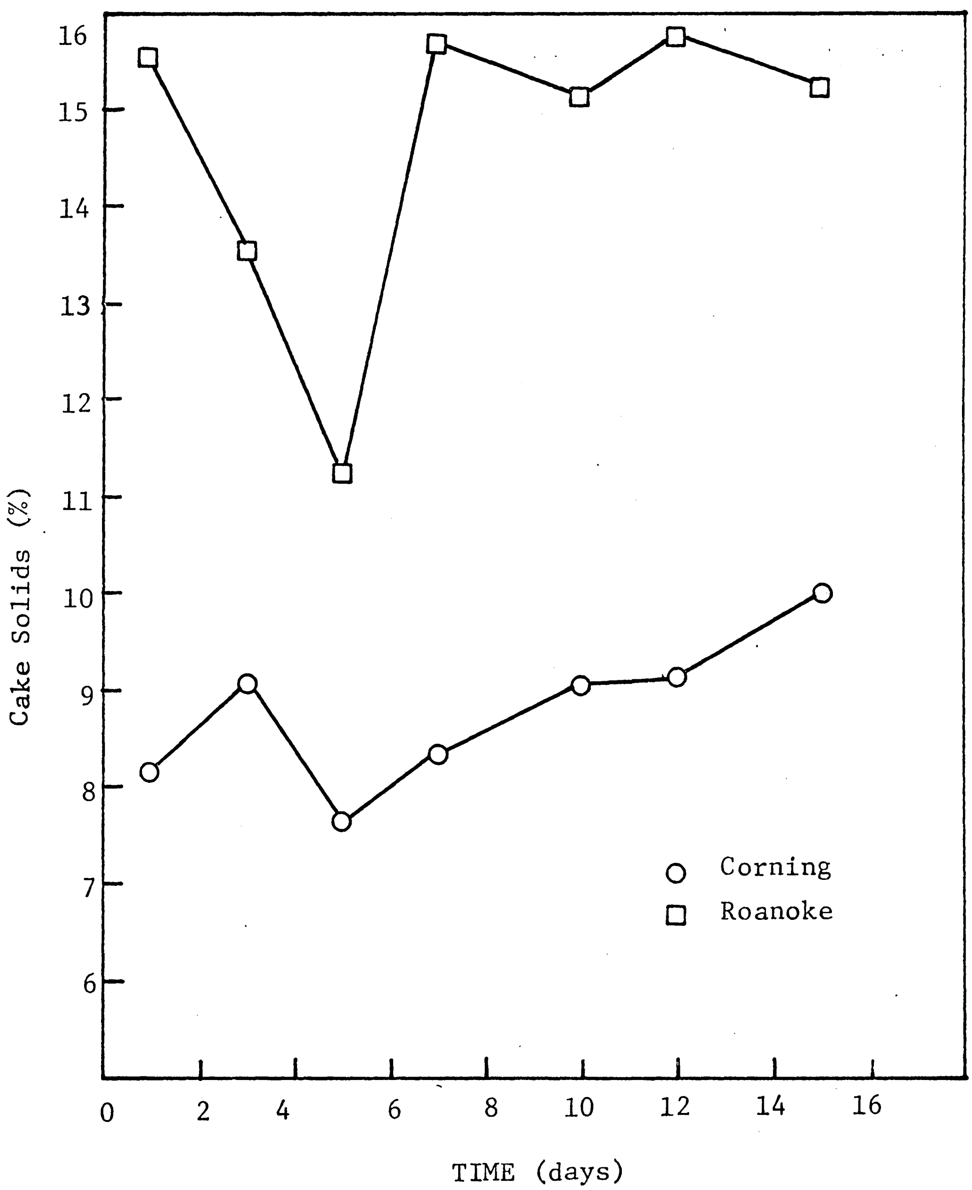

FIGURE 19. CAKE SOLIDS VARIATION FOR DIGESTION RUN 1.

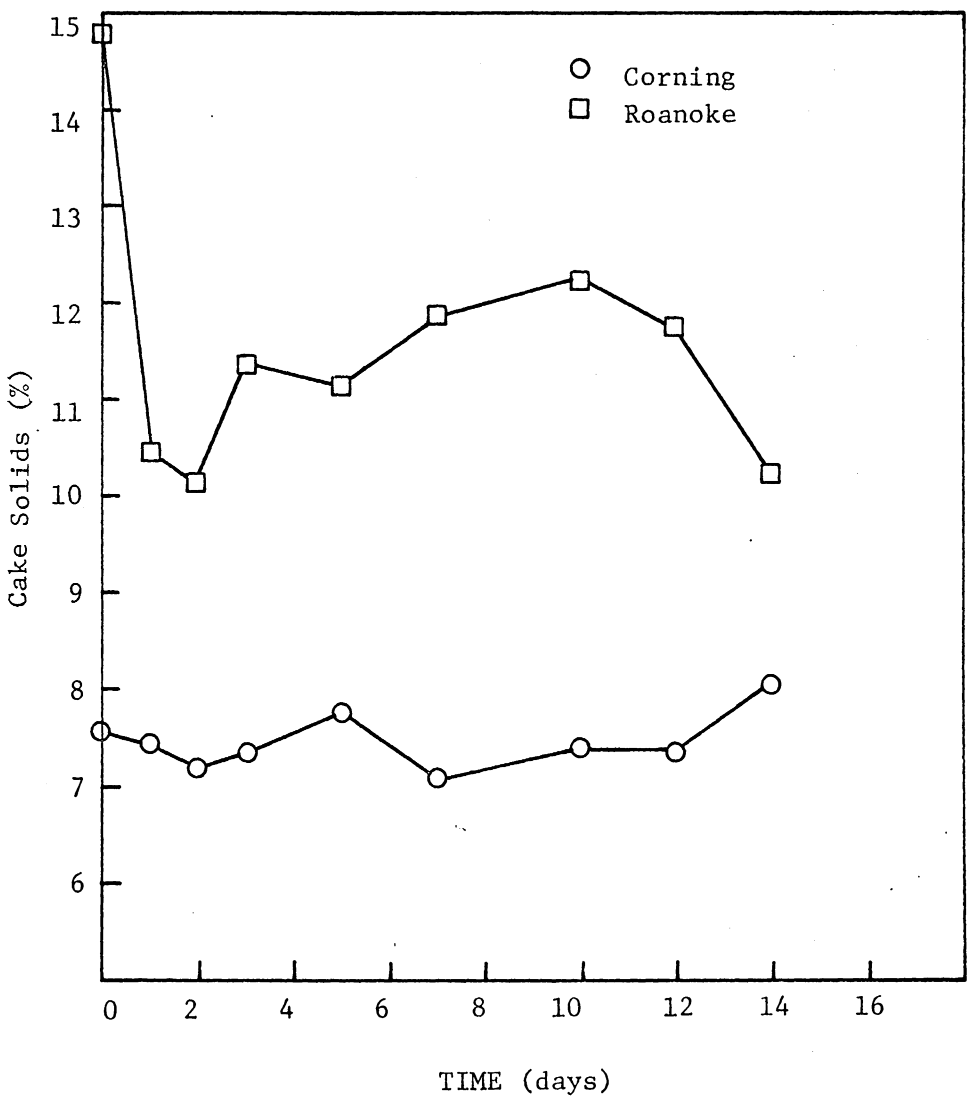

FIGURE 20. CAKE SOLIDS VARIATION FOR DIGESTION RUN 2.

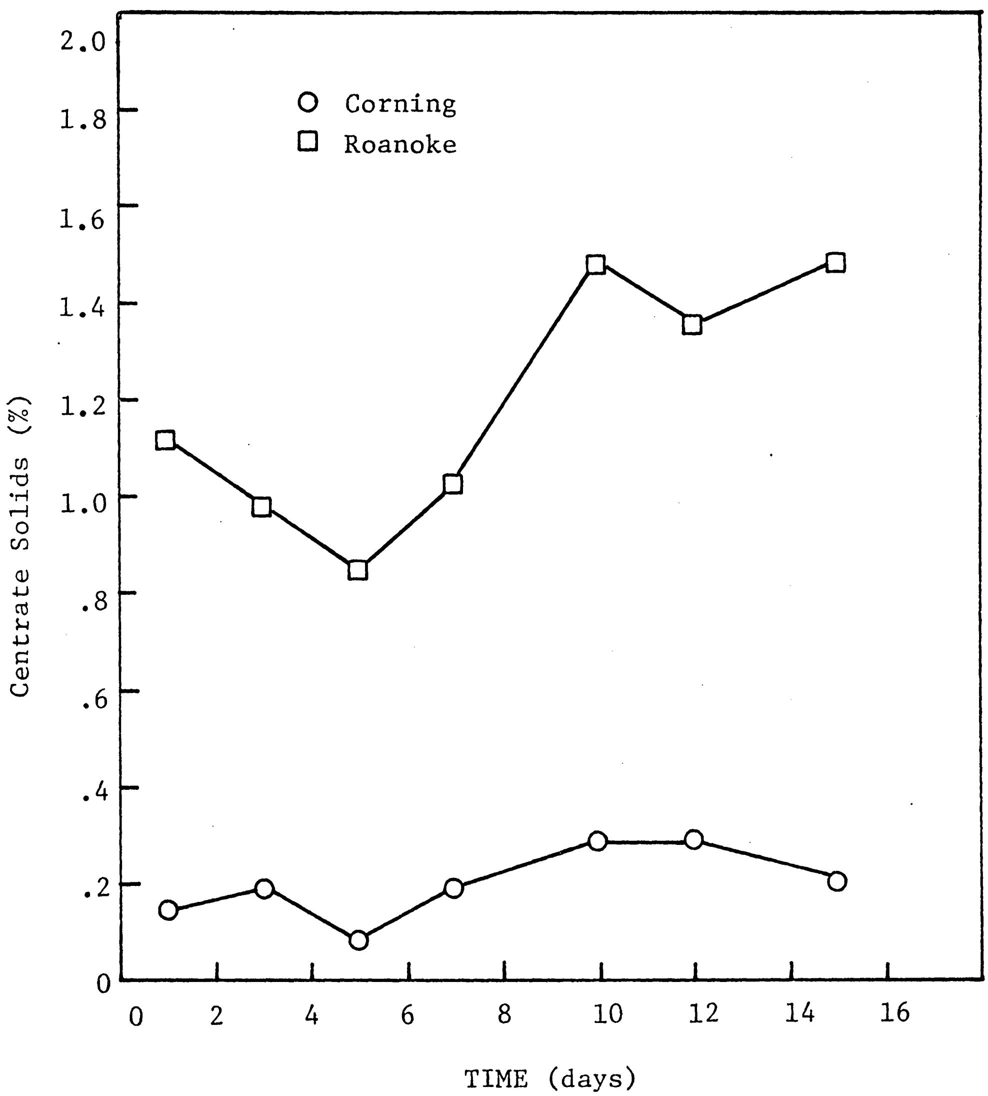

FIGURE 21. CENTRATE SOLIDS VARIATION FOR DIGESTION RUN 1.

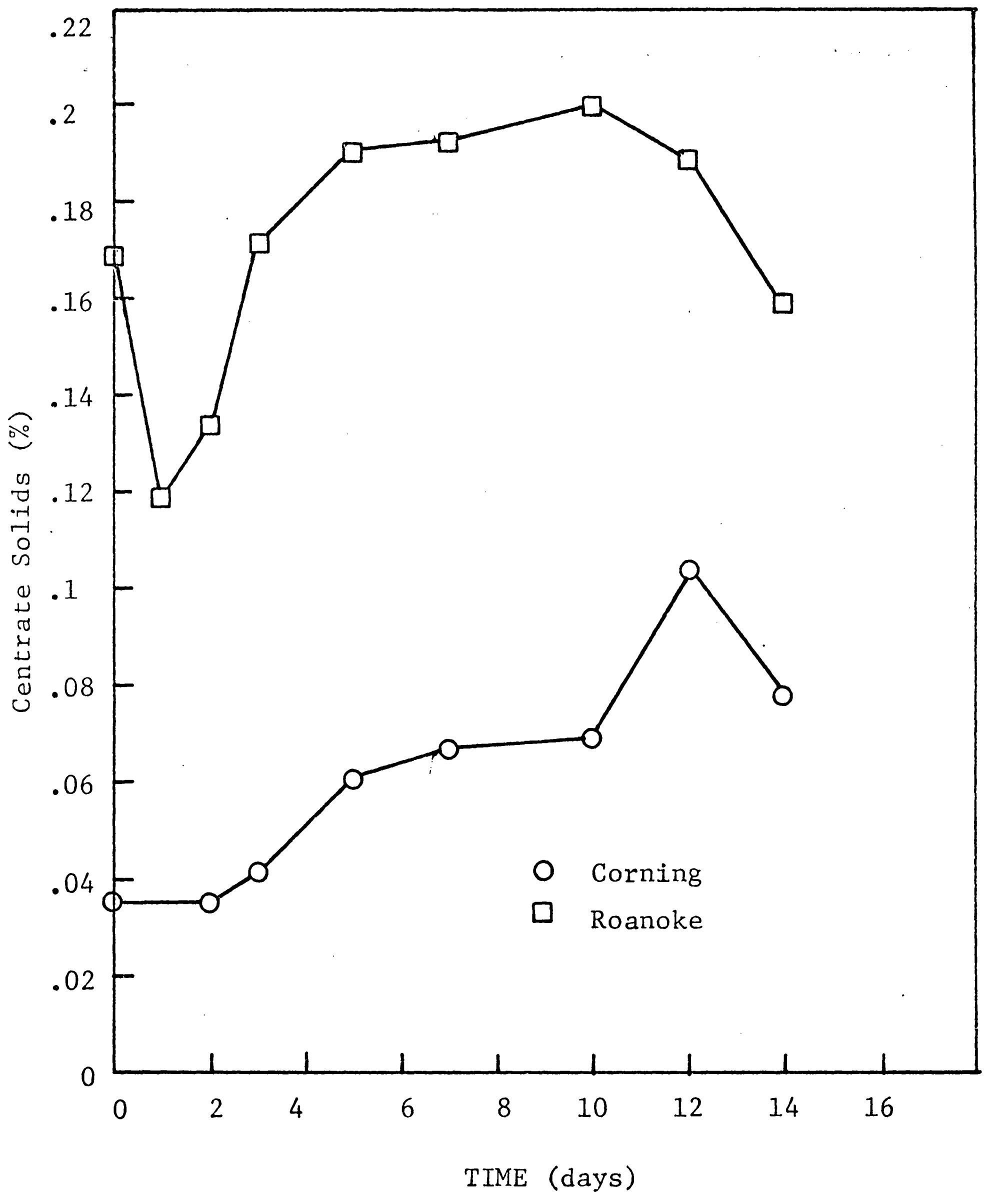

FIGURE 22. CENTRATE SOLIDS VARIATION FOR DIGESTION RUN 2.

the Roanoke sludge cake solids decreased considerably over the entire digestion period, but after decreasing sharply the first two days, increased steadily from day 2 until day 10 at which time it declined. The Corning sludge cake solids, on the other hand, were fairly constant, showing a slight increase in cake solids over the length of the run. It should be noted that higher cake solids were obtained for run #1, this being attributed to the fact that the feed solids concentration was much higher during this run.

The centrate solids followed the same general trend that the cake solids followed, indicating that the percent recovery did not alter a great deal, during run #2. In run #1, however, although the centrate and cake solids followed the same general trend, the centrate solids increased at a greater rate than the cake solids causing a decrease in percent recovery.

Figures 23 and 24 show the effects of digestion on percent recovery. Recovery of Corning sludge during run #1 decreased up to day 3, then increased to day 5 and then declined at a uniform rate thereafter. Recovery of the Roanoke sludge, on the other hand, increased to day 5, after which it declined sharply for the remainder of the digestion period. The maximum percent recovery occurred after 5 days of digestion for both sludges.

For run #2 the sludges exhibited different characteristics. Both sludges followed the same general trend, with the maximum percent recovery occurring after only one day of digestion. Neither sludge varied more than 8 percent in recovery during the entire run.

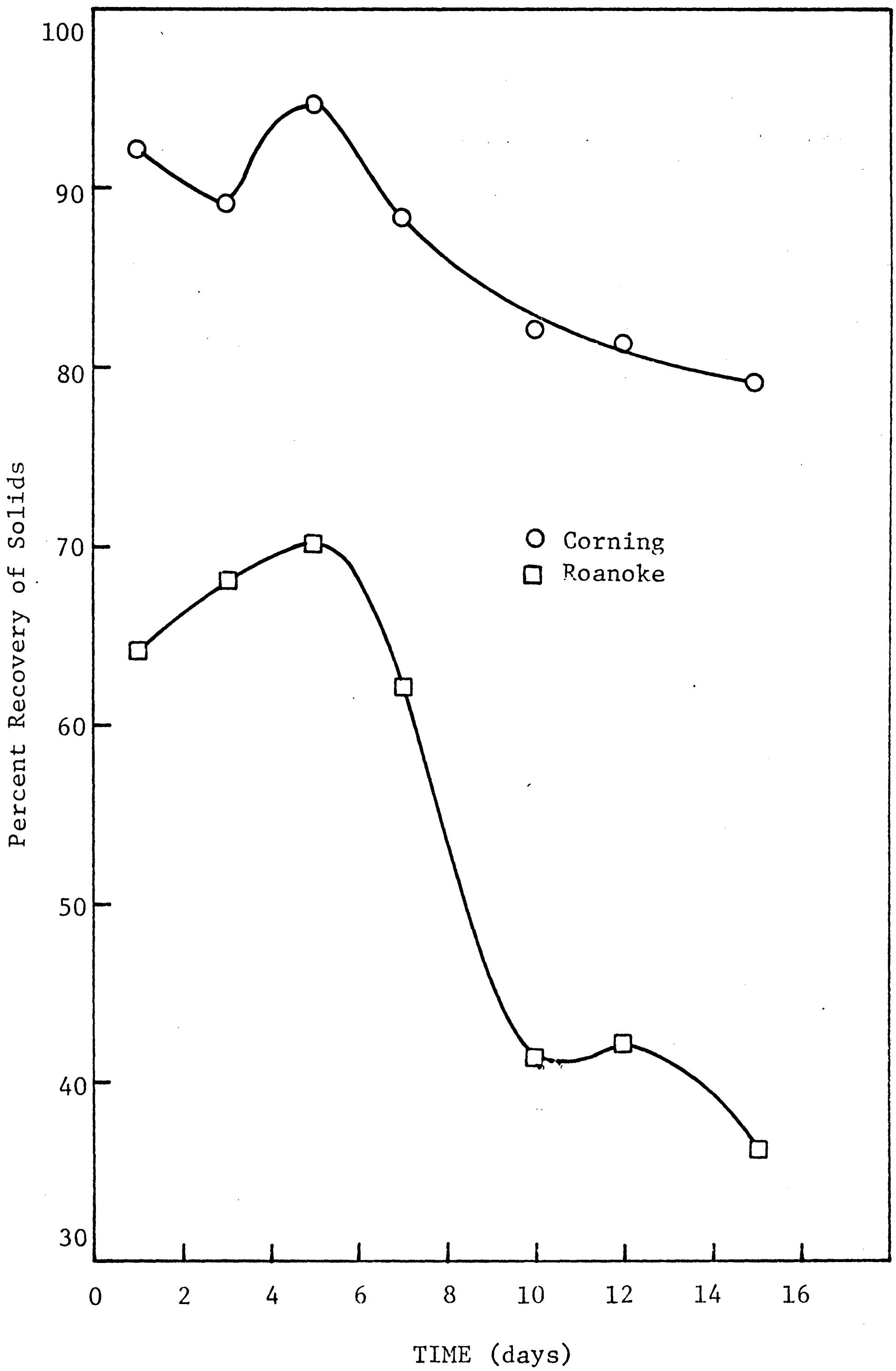

FIGURE 23. PERCENT RECOVERY DIGESTION RUN 1.

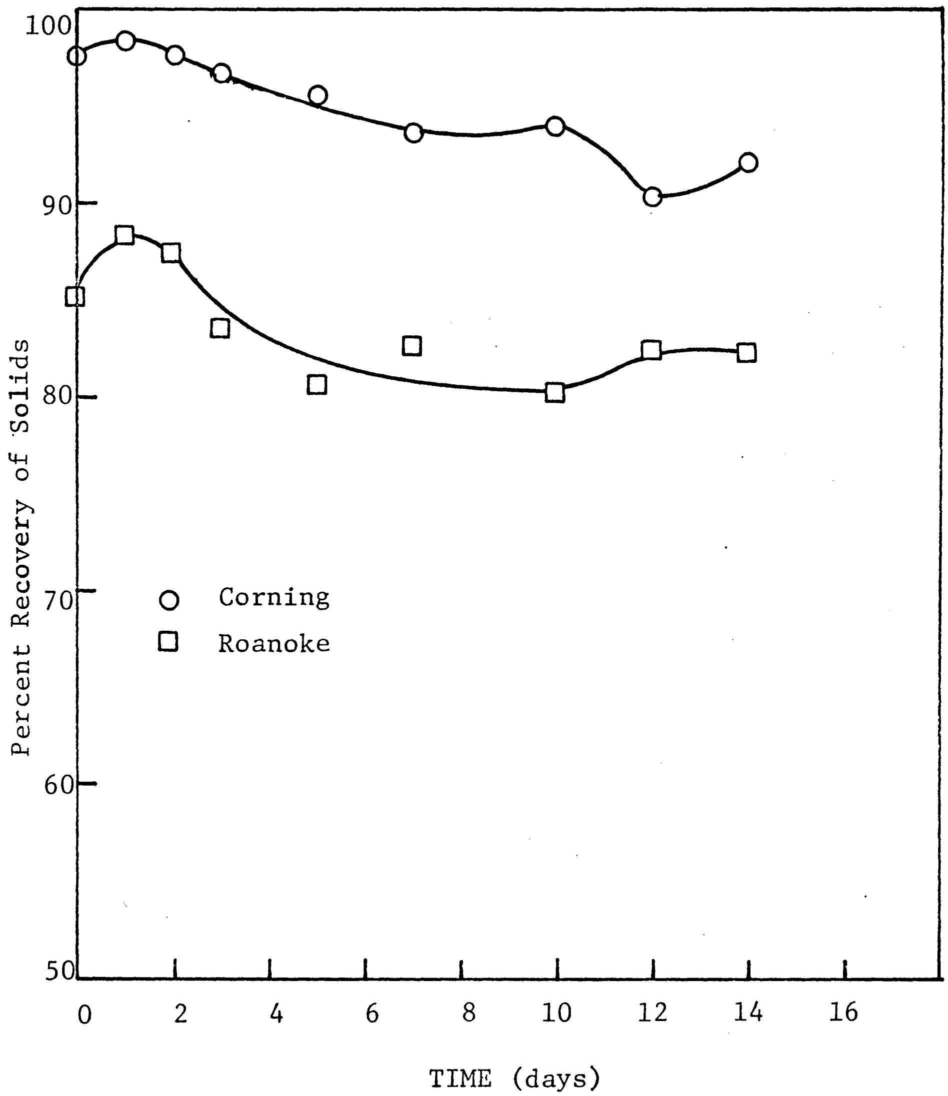

FIGURE 24. PERCENT RECOVERY FOR DIGESTION RUN 2.

This would seem to indicate that although the sludge cake is not quite as concentrated when lower feed solids are used, the percent recovery is much higher.

Figures 25 through 28 are plots of centrate and cake solids concentrations versus percent recovery. As is evident from Figure 25 and 26, as the centrate solids concentration increases the percent recovery decreases, as might be expected. These plots simply illustrate the reliability of the data. One line can be drawn for both sludges to show that the decrease occurs at a linear rate. Cake solids also increase as the percent recovery decreases but this result is less obvious from a theoretical standpoint. For both runs one curve was drawn for the two sludges to illustrate this result. For run #1 the curve was approximated to show that a leveling off of cake solids concentration occurred when a 65 percent recovery was obtained. This could also have been the case for the sludge used in run #2, but 80 percent recovery was the lowest value obtained for that run. However, the curve for run #2, describes the same general form of that for run #1 above 80 percent recovery, so it is very possible that it would have the same general shape as the curve for run #1. The only explanation for such an occurrence in lieu of the fact that centrate solids also increase with a decrease in the percent recovery, is that when poor recoveries occur, the larger more dense particles are entrapped in the basket, and the flocculent fines are passed on as centrate, thereby causing an increase in both cake and centrate solids concentration.

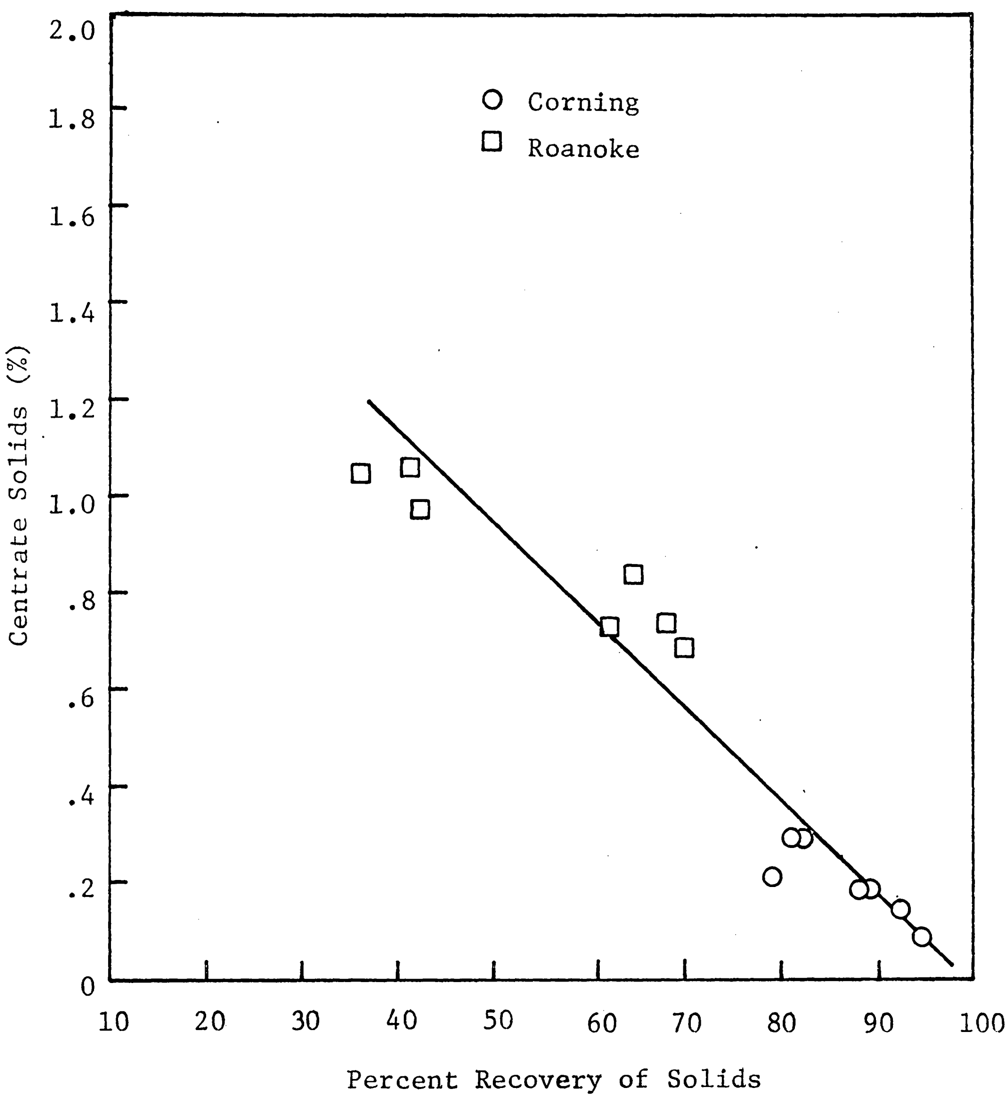

FIGURE 25. CENTRATE SOLIDS VERSUS PERCENT RECOVERY FOR DIGESTION RUN 1.

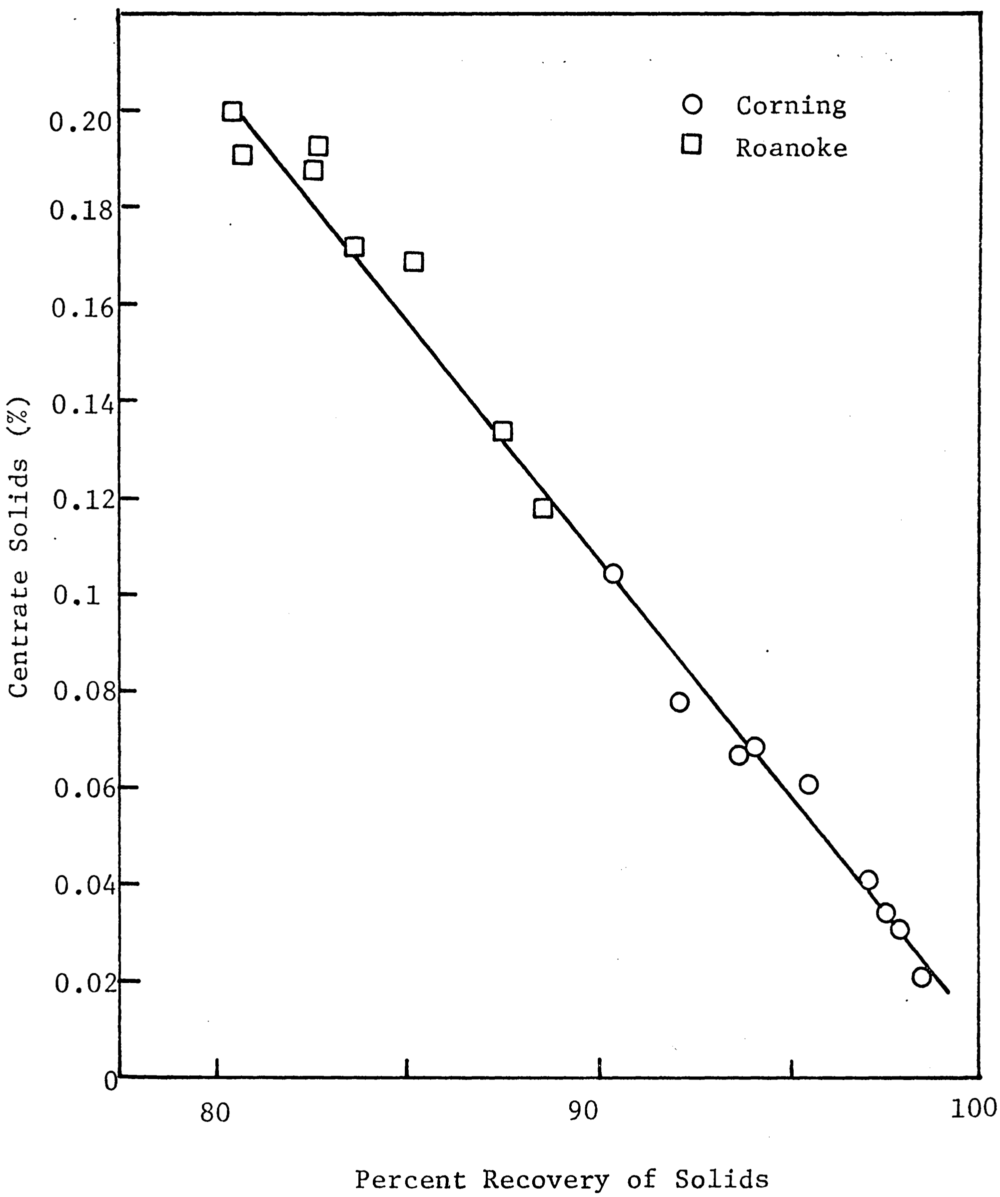

FIGURE 26. CENTRATE SOLIDS VERSUS PERCENT RECOVERY FOR DIGESTION RUN 2.

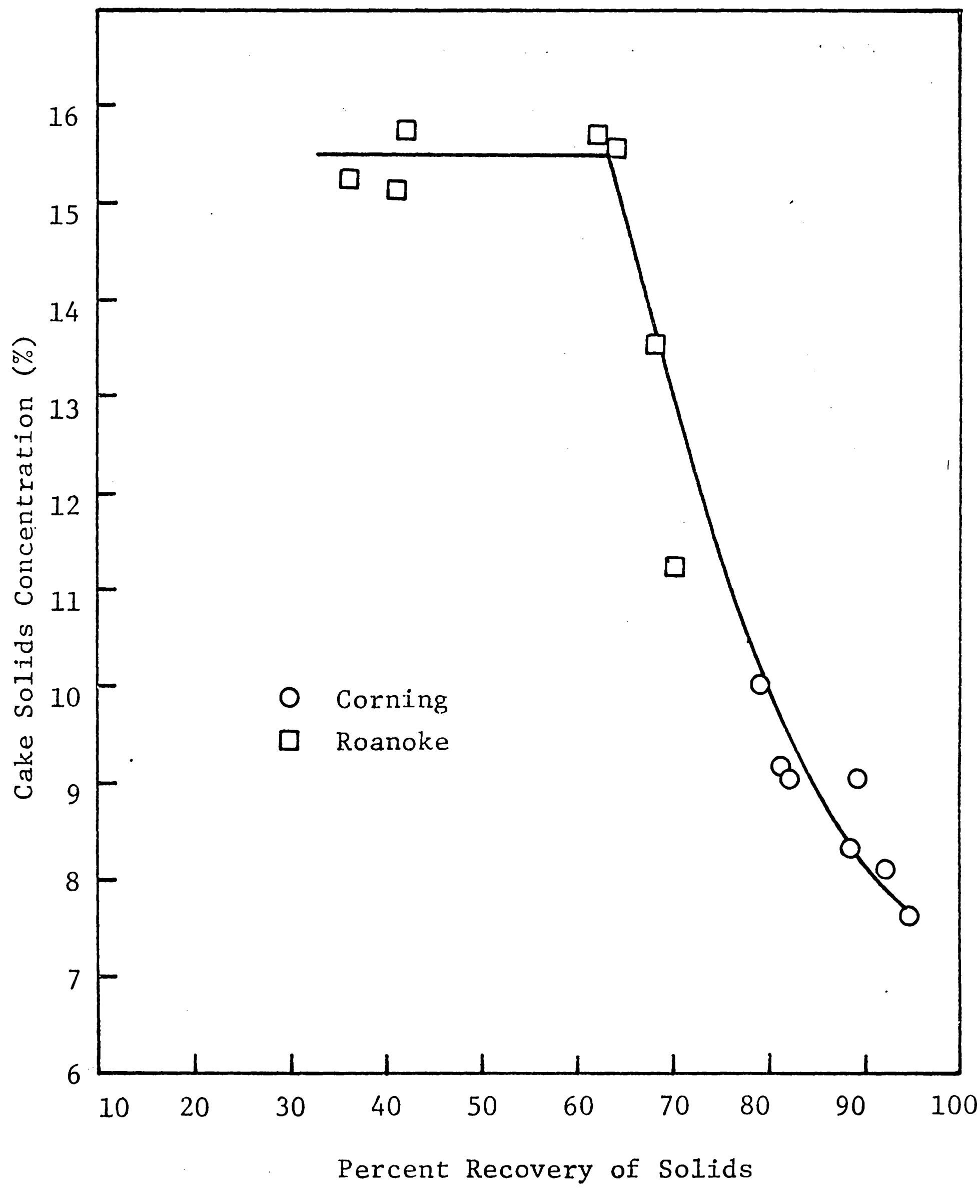

FIGURE 27. CAKE SOLIDS VERSUS PERCENT RECOVERY FOR DIGESTION RUN 1.

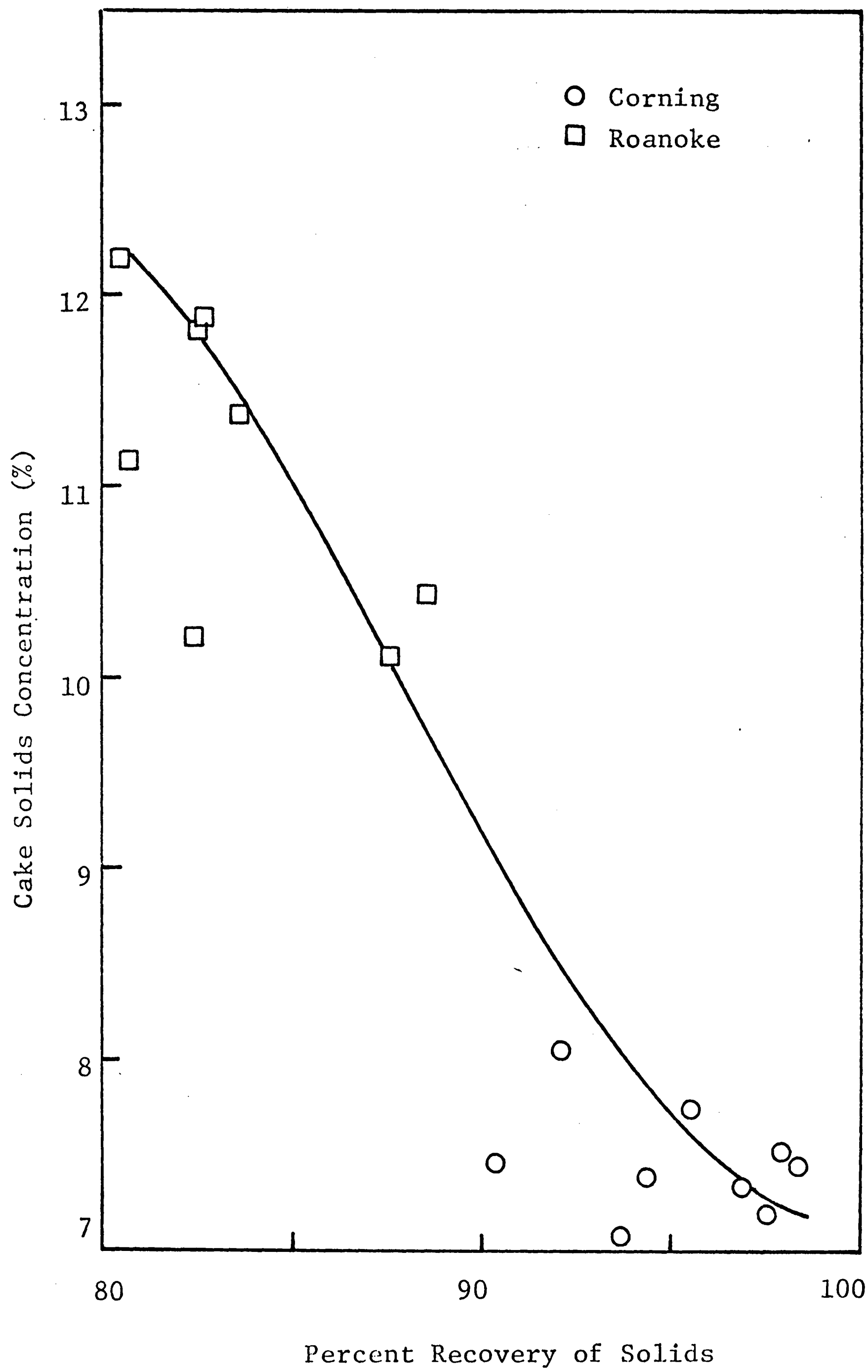

FIGURE 28. CAKE SOLIDS VERSUS PERCENT RECOVERY FOR DIGESTION RUN 2.

Plots of cake solids concentrations versus centrate solids concentrations, in Figures 29 and 30, show that as the centrate solids concentration increased, cake solids concentration also increased. Again, one curve can be drawn for both sludges to illustrate this relationship. This trend can again be attributed to the same causes explained in the previous paragraph.

Settleability

A very small degree of settleability (1 to 2 ml) was recorded throughout digestion run #1. The reason for this being that the test was conducted for only one hour, and that the solids concentrations of both sludges were exceptionally high. However, for run #2 (Figure 31) when lower solids concentrations were used, some settleability occurred, but only for the Roanoke sludge. In spite of the improved settleability, however, there was never more than 2 to 3 ml of truly clear supernatant above the Roanoke sludge. The supernatant was generally extremely cloudy.

Frothing

Frothing occurred in both digesters during both runs at various times with no discernable pattern being established. However, it was much worse in the digester containing Roanoke sludge. Since there was ample freeboard in both digesters no steps were taken to correct this problem.

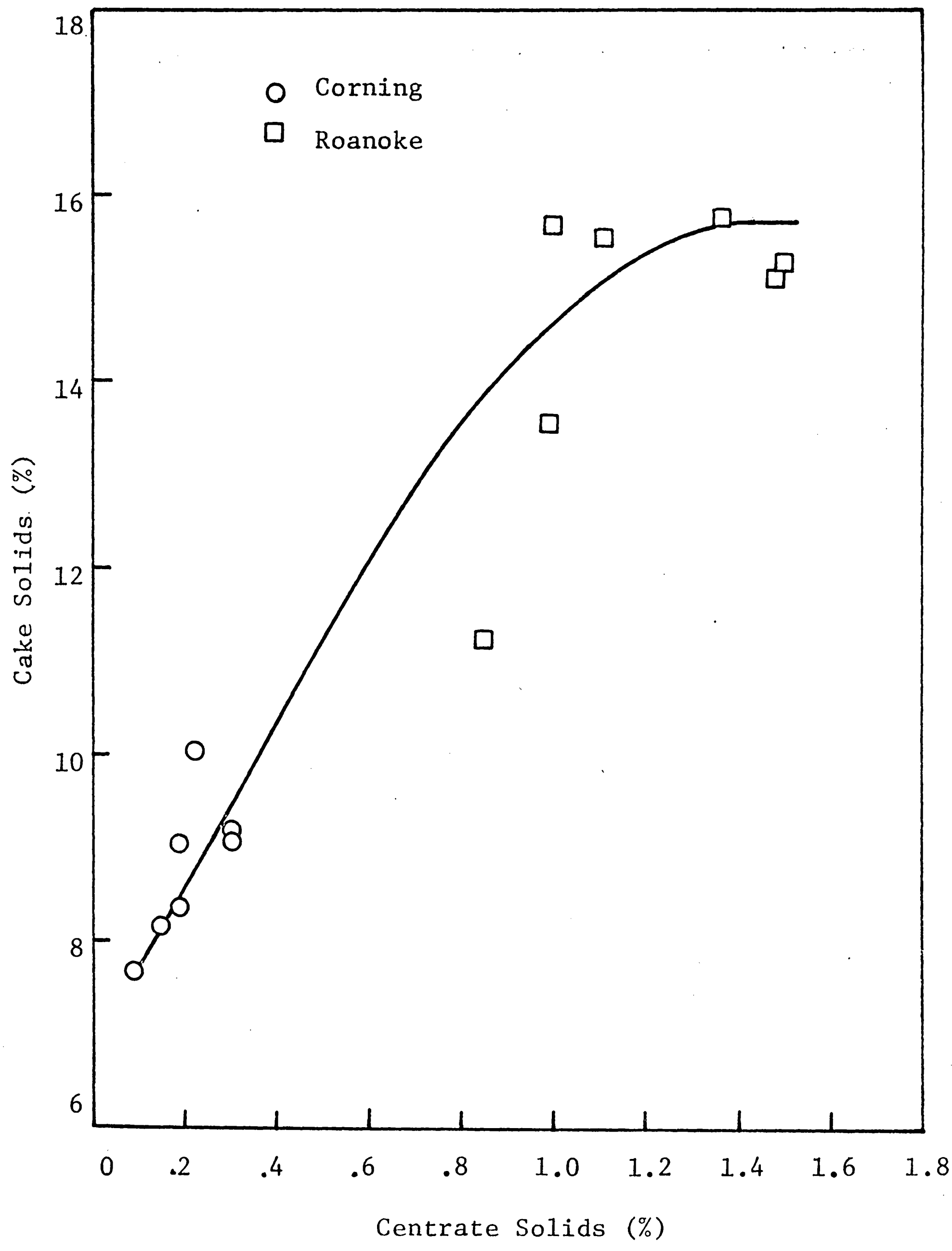

FIGURE 29. CAKE SOLIDS VERSUS CENTRATE SOLIDS FOR DIGESTION RUN 1.

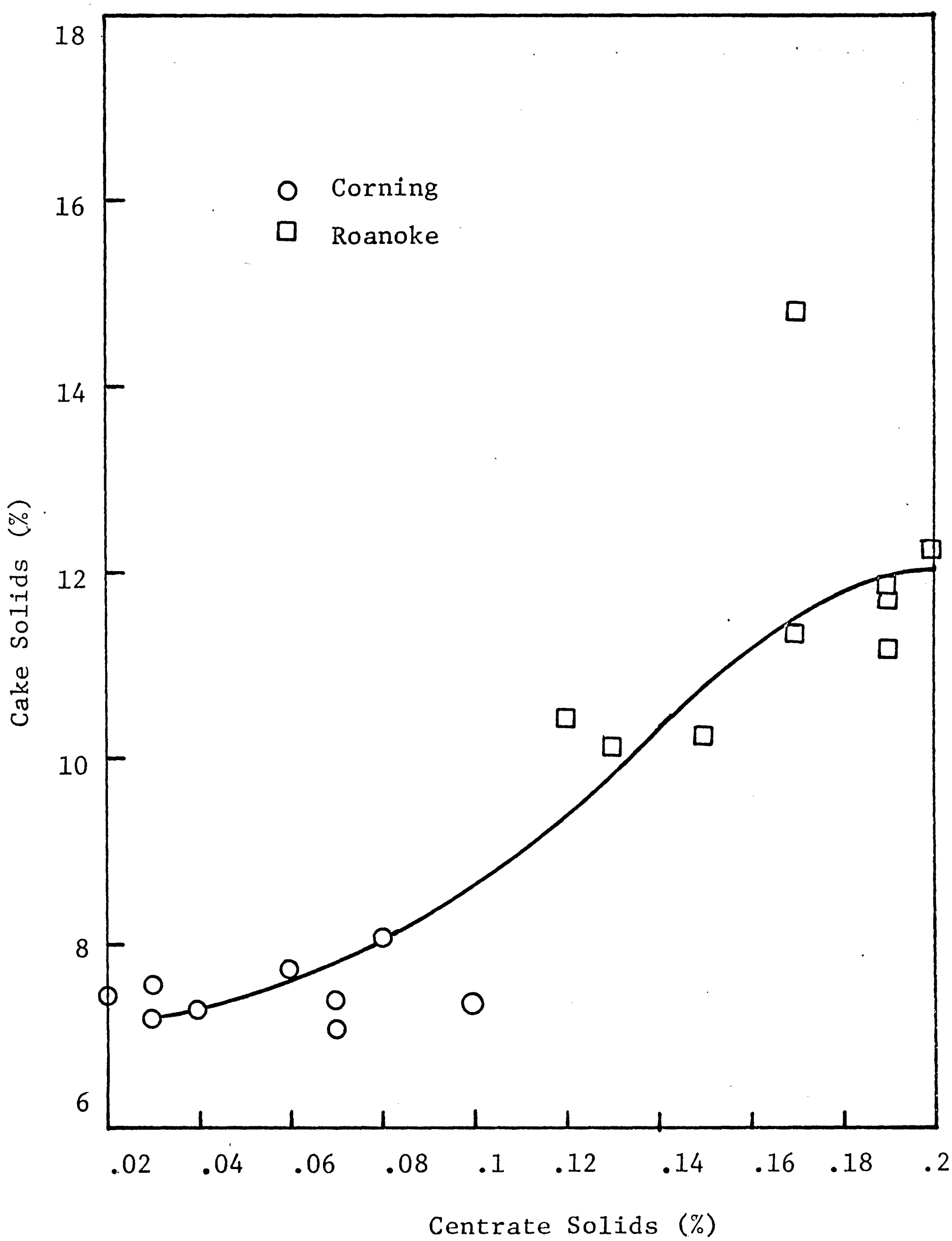

FIGURE 30. CAKE SOLIDS VERSUS CENTRATE SOLIDS FOR DIGESTION RUN 2.

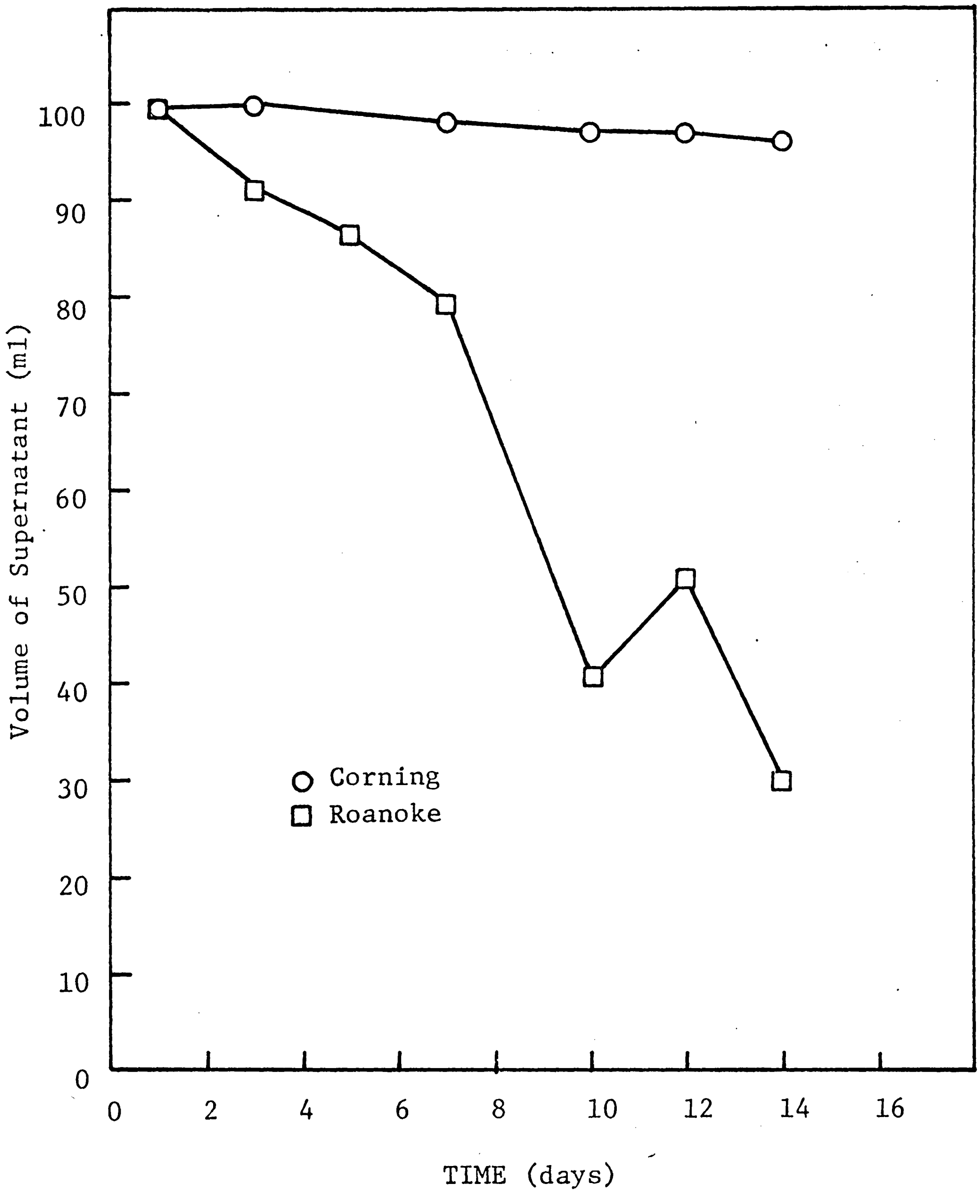

FIGURE 31. CHANGE IN SETTLEABILITY FOR DIGESTION RUN 2.

V. DISCUSSION OF RESULTS

Since the principal purpose of this study was to investigate the effects of aerobic digestion on subsequent waste activated sludge centrifugation and filterability, the discussion of the results of this experimentation will be presented primarily in terms concerning these aspects.

The most interesting aspects of this particular study deal with the results from the tests using the centrifuge. The prototype model that was supplied by Sharples has been used throughout the country, but it is doubtful that it was ever used in the manner employed during this study. A constant volume of sample (5 gallons) was fed to the centrifuge on testing days, with all other control variables (feed rate, detention time, bowl speed) held constant. The reason for this being that in no way was the testing procedure designed to evaluate the performance of the centrifuge, but rather, it was designed to evaluate what effects aerobic digestion has on centrifugation.

Figures 23 and 24 illustrate that the percent recovery peaked rather early in the digestion period and then declined during the remainder of the period, with a small upswing at the very end. This in essence would indicate that short periods of digestion time must be used to optimize the percent recovery during subsequent centrifugation. Since percent recovery is solely a function of feed, cake, and centrate solids (all other variables are held constant) it would be expected that feed and cake solids concentrations would decrease and centrate solids increase to explain the trend of the percent recovery. However, this was not the case. Centrate solids did increase as expected, but, as can be seen in Figures 25 through 28, as percent recovery decreased and centrate solids increased, the cake solids concentration also increased. This occurrence presents something of a problem when attempts to explain the trend in the percent recovery are made. One possible explanation, as stated in the previous Chapter, would be that, as the digestion time increased, more and more fine solids were sloughed from the walls of the centrifuge into the centrate and a larger percentage of the solids captured were coarse, thereby causing an increase in both cake and centrate solids concentrations. This explanation does not seem to be unreasonable since aerobic digestion tends to promote biological flocculation while simultaneously causing the fragmentation of dead cells. The intact cells tend to agglomerate into large, dense particles whereas the cellular debris becomes extremely fine lightweight solids.

When considering centrate and cake solids versus percent recovery, and cake solids versus centrate solids, it was possible to fit a single curve to data from both sludges. This indicates that these relationships generally will follow the same general trend regardless of the origin of the waste activated sludge used.

Specific resistance is another test which is affected by digestion, and it was thought that there would probably be a direct correlation between it and percent recovery for the centrifugation test. This was not the case for the Roanoke sludge, as percent recovery increased, filterability worsened. However, for the Corning sludge, as percent recovery increased so did filterability, especially in run #1 and to some degree in run #2. The specific resistance of both sludges varied for the two runs, however, the Corning sludge generally behaved as expected in both runs in accordance with results reported by Rivera-Cordero (39) and Parker (34). The Roanoke sludge has such a wide variety of constituents that its specific resistance was very unpredictable, although for run #2 it did follow a similar pattern to that reported by Rivera-Cordero (39). Overall the results of the specific resistance test showed that the filterability was poor throughout each run. The magnitude of the specific resistance values (m/kg 10^{13}, m/kg 10^{14}) was in the same range as the values obtained by Rivera-Cordero (39).

The oxygen uptake data for the two runs should be used in conjunction with the vacuum filtration data and the centrifugation data to explain the relative filterabilities and percent recovery of the sludges throughout the digestion periods. Since the efficiency of both processes depends somewhat upon the degree of natural biological flocculation achieved by the sludge, it would normally be expected that the maximum filterability and percent recovery would occur at the periods of highest biological activity (i.e. periods of maximum rate of oxygen uptake), if the activity is endogenous metabolism. This was not always the case. In run #2 this correlation did exist for percent recovery, and it existed for the specific resistance of the Roanoke sludge, but it did not correlate with the specific resistance of the Corning sludge. For run #1, however, only the percent recovery of the Roanoke sludge followed this correlation. The reason such a correlation was expected is that when high endogenous microbial activity exists, extracellular polymers that aid in flocculation and consequently, improve filterability, are produced in considerable quantities. If this interrelationship had not existed in any case, then it could be concluded that the biological polymer was not being produced. However, this was not the case. It is possible that the microbial activity was not predominantly endogenous when the exceptions occurred.

One of the most important parameters in evaluating a sludge stabilization process is the reduction of total and volatile suspended solids concentrations. During the course of this study, good solids reduction for both digestion runs occurred in only 15 days of digestion. It has been reported by Randall, Saunders, and King (37) that for waste activated sludge, solids reduction may continue to be significant after 15 days of aerobic digestion so it is possible that further solids reductions could have been obtained.

The relative rates of solids destruction were observed to be greatest through days 15 and 14 for run #1 and run #2, respectively. Although there was a wide variation in run #2, approximately 23 percent of overall solids destruction was good with both sludges being reduced.

The general trend for the reduction of suspended and volatile solids was similar indicating that percent volatility remained constant throughout the digestion period.

The pH data showed that a very small drop in pH occurred throughout the runs. This is contrary to the general findings of other studies (24, 25, 32). These studies have reported pH's as low as 4 and 5 after 15 days of digestion. However, as previously mentioned, (Chapter III) lime is added to the Corning plant during treatment. Furthermore, several industrial wastes, both pretreated and untreated, enter the Roanoke plant, and it is possible that both sludges had very high buffering capacities during the period of study. Such buffering capacities could prevent noticeable drops in pH during digestion.

As aerobic digestion proceeded during both runs, a decrease in biodegradable organic matter was expected. This occurred, as can be seen from the supernatant COD values in Figure 15, except for the Roanoke sludge of run #1. The behavior of the Roanoke sludge can be most easily explained as experimental error, however, the COD's were run in duplicate. As percent recovery decreased, centrate solids increased, thereby increasing the centrate COD, which was as expected. However, as centrate solids increased the COD value did not increase quite so sharply because the solids had undergone some degree of stabilization. This explains why the centrate COD value of days 14 and 15 are less than the initial COD values, although the percent recovery is lower. As previously stated, the Roanoke sludge for run

#1 does not follow this explanation and as before it can only be attributed to experimental error or left unexplained.

The BOD_5 data, as previously stated, was collected to see how centrifugation might effect the BOD_5 loading on a wastewater treatment plant when the centrate is returned to the head of the plant. It also was used as an indicator of the effectiveness of aerobic digestion. As might be expected, supernatant BOD_5 decreased throughout the entire digestion period. In the case of centrate BOD_5, as percent recovery decreased, BOD_5 increased. Both of these occurrences were expected.

Perhaps the most noticeable change that occurred as a direct result of aerobic digestion was that of odor. At the time of procurement, and especially for the first day of digestion, extremely offensive odors were produced by both sludges (with Roanoke being extremely nauseating). However, after the first day no further offensive odors were noticed throughout the duration of any of the digestion periods.

Based on all the data compiled and observations made during the course of this investigation, it was felt that aerobic digestion of the two waste activated sludges was successful. However, aerobic digestion followed by centrifugation was concluded to be a questionable solution to the sludge handling problem. Possible areas for further studies on this problem include:

(1) effect of pH

(2) effect of temperature

(3) effect of polymer and flocculant addition

Another area which could prove exceedingly valuable information would be that of using a solid bowl centrifuge.

VI. CONCLUSIONS

From the results of this investigation, the following conclusions have been derived.

1. The basket prototype centrifuge proved to be successful in the dewatering of both raw and digested waste activated sludge even with no polymer or flocculant aid addition.
2. Both filterability and centrifugation follow the same pattern of improvement and decline for prolonged periods of aerobic digestion.
3. Aerobic digestion generally improves both filterability and centrifugation during the early periods of digestion, after which the efficiency of both decline gradually for the remainder of the run.
4. Cake solids concentrations obtained during centrifugation varied inversely with increasing percent recovery.
5. Aerobic digestion does not benefit the percent recovery by centrifugation without polymer addition sufficiently to provide for the added cost of an aerobic digester prior to centrifugation.
6. Percent recovery increased when a feed sludge with a lower solids concentrations was used.

7. Future studies concerning centrifugation for sludge handling should be made. Objectives of these studies should include the centrifugation of fresh, aerobic, and anaerobically digested sludge to investigate the relative effects both types of digestion have on centrifugation. Also the effects of pH, temperature, solids loading, and flocculant and polymer addition should be investigated for a complete evaluation of the overall feasibility of centrifugation.

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VIII. APPENDIX

SPECIFIC RESISTANCE FILTRATION DATA

Filtrate Time (sec) for Digestion Run 1 - Corning Sludge

Digestion Time (days)	5	10	15	20	25	30	35	40	45	50	C (%)	r (m/kg x 10^{14})
1	12	31	59	94	139	193	255	327	407	499	1.66	0.168
3	14	36	68	111	164	226	300	385	485	593	1.54	0.209
5	9	27	52	83	120	165	217	276	344	418	1.44	0.151
7	12	25	50	69	-	160	212	268	334	406	1.45	0.147
10	21	48	83	127	178	240	309	386	473	566	1.46	0.174
12	18	45	82	130	190	260	341	431	531	640	1.41	0.228
15	10	26	48	77	113	154	203	259	320	388	0.98	0.202

Filtrate Time (sec) for Digestion Run 2 - Corning Sludge

Digestion Time (days)	5	10	15	20	25	30	35	40	45	50	C (%)	r (m/kg x 10^{14})
0	8	24	45	75	159	213	277	348	-	-	1.18	0.203
1	6	20	35	56	84	117	157	204	255	314	1.11	0.185
2	9	23	41	64	93	127	166	210	260	315	1.07	0.145
3	6	15	29	46	67	93	122	157	195	240	1.10	0.111
5	7	23	44	71	105	145	191	246	306	376	1.15	0.171
7	6	16	27	44	63	87	114	146	182	222	0.97	0.119
10	7	17	32	50	72	100	130	165	208	252	1.05	0.122
12	6	15	28	45	66	90	119	152	190	231	0.93	0.127
14	5	15	28	45	65	90	120	151	190	230	0.92	0.131

APPENDIX (Continued)

SPECIFIC RESISTANCE FILTRATION DATA

Filtrate Time (sec) for Digestion Run 1 - Roanoke Sludge

Digestion Time (days)	5	10	15	20	25	30	C (%)	r (m/kg x 10^{14})
1	190	482	933	1,516	2,262	-	2.76	0.501
3	500	1,262	2,390	3,850	-	6,194	2.68	3.60
5	490	1,280	2,420	3,960	-	-	2.42	4.23
7	658	1,618	2,918	4,622	6,707	-	2.39	4.40
10	945	2,313	4,193	6,610	9,600	-	2.38	6.39
12	860	2,185	4,063	5,917	9,216	-	2.23	6.33
15	902	2,235	4,062	6,214	9,406	-	2.23	5.83

Filtrate Time (sec) for Digestion Run 2 - Roanoke Sludge

Digestion Time (days)	1	2	3	4	5	6	7	8	9	10	C (%)	r (m/kg x 10^{14})
0	7	16	27	40	55	72	90	111	135	160	1.08	1.42
1	18	43	65	97	131	170	-	262	315	376	0.96	3.47
2	12	33	51	75	102	132	175	212	260	310	0.96	3.36
3	32	71	-	161	216	277	337	407	477	559	1.07	3.84
5	26	55	90	128	169	215	263	316	371	430	0.92	3.16
7	10	22	36	52	70	92	115	141	166	205	1.02	1.49
10	20	40	63	93	125	160	198	237	280	330	0.96	2.59
12	17	37	61	90	118	150	183	225	265	310	1.01	2.36
14	14	28	45	66	89	114	142	173	205	243	0.80	2.54

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THE EFFECTS OF AEROBIC DIGESTION ON CENTRIFUGATION

by

William E. Seyler, Jr.

ABSTRACT

The purpose of this investigation was to study the effects of activated sludge aerobic digestion on the subsequent performance of a centrifuge. Two runs, utilizing two, 55 gallon barrels as digesters per run, were conducted using detention periods of 15 and 14 days, for run #1 and #2, respectively. Besides centrifugation, various water quality parameters were monitored during the two digestion runs.

Results of this investigation indicated that the aerobic digestion process is suitable for waste activated sludge stabilization. Significant total and volatile solids reductions in conjunction with consistent supernatant COD and BOD_5 reductions were noted. However, prolonged periods of aeration caused a decrease in both the filterability and the centrifugation performances. Both reached their optimum peaks within the first 5 days of aeration and then gradually declined. This seems to indicate that once a sludge reaches the endogenous respiration state that sludge handling becomes much more difficult. The improvement in centrifugation efficiency that occurred during the early stages of aerobic digestion was not enough to justify the expense of aerobic digestion prior to centrifugation.