THE EFFECT OF SLUDGE AGE AND MICRO-
ORGANISM CONCENTRATION ON THE
THICKENING PROPERTIES OF
ACTIVATED SLUDGE

By

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1966

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1975

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ACKNOWLEDGEMENTS

I wish to extend my sincere appreciation to Dr. Don F. Kincannon, my principal advisor, for the guidance, advice, anc friendship he has extended during the past two years. I also wish to thank Drs. Anthony F. Gaudy Jr. and Richard N. DeVries for their instruction and consideration.

This investigation was made possible in part through financial support provided by the Federal Environmental Protection Agency training grant T-9000-78.

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CHAPTER I

INTRODUCTION

Because of our ever increasing population and expanding technology, the performance of secondary wastewater treatment systems is becoming more critical each year. Much work has been done in recent years on predicting the performance of the bio-mass in removing BOD in secondary wastewater treatment systems. Unfortunately, the performance of a secondary wastewater treatment system is dependent not only on the performance of the bio-mass in removing BOD, but is also dependent on the performance of the system in retaining the bio-mass in the system. The micro-organisms in the bio-mass are themselves BOD.

The operation which has traditionally been used for removal of the bio-mass from the treatment plant overflow is gravity settling in the form of a "secondary clarifier". In addition to the clarification function, the secondary clarifier in an activated sludge system must also provide a concentrated sludge for return to the aeration basin. While there are other physical operations which will produce either a more clarified overflow or a more concentrated sludge; there is no physical operation which will perform both functions as efficiently, economically, and with the same degree of simplicity of operation as gravity settling.

Many treatment plants have gone to the use of an additional thickening operation for waste activated sludge prior to final disposal. Possibly in the future activated sludge treatment plants will go to some additional thickening operation for return activated sludge and an additional clarification operation for plant overflow. Even should this be so; it would still be to our economic good to use gravity settling to its maximum capacity in order to reduce the necessary size of other, more expensive operations. At present, little is known concerning the parameters affecting the clarification and thickening operations of the secondary clarifier. It is quite likely that the performance of the secondary clarifier following the activated sludge process could be greatly enhanced by increased knowledge of the effects of the many variables which affect the performance of the secondary clarifier. The purpose of this study is to investigate the effect of sludge age on the thickening of activated sludge.

CHAPTER II

LITERATURE REVIEW

A. Description of Sedimentation Process

Sedimentation is a physical operation widely used in wastewater treatment plants to remove undesirable solids from the carrying water. In order for solids to be separable from the carrying water by sedimentation, certain conditions must be met. First, the solids must be of greater density than the water. Second, the solids must either be of sufficient particle size to allow gravity settling to occur or be capable of agglomeration into sufficiently large particles for gravity settling to occur. These requirements are due to the nature of the sedimentation operation and the physical laws governing it. Due to the influence of gravity, suspended particles of greater density than the suspending liquid tend to move toward an equilibrium state; i.e., when the buoyant force on a particle or some other supportive force is equal to the downward force of gravity on the particle. As long as the force of gravity pulling the particle downward is greater than the forces exerted upward on the particle, the particle will continue to move downward. The rate of downward movement of the particle in a given liquid, at a given temperature, is dependent on the size of the particle and its relative density with respect to the liquid. Where particle size and density are sufficiently great to overcome the retarding effects of the suspending liquid, sedimentation can occur and is a practical means of separation of the suspended solids and the suspending liquid.

Sedimentation, as applied to wastewater treatment, has two functions. First, the solids are separated from the bulk of the water, producing a clarified supernatant. Second, the solids are allowed to settle further - after separation from the bulk of the liquid - to reduce the water content of the solids. Both functions are important in wastewater treatment and both always occur.

Fitch (1) has defined four distinct classifications of sedimentation. At dilute solids concentrations, two types of settling can occur. Both are classified as "clarification" by Fitch. During "clarification" there is no clear line of demarcation between settling solids and supernatant water, but rather a changing concentration gradient. Initially the solids concentration is uniform throughout the water. As the larger, more dense particles begin to settle more rapidly than smaller, less dense particles; a concentration gradient develops in the water. In a batch settling tube, the particle concentration at a given level decreases as the particles settle. During clarification, the particles may or may not agglomerate. This is a significant point, as particle agglomeration can affect both the rate of solids removal and total solids removed. Fitch terms particulate settling with no particle aggomeration, "class 1 clarification". Where particle agglomeration occurs, the settling process is "class 2 clarification". As the particles continue to settle and are crowded more closely together, they enter Fitch's third settling regime. Now the solids settle as a single mass, in which all particles retain their positions in the suspension relative to each other. A well-defined boundary now exists between supernatant liquid and settling particles. This is termed "zone settling" by Fitch. As the mass of particles settles further, a slowing of rate of fall of the particles is observed. The settling mass has now entered the fourth regime of settling, "compression". Coe and Clevenger (2) felt that the reason for the observed slowing of descent of the mass of solids was mechanical support by lower solids layers of overlying solids layers. Fitch (3) discussed the mechanical support theory and other possible mechanisms in greater detail. He found that the static pressure head in the compression zone was not entirely accounted for by depth and density of the water; suggesting that mechanical support of particles is not entirely responsible for the observed decrease in rate of fall of the solids mass, but rather some change in flow regime is also probably involved. The four classifications are not quite so distinct as the above descriptions might lead the reader to believe, but they do provide a basis for selection of the most applicable design procedure by the environmental engineer.

B. History of Sedimentation Design

Quantitative descriptions of gravity settling began with people like Stokes and Newton. It was not until after the turn of the century that quantitative descriptions of gravity settling appeared which were of value to the engineer who dealt with the settling of heterogeneous suspensions. Development of quantitative models for clarification and thickening have occurred separately. The history of both will be traced here.

Hazen (4), in 1904, published a quantitative analysis of clarification of a class 1 suspension. Camp (5), in 1945, published a refined version of Hazen's analysis along with a straightforward design procedure and design equation. Camp's equation for predicting solids removal in a class 1 suspension for a given overflow rate is now found in most environmental engineering design books along with his design procedure (data collection procedure). Camp also attempted to apply his equation and data collection procedure to class 2 clarification. Fitch (6)(7) was later able to demonstrate that both overflow rate and detention time influence solids removal in class 2 suspensions. Initially, while particles of sufficient size to settle spontaneously without agglomeration are present, solids removal is a function of overflow rate. After the larger particles have been removed, leaving only solids of insufficient size to settle spontaneously without agglomeration, detention time becomes the independent variable controlling solids removal. Consequently, the accepted design equation for class 2 suspensions is a slightly altered form of Camp's original equation for class 1 suspensions. The form of Camp's equation applied to class 2 suspensions accomodates the effects of both overflow rate and detention time on removal. Camp's data collection procedure is applicable to both class 1 and class 2 clarification. A third equation describing clarification in an activated sludge secondary clarifier has been derived from the Talmadge and Fitch thickening model (8). It is simply the equation describing the required overflow rate for the initial gross removal of floc particles in the secondary clarifier. It does not account for removal of dispersed growth or very small floc particles which are removed with increased detention time in the clarifier. If the area (or volume) required for clarification is to be considered in the design of an activated sludge secondary clarifier, the modified Camp equation for class 2 clarification more accurately and completely describes solids removal in this situation. With the new Environmental Protection Agency regulations for waste treatment plant effluent suspended solids, the clarification function has become a critical consideration.

The first significant thickening model was developed by Coe and Clevenger (2) in 1916. As mentioned earlier, the dependent variable of interest with thickening is the production of a concentrated sludge or underflow (elimination of water from the solids). Coe and Clevenger presented no derivation of their equations, but one may be found in Behn and Liebman (9). The Coe and Clevenger model dealt with solids concentrations in the zone settling and compression range. Solids flux is the parameter controlling thickening in the Coe and Clevenger model. With zone settling and compression, the velocity of downward travel of solids decreases with increasing solids concentration. Solids flux is defined as the mass of solids transmitted downward per unit time per unit area. In the Coe and Clevenger model; for a given underflow solids concentration, each solids concentration between the influent solids concentration and the underflow solids concentration has a characteristic settling velocity or velocity at which solids may move vertically through a layer having that concentration. By running a series of batch settling tests at initial concentrations ranging from the expected clarifier influent solids concentration to the desired underflow solids concentration and observing the initial or "zone" settling velocity, the solids flux at each concentration may be computed using the Coe and Clevenger analysis. At some solids concentration in this range, the solids flux will be at a minimum. The required area for thickening may be computed from this minimum solids flux. The Coe and Clevenger analysis never caught on in the environmental engineering field possibly because Coe and Clevenger were mining engineers and published their article in a mining engineering journal or possibly because of the time consuming data collection procedures required by their design model.

In 1952, Kynch (10) described an analysis of the thickening process, which was later transformed into a readily understandable and useable form for thickener design by Talmadge and Fitch (8). One very basic assumption is made in Kynch's analysis, that settling velocity is a function only of local solids concentration. This assumption is also made in the Coe and Clevenger analysis, but the Coe and Clevenger analysis relies much less heavily on this assumption in actual application than does the Kynch analysis as applied by Talmadge and Fitch. The Talmadge and Fitch procedure requires a single batch settling test. The Talmadge and Fitch method also requires that the "critical" concentration be known. Unfortunately this is not a fixed point. It varies in the Coe and Clevenger analysis depending on desired underflow concentration and/or underflow removal rate. Eckenfelder and Melbinger (11) suggested an arbitrary method for determing the critical concentration. This method has since become an integral part of the Talmadge and Fitch design procedure. In the same article, Eckenfelder and Melbinger noted that the "critical" concentration derived using their procedure increased with increasing initial concentration. What one finally winds up with using the Talmadge and Fitch analysis as it is usually presented in design texts now, is an arbitrarily derived overflow rate. The area required for thickening of a given activated sludge, computed using the Talmadge and Fitch design procedure, will always be much smaller than the required thickener area computed by means of the Coe and Clevenger design procedure. Although the Coe and Clevenger analysis is theoretically and empirically more sound, the Talmadge and Fitch analysis is much simpler to apply and consequently appears in design texts as the preferred method of thickener design. Fitch (3), a co-author of the original Talmadge and Fitch article presenting this analysis, indicated the inadequacies of this analysis and disinherited it.

Two papers were published by chemical engineers on thickener models similar to Coe and Clevenger's thickener model - one in the mid-1950's and the other in the mid-1960's. Yoshioka et al (12), using the Coe and Clevenger solids flux equation, presented a very useful graphical solution to the Coe and Clevenger equation. However, the graphical solution of Yoshioka et al is much more aptly applied to the solids flux equation of Hassett (13), who also presented a trial and error graphical solution which is more aptly applied to the Coe and Clevenger equation. The Coe and Clevenger and Hassett equations for solids flux are different forms of the same relationship. Either may be derived from the other. Dick (14)(15) put the

Hassett equation and the Yoshioka graphical solution together and introduced them to the environmental engineering field. Dick's thickening analysis produces the same results as the Coe and Clevenger analysis, but the required computations are somewhat less in the Dick analysis. The data collection procedure is the same in both cases.

Collection of thickening data for design of an activated sludge secondary clarifier is somewhat complicated by the fact that the observed zone settling velocity varies not only with initial concentration, but with several other factors as well. For a given activated sludge suspension at a given initial concentration, the zone settling velocity varies with settling tube diameter, settling tube depth, and stirring. Dick (16) found that the zone settling velocity of an activated sludge suspension increased at all concentrations observed with increased settling tube depth. Vesilind (17) found that the zone settling velocity of activated sludge increased with increasing settling tube diameter at high concentrations and decreased with increasing settling tube diameter at low concentrations. Vesilind also mentioned that stirring increases the observed settling velocity. Temperature would of course affect the settling rate of activated sludge by changing the viscosity of the water. Temperature, stirring, and other physical and chemical variables can be easily controlled in a batch settling test. The tube depth and diameter are not so easily controlled, as the effect of these two factors varies between activated sludge suspensions. A settling tube of sufficient size to allow the observed zone settling velocity to approximate the maximum possible value would require far more activated sludge solids than could be grown in a laboratory, bench-scale, activated sludge unit. Use of smaller settling tubes for design data collection would result in considerable overdesign.

C. Effect of Sludge Age on Thickening

In designing a secondary clarifier for the activated sludge process; overflow area, volume, and sludge removal rate can be varied to meet the desired operational characteristics. Once the plant has been built and is operating, the only clarifier control variable open to the treatment plant operator is the sludge removal rate. But is this true? The solids loading on the secondary clarifier may be reduced by wasting more solids from the system. In fact, this is a strategy often used by treatment plant operators. Decreasing the mixed liquor suspended solids decreases sludge age. This seems to be a reasonable strategy, but what of the effect of sludge age on the settling characteristics of the activated sludge bio-mass? It is well known that sludge age affects other characteristics of the bio-mass such as sludge yield and BOD removal. Sludge age may also have a gross effect on the settling properties of activated sludge bio-mass. If in fact sludge age does have a significant effect on the settling properties of activated sludge, the relationship between sludge age and the various settling properties of an activated sludge could be of great significance both to the treatment plant designer and the operator.

In 1967, Ford and Eckenfelder (18) ran three bench-scale activated sludge units using three different wastes - brewery waste, petrochemical waste, and domestic waste. Each of the units was run over a range of F/M ratios (BOD_5) from zero to one or greater. The sludge volume index for all three units was observed to decrease over the range of F/M ratios from near zero to about 0.2 or 0.3 and then increase again with increasing F/M ratio. The inverse occurred with zone settling velocity, which first increased up to a F/M ratio of about 0.2 or 0.3 and thereafter decreased with increasing F/M ratio. This data suggests that sludge age does in fact affect the settling characteristics of an activated sludge bio-mass. However, without further information not supplied in this study; F/M ratio cannot readily be related to sludge age. Further, both the zone settling velocity and sludge volume index of an activated sludge is dependent on initial bio-mass concentration (mixed liquor suspended solids in this study). The bio-mass concentration at each F/M ratio was not reported in this study.

In 1971, Bisogni and Lawrence (19) ran several bench-scale activated sludge units simultaneously varying only the sludge age of the units. The sludge ages of the units varied from 0.25 days to 12 days. They found that the zone settling velocity of a sludge suspension having an initial concentration of 2000 mg/l decreased linearly from a sludge age of 12 days to a sludge age of 4 days and decreased little more in going to a sludge age of 2 days. They also found that the sludge volume index slowly increased as the sludge age decreased from 12 days to 4 days, jumped to very high values at sludge ages of 2 and 3 days, and dropped to a much lower value at a sludge age of one day. The sludge volume index at each sludge age was determined at the different mixed liquor suspended solids levels (which decreased with decreasing sludge age). They also found that effluent suspended solids increased from a minimum at a sludge age of one day to a maximum at a sludge age of three days. The effluent suspended solids then decreased to a minimum at a sludge age of six days and again increased with increasing sludge age. In this study, the zone settling data at each sludge age is comparable, unlike the data from the previous study by Ford and Eckenfelder. However, in order to determine how sludge age might affect thickener design and operation, knowledge of the effect of sludge age on the relationship between a given sludge concentration and zone settling velocity at that concentration is essential. If the preferred thickening model, Coe and Clevenger's or Dick's (which are equivalent), is to be applied; this information must be known. The Talmadge and Fitch thickening model, which cannot be applied to operation and only questionably to design, would require the same information for design. That is, in designing an activated sludge plant; a trade-off may be made between the interdependent variables of aeration basin volume and mixed liquor suspended solids concentration. Knowledge of the zone settling velocity for a given concentration and sludge age would be of little value. The criticism made of the sludge volume index data in the study by Ford and Eckenfelder also applies here. Sludge volume index for a given activated sludge suspension varies with initial concentration. The effluent suspended solids data suggest a complex relationship between sludge age and clarification.

Roper and Grady (20) produced a mathematical model to describe thickening using Dick's equation for solids flux. Roper and Grady substituted equations from Vesilind (21) and Bisogni and Lawrence (19) - actually derived by Roper and Grady from Bisogni and Lawrence's data, using Vesilind's equation - into the Dick equation. Their intent was to incorporate the effect of both sludge concentration and sludge age on zone settling velocity and consequently on solids flux. The major objection to their model is the implied general applicability of their model to thickening of activated sludge. Roper and Grady suggested that Vesilind's equation always describes the relationship between sludge concentration and zone settling velocity and that the constants in the equation are invariant. Vesilind himself notes that the applicability of his equation or any other for describing the relationship between sludge concentration and zone settling velocity must be individually determined for each sludge suspension (21). Vesilind himself presented two slightly different equations in the two articles previously cited (17)(21). As noted by Dick (22), other authors have presented very different equations to describe the relationship between zone settling velocity and sludge concentration. Vesilind further noted that the constants in his equations are not invariant and their values must be determined for each sludge suspension. Bisogni and Lawrence only presented a single zone settling velocity for each sludge age at a constant initial concentration of 2000 mg/l. They presented no equations describing the relationship between zone settling velocity and sludge age. Had Bisogni and Lawrence determined the zone settling velocities at various initial sludge concentrations, as well as at various sludge ages; there might have been some basis either for the existence of or for evaluating Roper and Grady's computer simulation model. As it stands at present, there is no empirical basis for a general thickening model relating zone settling velocity, sludge age, and sludge concentration for all sludge suspensions. Because of the variability of settling characteristics among sludge suspensions, the accuracy and value of Roper and Grady's model or any other model is questionable. The preferred design method would of course be pilot plant data relating sludge age, sludge concentration, and zone settling velocity for activated sludge developed from a particular waste.

CHAPTER III

MATERIALS AND METHODS

In order to observe the settling properties of activated sludge bio-mass of various ages, a bench-scale activated sludge unit was operated continuously under controlled conditions for approximately eight months.

A. Laboratory Apparatus

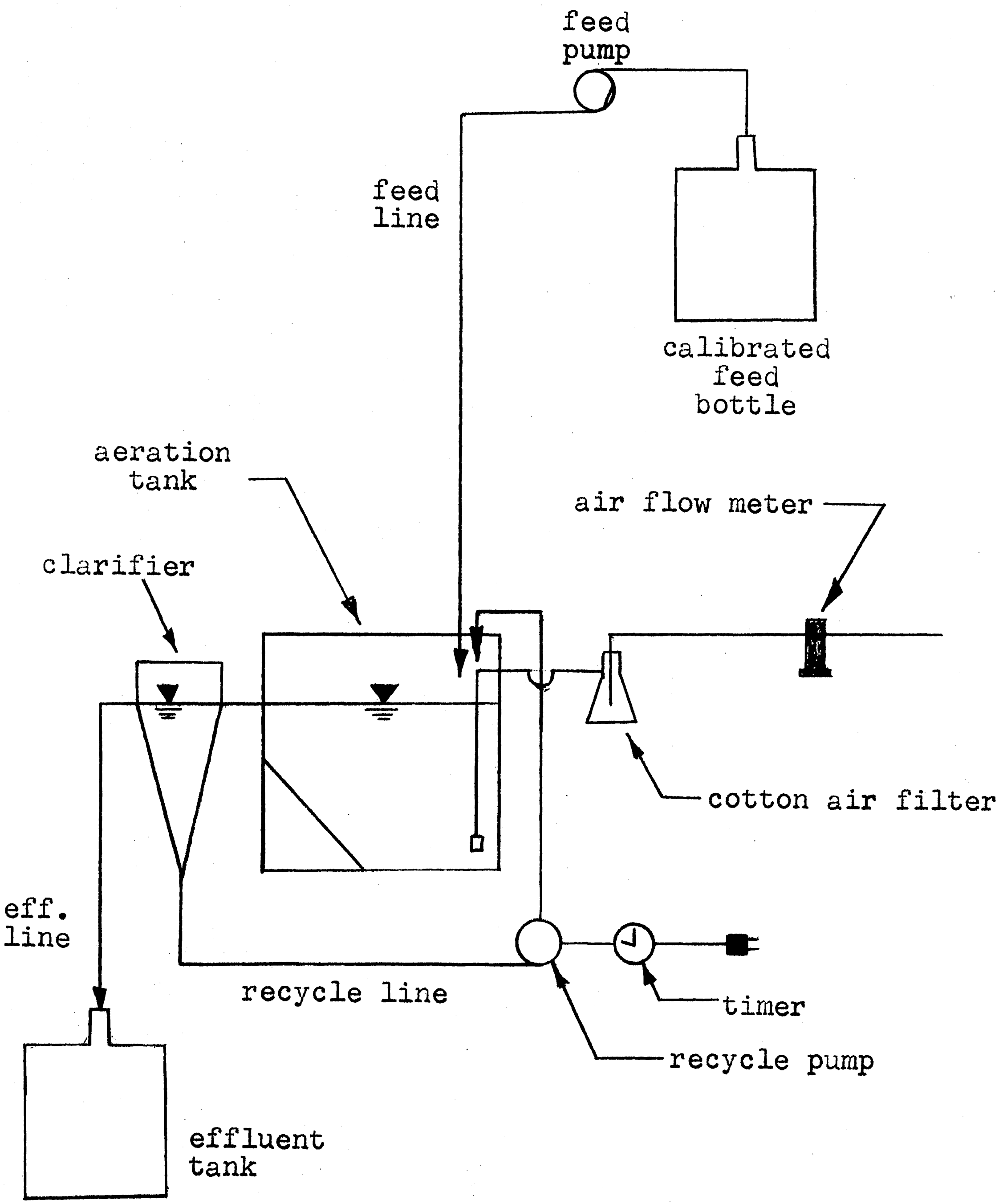
A diagram of the experimental apparatus is presented in Figure 1.

The aeration tank was a bench scale unit having a volume of 8.6 liters. The tank was rectangular in shape and made of one-fourth inch thick plexiglass.

A feed rate of 8.6 liters/day was supplied to the reactor by means of a Milton Roy "Mini-pump" (model MM2-B-96R). The feed rate was checked daily by reading the volume pumped during the previous twenty-four hours (see description of feed bottles below). If the pumping rate was incorrect, a graduated cylinder and timer were used to adjust the pumping rate.

The feed was mixed every other day in a five gallon, glass bottle (17.2 liters/2 days). The bottle volume was marked in one liter graduations to 18 liters.

Figure 1. Experimental Activated Sludge Unit


feed
pump
feed
line
calibrated
feed
bottle
aeration
tank
air flow meter
clarifier
cotton air filter
eff.
line
recycle line
timer
recycle pump
effluent
tank

Air was supplied to the aeration tank through two sintered glass diffusers. The air flow was maintained at 7.5 ± 0.5 cubic feet/hour. A Gelman air flow meter was used to monitor the air flow. A glass cotton filter was placed between the diffusers and the air outlet to prevent any oil in the air lines from entering the experimental unit.

The aeration tank overflow flowed by gravity into a conical glass clarifier having a volume of 5.4 liters. Flow into the clarifier entered through a vertical, cylindrical baffle in the center of the clarifier. The clarifier overflow flowed by gravity to a five gallon glass bottle, which was emptied daily. Solids were withdrawn from the bottom of the clarifier every thirty minutes and pumped back into the aeration tank by means of a Sigmamotor finger pump (model T8) operated automatically by a Dayton timer.

The pH of the system was monitored daily using a Beckman Expandomatic SS-2 pH meter. The pH of the system, both influent and effluent, was maintained at 7.2 ± 0.1 by means of a phosphate buffer system.

The temperature was monitored with a Curtin laboratory thermometer. The temperature in the aeration tank was maintained at 23 ± 1 °C. During the summer, when operation of the unit was initiated, temperature control was no problem. However, the temperature in the laboratory began to fluctuate with the onset of winter. The aeration tank was then placed in a Thelco water bath (model 83), in order to maintain the selected temperature. The temperature in the clarifier, which was not heated, stayed from 0.5 to 1 °C colder than the aeration tank.

B. Feed Solution

The chemical composition of the feed solution is listed in Table I. Four stock solutions were made up in concentrated form. The composition of the four stock solutions are as indicated in Table I. In mixing the feed solution; 45 mililiters of stock solutions one, two, and three, and 90 mililiters of solution four were added to enough tap water to make 18 liters of feed.

C. Experimental and Analytical Procedures

The microorganism seed was drawn both from several units already operating in the bio-engineering laboratories and from the primary clarifier overflow of the Stillwater municipal treatment plant. The unit was operated as a batch reactor until the biological solids reached approximately 3000 mg/l, at which time a conversion was made to a continuous flow process.

Sludge age was selected as the controlling parameter of operation. The selected sludge age was maintained by wasting of biological solids from the aeration tank. Microorganisms were wasted daily at the same time. The Amount to be wasted was computed using equations to be discussed later. The experimental unit was operated continuously at five sludge ages in descending order - eleven days, nine days, seven days, five days, and two days. After removal of the appropriate volume of biological solids from the aeration tank, an equal amount of effluent was returned to the aeration tank.

TABLE I

COMPOSITION OF SYNTHETIC WASTEWATER

Solution	Component	Stock Solution Conc.	Volume per Liter of Feed	Feed Conc.
number	-	(g/l)	(ml/l)	(mg/l)
1	glucose	200	2.5	500
2	$(NH_4)_2SO_4$	100	2.5	250
3	$MgSO_4$	10	2.5	25
	$FeCl_3$	0.05		0.125
	$MnSO_4$	1.0		2.5
	$CaCl_2$	0.75		1.875
4	KH_2PO_4	38.75	5.0	193.75
	K_2HPO_4	124.5		622.5
5	TAPWATER		987.5	

The use of sludge age as the operational parameter required periodic measurement of biological solids concentration and substrate concentration.

Biological solids in the aeration tank and clarifier effluent were monitored to establish operational parameters; e.g., sludge age, reaching of steady state, cell yield, etc. The suspended solids concentrations mentioned above were monitored aperiodically - approximately every other day. Suspended solids concentrations were measured in accordance with Standard Methods (23), except that membrane filters having a pore size of 0.45 micrometers were used in place of glass filters.

The substrate concentration of the feed and the filtered clarifier effluent were monitored by means of the Chemical Oxygen Demand test. The COD tests were run in accordance with the methods stated in Standard Methods (23). The COD of the feed and filtered effluent were monitored two to three times per week.

The additional variables measured were zone settling velocity, sludge volume index, and settled sludge concentration after 24 hours.

The settling velocity was measured by placing one liter of aeration tank liquor containing a known concentration of suspended, biological solids in a one liter graduated cylinder. The suspension was mixed by slowly pouring back and forth between two one-liter cylinders three times. After the third pouring the suspension was allowed to settle and the position of the solids-liquid interface was recorded at various intervals between time zero and sixty minutes (minutes 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, 30, 40, 50, and 60). Greater suspended solids concentrations than the mixed liquor suspended solids was achieved by allowing the mixed liquor to settle and drawing off supernatant. Suspended solids concentrations less than that of the mixed liquor was achieved by diluting the mixed liquor with clarifier effluent. The measurement of settling velocities at each sludge age was begun when the system reached steady state; i. e., a stable solids concentration was reached. One or two measurements were made per day, every other day. One set of measurements of settling velocity, at various solids concentrations across the range of concentrations to be measured, was made and then a second set of measurements was made in the same manner. More settling tests were made at lower sludge ages, as there was more variability in settling velocities at the lower sludge ages. Two one-liter, graduated cylinders of clear glass were used to run the settling tests. The depths of the cylinders (to the 1000 milliliter mark) were 1.18 and 1.19 feet. The diameter of the cylinders was 2 5/16 inches. There was no stirring during the settling tests.

The sludge volume index was measured during each test of settling velocity in accordance with the method described in Standard Methods (23).

After approximately every other of the above settling tests, the solids were allowed to settle quiescently for 24 hours in the cylinder (where the mass of solids in the cylinder were equal to or less than the mass of solids to be wasted).

D. Methods of Data Analysis

The data obtained during the course of this investigation were analyzed by means of the mathematical relationships for a completely-mixed, activated sludge process presented by Sherrard, Schroeder, and Lawrence (24).

COD removal efficiency was calculated by means of the equation

$$E = \frac{(S_o - S)}{S_o} \times 100 \qquad (1)$$

where

E = COD removal efficiency, percent

S_o = influent COD concentration, mg/l

S = effluent COD concentration, mg/l

Sludge age or mean cell residence time was calculated by means of the equation

$$\theta_c = \frac{VX}{Q_w X + (Q - Q_w)X_e} \qquad (2)$$

where

θ_c = sludge age, days

V = volume of aeration tank, liters

X = aeration tank solids concentration, mg/l

Q_w = waste flow rate, liters/day

Q = flow rate through system, liters/day

X_e = effluent solids concentration, mg/l

The observed yield coefficient was calculated by means of the equation

$$Y_o = \frac{Q_w X + (Q - Q_w)X_e}{Q(S_o - S)} = \frac{\Delta X/\Delta t}{\Delta S/\Delta t} \qquad (3)$$

where

Y_o = observed yield coefficient, mg/mg

The specific utilization of substrate was calculated using the equation

$$U = \frac{\Delta S/\Delta t}{X} = \frac{Q(S_o - S)}{VX} \qquad (4)$$

U = specific utilization, days^{-1}

The true yield coefficient and the maintenance energy coefficient (or decay coefficient) were graphically determined by plotting the experimentally derived values of observed growth rate versus the specific utilization. The relevant equations are

$$\mu = \frac{1}{\theta_c} \qquad (5)$$

$$\mu = Y_t U - b \qquad (6)$$

where

μ = observed specific growth rate, $days^{-1}$

Y_t = true yield coefficient, mg/mg

b = maintenance energy coefficient, $days^{-1}$

The true yield coefficient and the decay coefficient were also graphically determined by plotting the observed yield coefficient versus sludge age. The relevant equation describes a straight line relationship of the form

$$\frac{1}{Y_o} = \frac{b}{Y_t}\theta_c + \frac{1}{Y_t} \tag{7}$$

where

Y_o = observed yield coefficient, mg/mg

Y_t = true yield coefficient, mg/mg

b = decay coefficient, day^{-1}

θ_c = sludge age, day

The microorganism concentration in the aeration tank was estimated using the equation

$$X = \frac{Y(S_o - S)\theta_c}{(1 + b\theta_c)\theta} \tag{8}$$

where

θ = hydraulic detention time, days

Waste sludge production was calculated using the equation

$$P_x = Q_w X + (Q - Q_w)X_e \tag{9}$$

where

P_x = waste sludge production, mg/day

In addition to the above equations describing the kinetics of a completely mixed activated sludge system, the following relationships were used to present the experimental data in a meaningful form.

The solids flux due to gravity was calculated using the following equation

$$G_g = C_i V_i \tag{10}$$

where

G_g = solids flux due to gravity, lb/ft^2- day

C_i = concentration at some point in thickener, lb/ft^3

V_i = zone settling velocity at C_i, ft/day

The ratio of solids underflow concentration to mixed liquor suspended solids concentration was calculated using the equation

$$\beta = \frac{X_r}{X} \tag{11}$$

where

β = ratio of solids underflow concentration to mixed liquor suspended solids concentration

X_r = solids underflow concentration, mg/l

X = mixed liquor suspended solids concentration, mg/l

CHAPTER IV

RESULTS

The results of this study are presented below. The observed operational parameters of the experimental activated sludge unit are presented first in order to provide a basis for evaluating the settling and compaction data. The settling and compaction data are then presented.

A. Operating Data

The COD removal efficiencies for the activated sludge unit are presented in Figure 2. Removal efficiency is presented as a function of sludge age. As shown in Figure 2, the percentage COD removed was constant over the range of sludge ages investigated.

The effluent COD is shown in Figure 3 as a function of sludge age. As can be seen the effluent COD varied little over the range of sludge ages studied.

Specific utilization is shown in Figure 4 as a function of sludge age. Specific utilization decreased with increasing sludge age as expected.

An average value of observed yield was calculated for each sludge age. The relationship between observed yield and sludge age is shown in Figure 5. The observed yield

Figure 2. Percent COD Removed versus Sludge Age

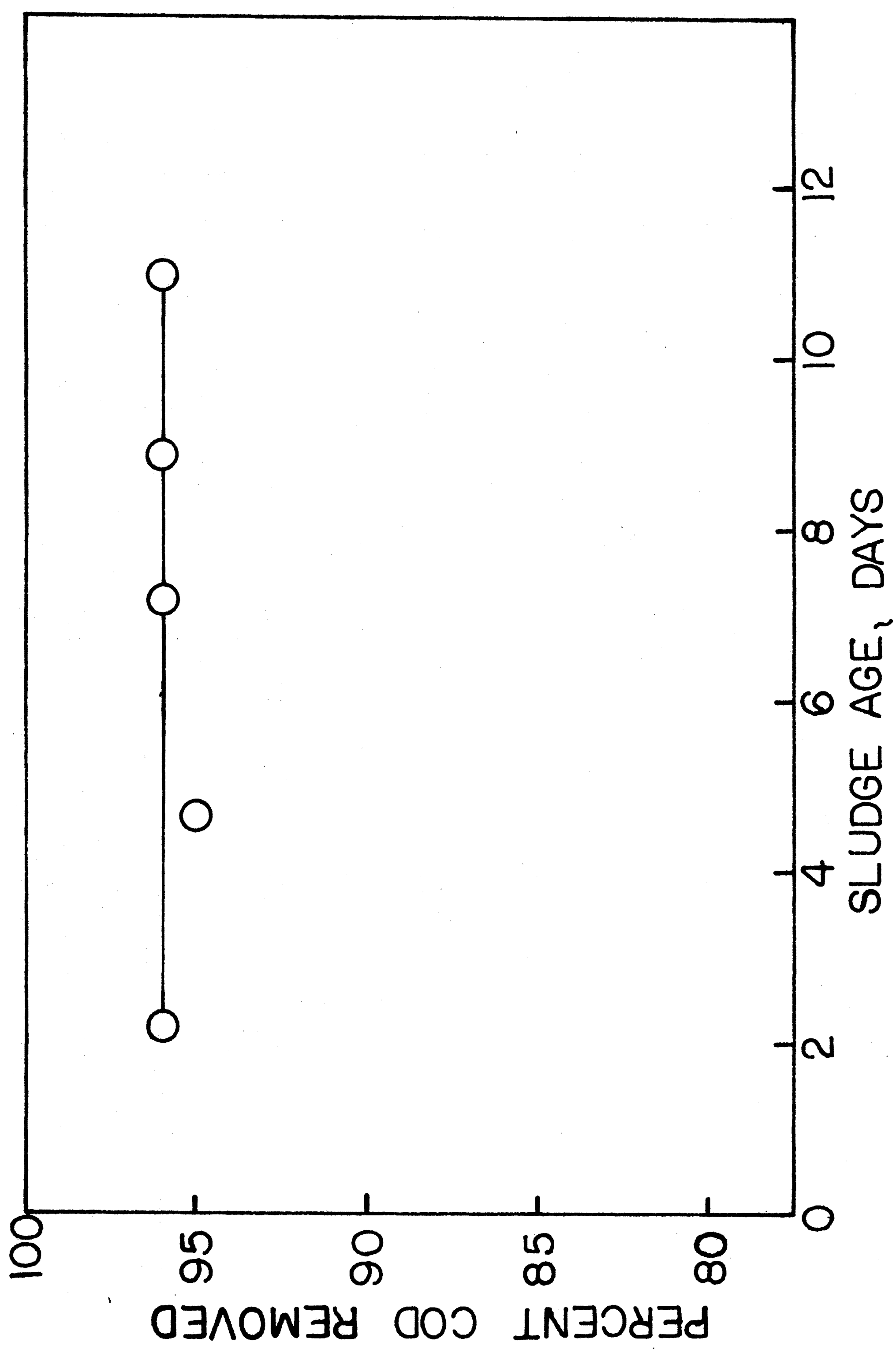

PERCENT COD REMOVED
100
95
90
85
80
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 3. Effluent COD versus Sludge Age

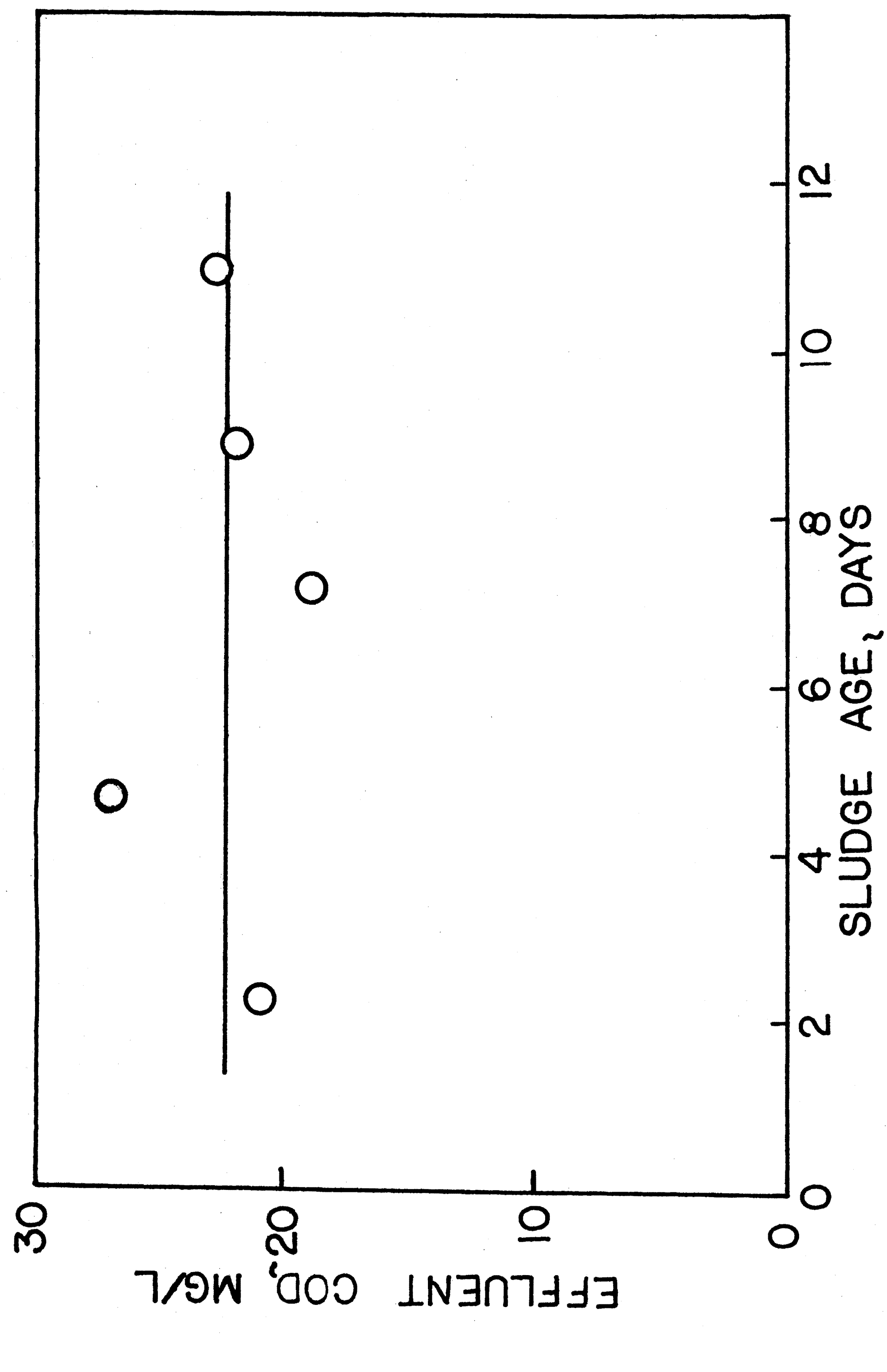

EFFLUENT COD, MG/L
30
20
10
0
SLUDGE AGE, DAYS
0
2
4
6
8
10
12

Figure 4. Specific Utilization versus Sludge Age

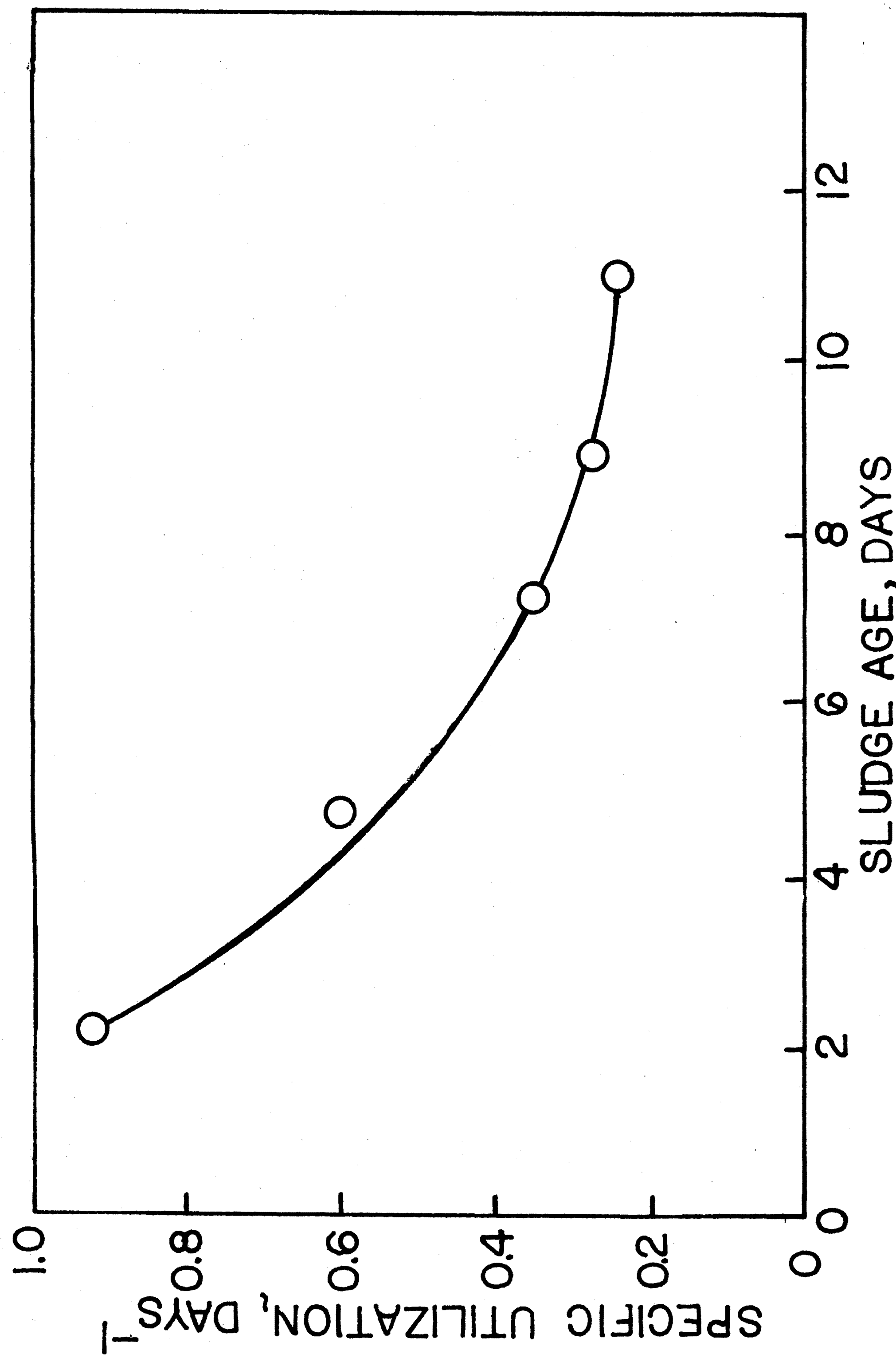
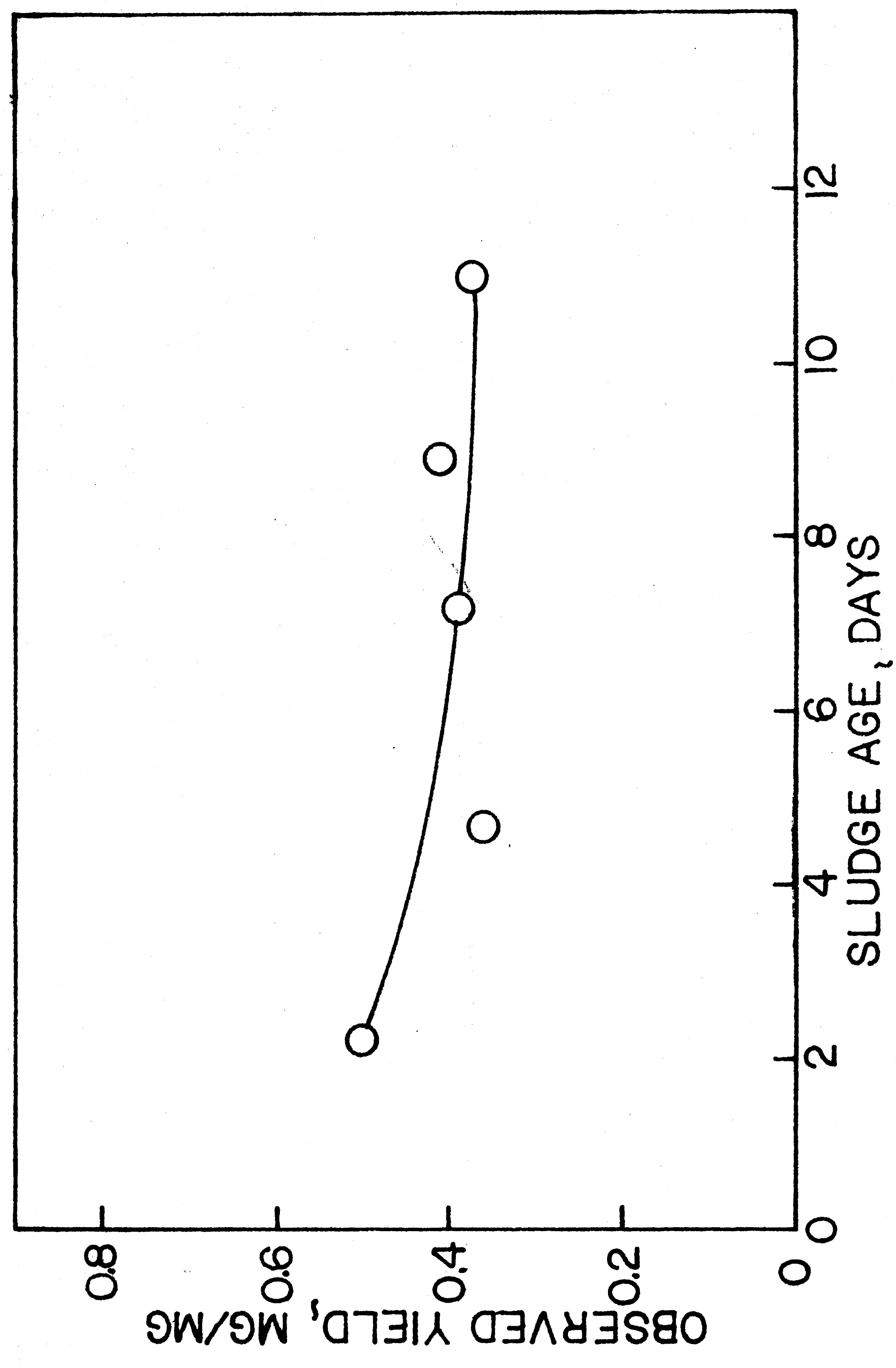

SPECIFIC UTILIZATION, DAYS^{-1}
1.0
0.8
0.6
0.4
0.2
0
SLUDGE AGE, DAYS
0
2
4
6
8
10
12

Figure 5. Observed Yield Coefficient versus Sludge Age


OBSERVED YIELD, MG/MG
0
0.2
0.4
0.6
0.8
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

increased with decreasing sludge age in the expected manner.

The specific utilization as a function of the reciprocal of sludge age is shown in Figure 6. The true yield coefficient and decay coefficient were derived from Figure 6 using equation 6. The true yield coefficient was found to be 0.57 mg/mg. The decay coefficient was found to be 0.057 $days^{-1}$.

The reciprocal of the observed yield versus sludge age is shown in Figure 7. The true yield coefficient and decay coefficient were determined again, using equation 7. The true yield coefficient was found to be 0.56 mg/mg and the decay coefficient was found to be 0.058 $days^{-1}$.

The mixed liquor suspended solids concentrations are presented versus sludge age in Figure 8. The points are the observed values of mixed liquor suspended solids concentration at each sludge age. The curve was derived using equation 8. As can be seen, the observed values are very similar to the values predicted by equation 8. The value of mixed liquor suspended solids concentration used at each sludge age was the maximum concentration achieved each day. Excess sludge was wasted only once a day and mixed liquor suspended solids concentration was determined just prior to sludge wasting.

The effluent suspended solids varied in a complex fashion with sludge age. The relationship between effluent suspended solids and sludge age is shown in Figure 9. Both the clarifier overflow rate and detention time were constant for

Figure 6. Specific Growth Rate versus Specific Utilization

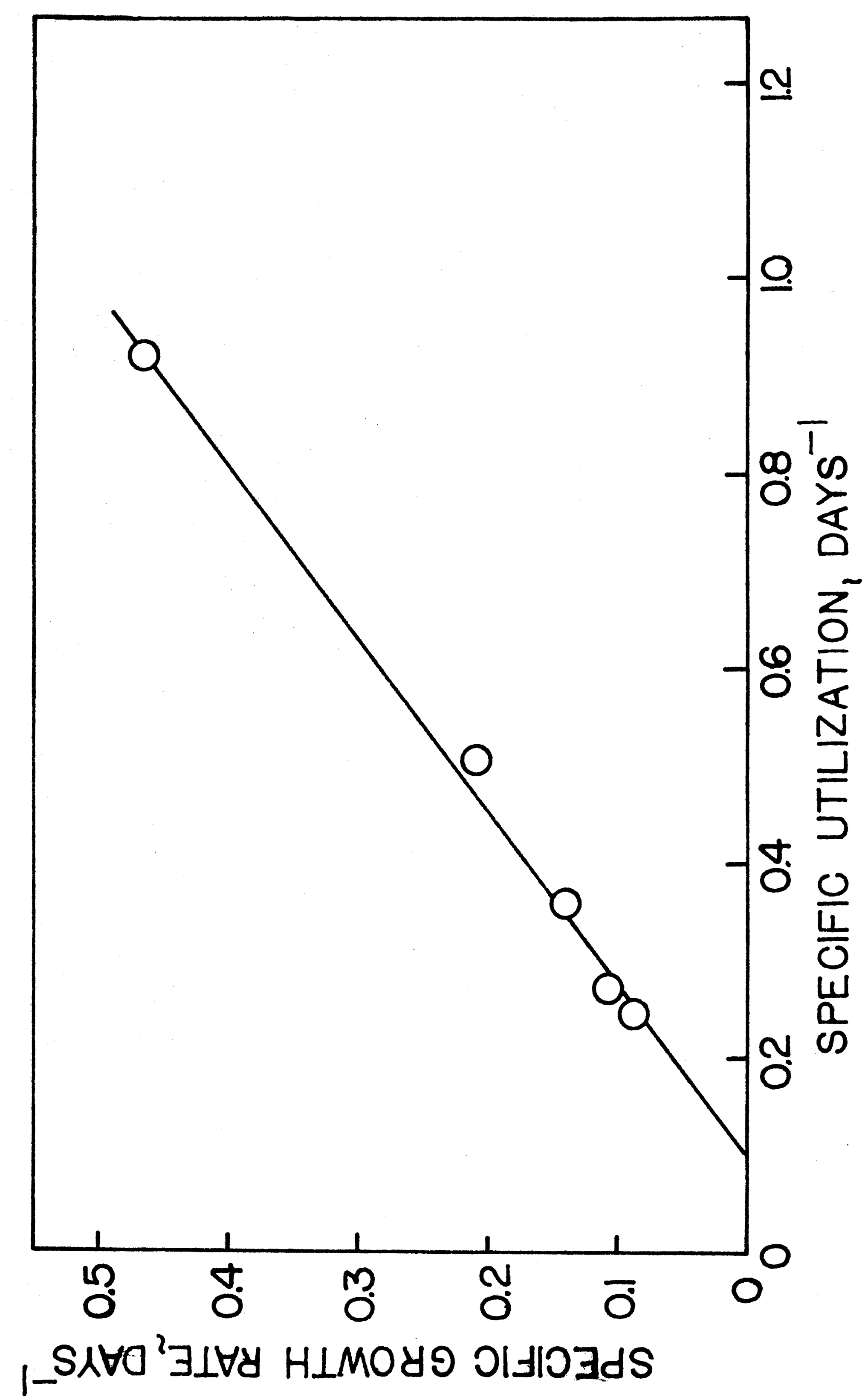

SPECIFIC GROWTH RATE, DAYS⁻¹
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1.0
1.2
SPECIFIC UTILIZATION, DAYS⁻¹

Figure 7. Reciprocal of Observed Yield versus Sludge Age

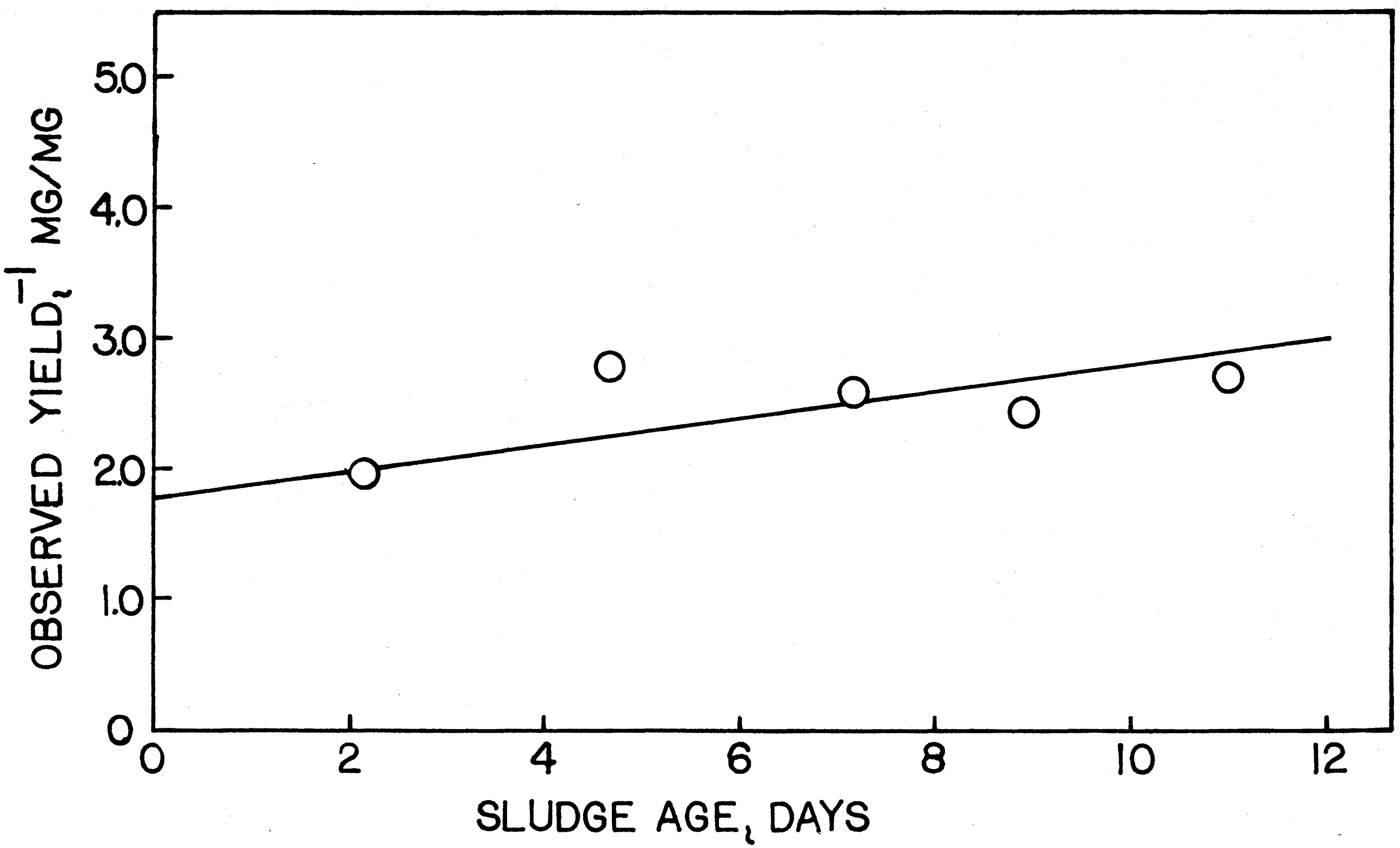

OBSERVED YIELD,⁻¹ MG/MG
5.0
4.0
3.0
2.0
1.0
0
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 8. Mixed Liquor Suspended Solids versus Sludge Age

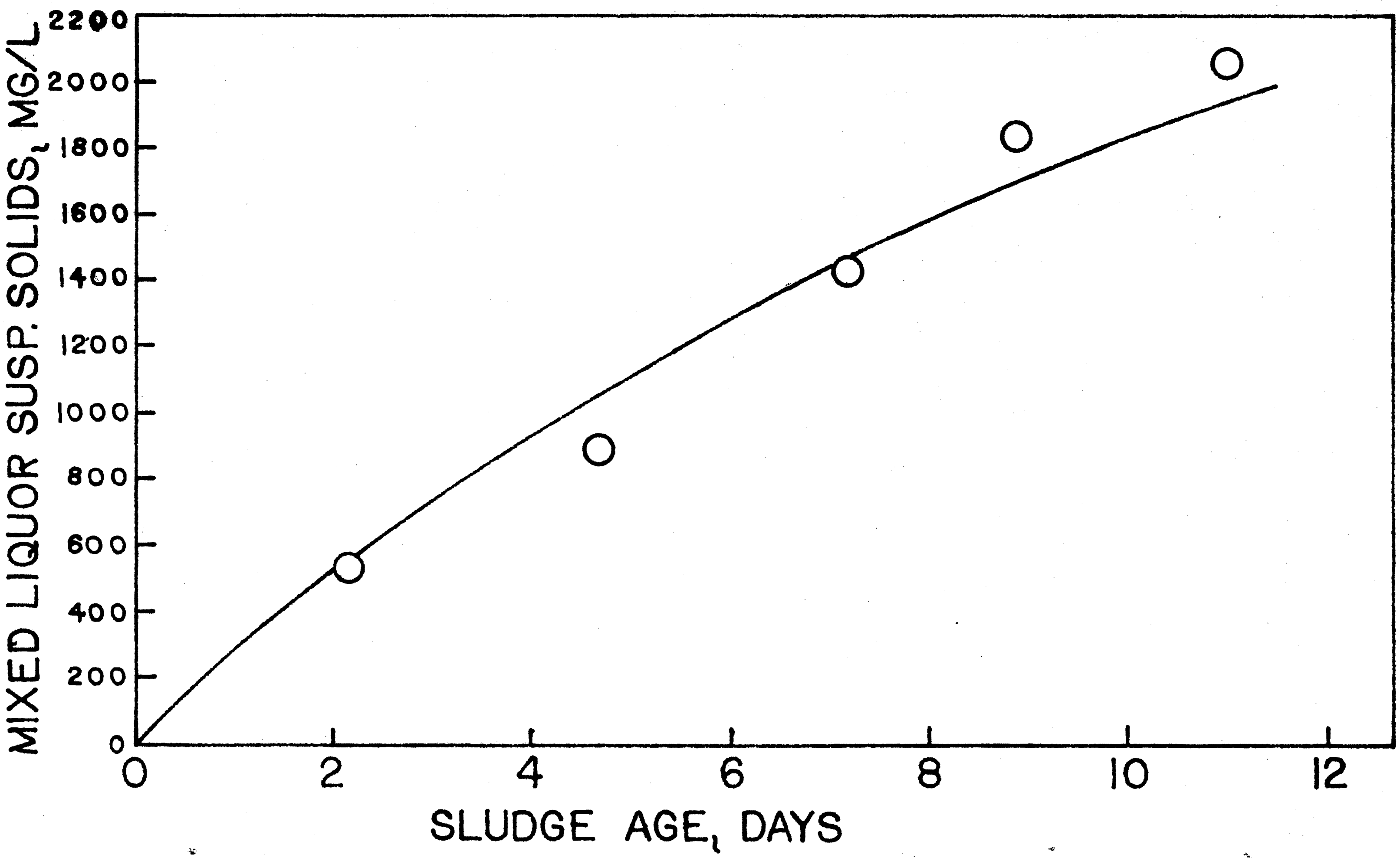
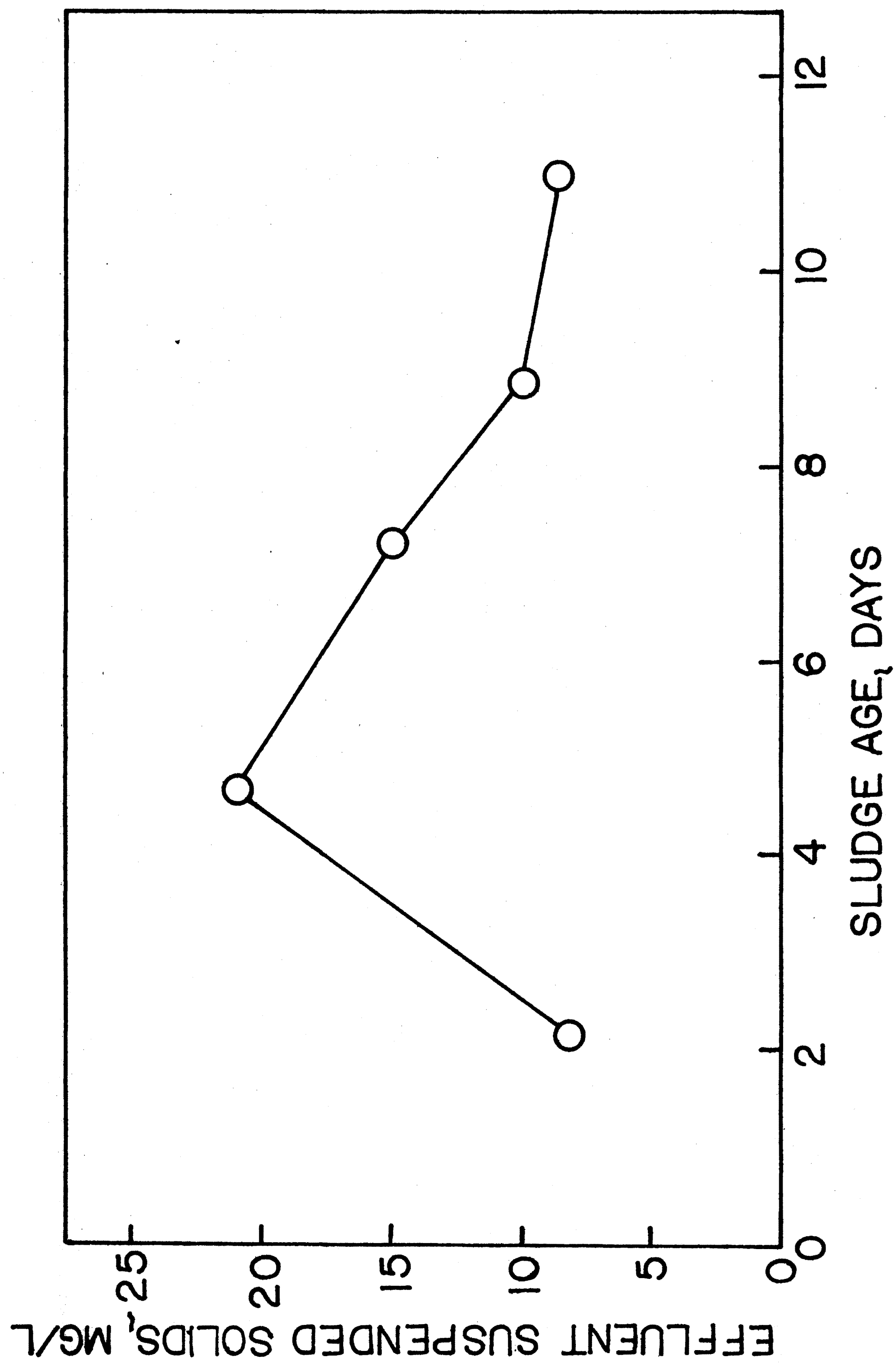

MIXED LIQUOR SUSP. SOLIDS, MG/L
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 9. Effluent Suspended Solids versus Sludge Age


EFFLUENT SUSPENDED SOLIDS, MG/L
0
5
10
15
20
25
SLUDGE AGE, DAYS
0
2
4
6
8
10
12

all sludge ages. The average effluent suspended solids were found to be somewhat greater at five and seven day sludge ages than at two, nine, or eleven day sludge ages.

Excess sludge production is presented versus sludge age in Figure 10. Sludge production decreased with increasing sludge age as predicted by the mean cell residence time equations.

B. Thickening and Compaction Data

When a given homogeneous sludge suspension is placed in a settling column; after a brief period, the top level of the sludge begins to gall due to settling of the sludge suspension. Initially the top level of the sludge suspension falls at a constant velocity and after a period begins to decelerate. During the initial, constant velocity period; the rate of fall is thought to be a function of the initial sludge concentration only. The velocity during this constant velocity period is referred to as the zone settling velocity. The zone settling velocities of sludge suspensions of various sludge ages and concentrations were observed during this study. Figures 11 through 15 present the observed relationship between zone settling velocity and initial sludge concentration. Figure 11 presents this relationship at a sludge age of 11.0 days. The succeeding figures show this relationship at successively lower sludge ages, going from a sludge age of 8.9 days in Figure 12 to a sludge age of 2.2 days in Figure 15. The zone settling velocity at a given sludge

Figure 10. Sludge Production versus Sludge Age

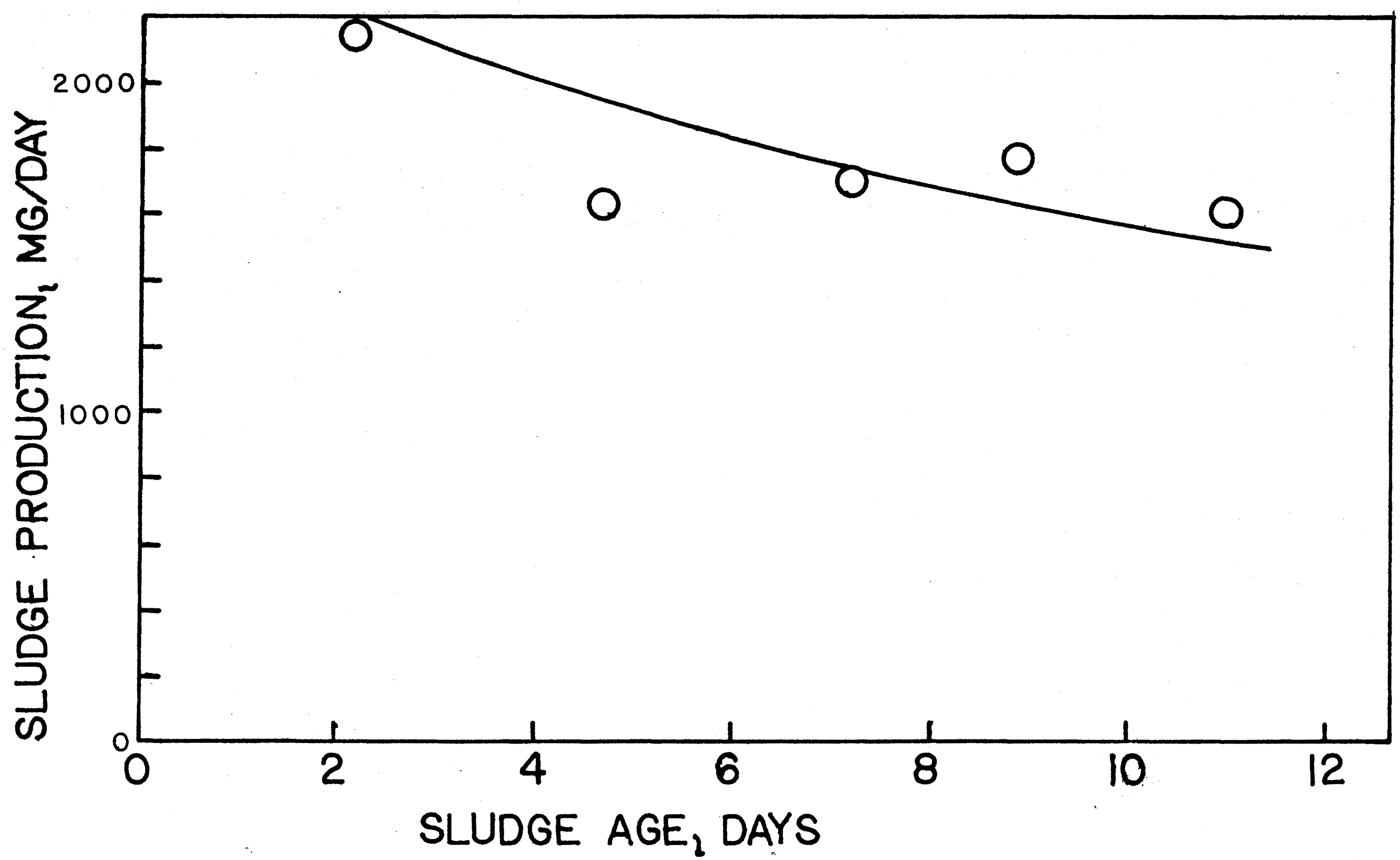

SLUDGE PRODUCTION, MG/DAY
2000
1000
0
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 11. Zone Settling Velocity versus Sludge Concentration at Sludge Age of 11.0 Days

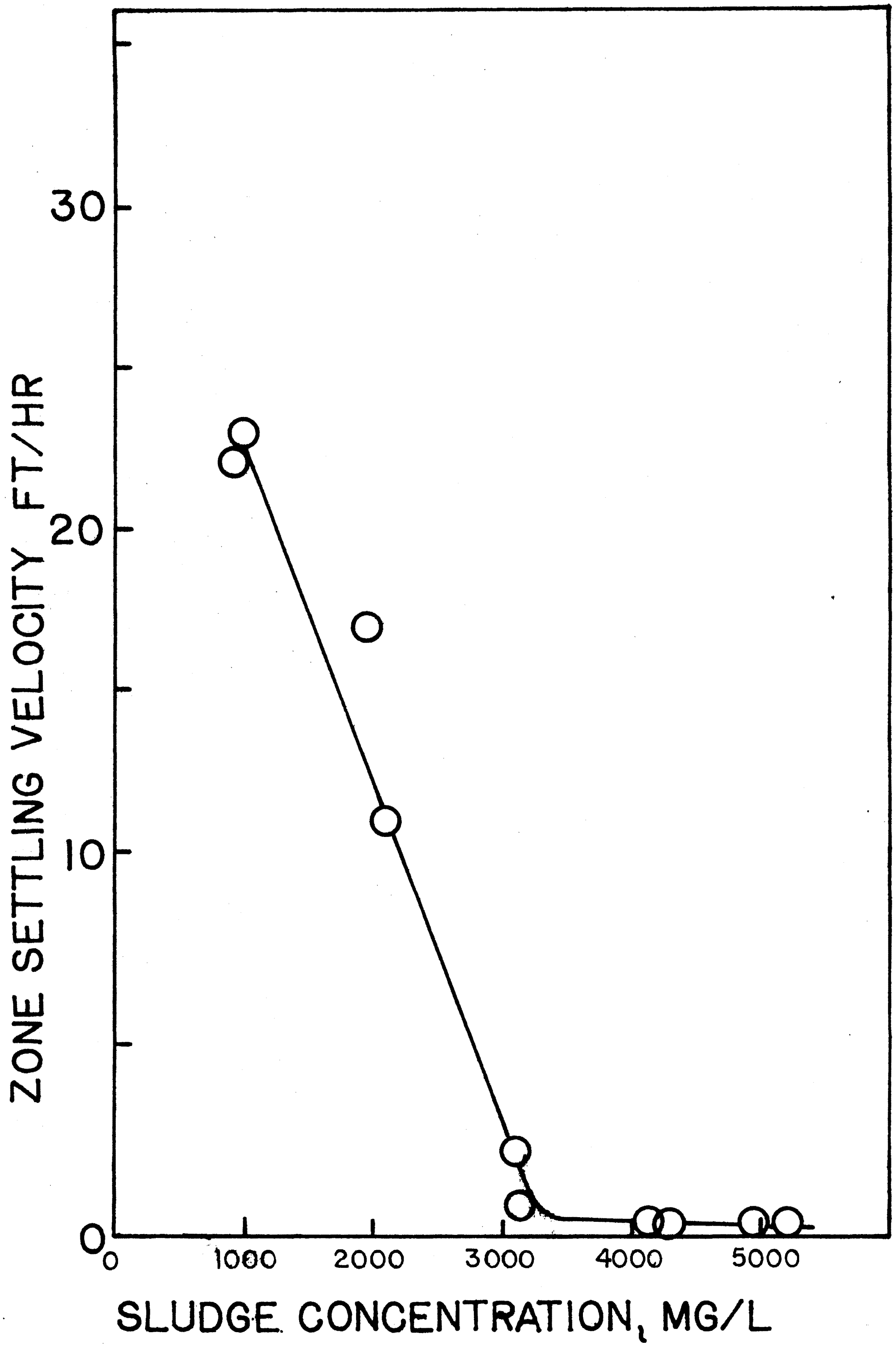

ZONE SETTLING VELOCITY, FT/HR
30
20
10
0
0
1000
2000
3000
4000
5000
SLUDGE CONCENTRATION, MG/L

Figure 12. Zone Settling Velocity versus Sludge Concentration at Sludge Age of 8.9 Days

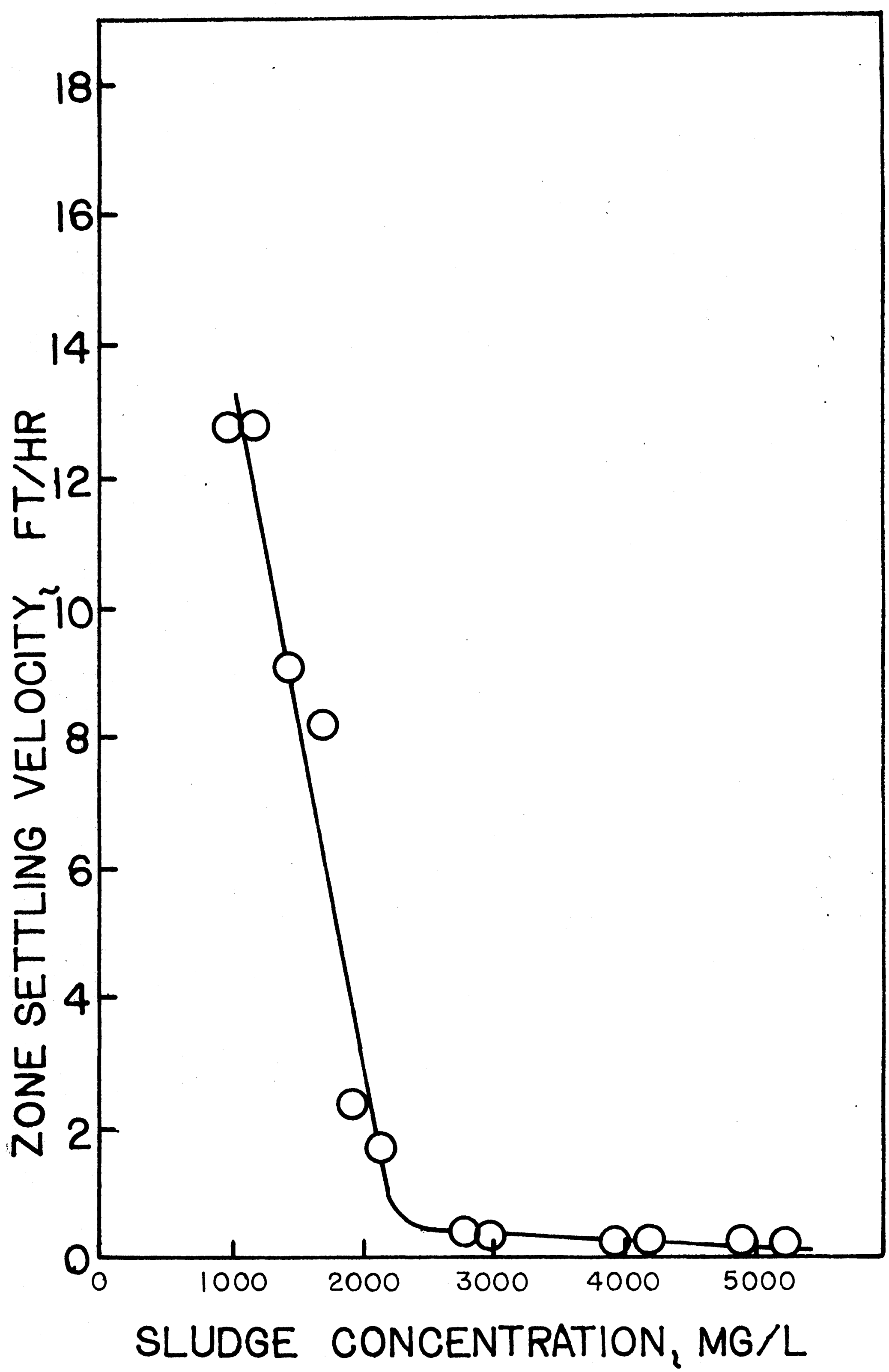

ZONE SETTLING VELOCITY, FT/HR
0
2
4
6
8
10
12
14
16
18
0
1000
2000
3000
4000
5000
SLUDGE CONCENTRATION, MG/L

Figure 13. Zone Settling Velocity versus Sludge Concentration at Sludge Age of 7.2 Days

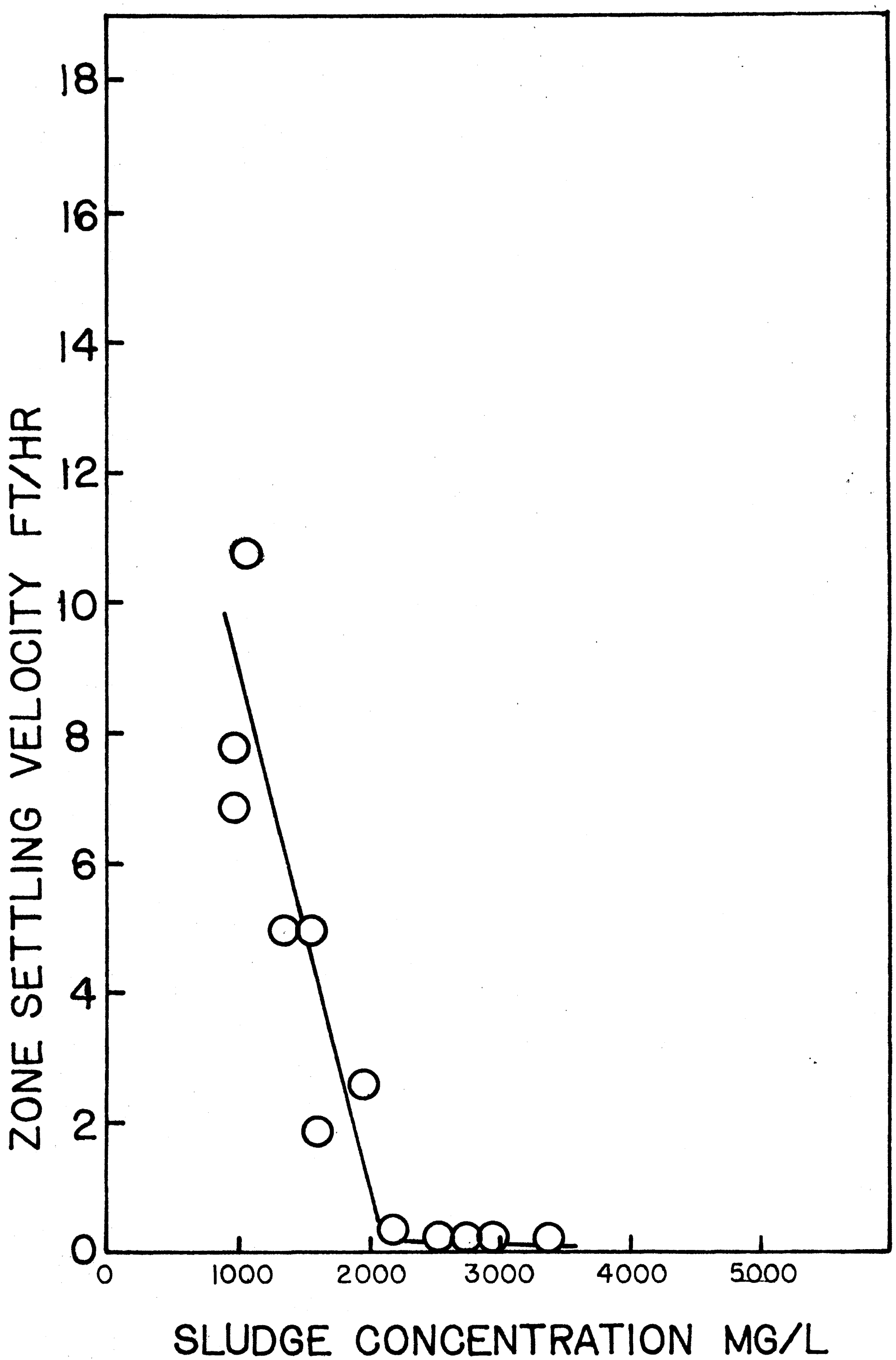

ZONE SETTLING VELOCITY FT/HR
0
2
4
6
8
10
12
14
16
18
0
1000
2000
3000
4000
5000
SLUDGE CONCENTRATION MG/L

Figure 14. Zone Settling Velocity versus Sludge Concentration at Sludge Age of 4.7 Days

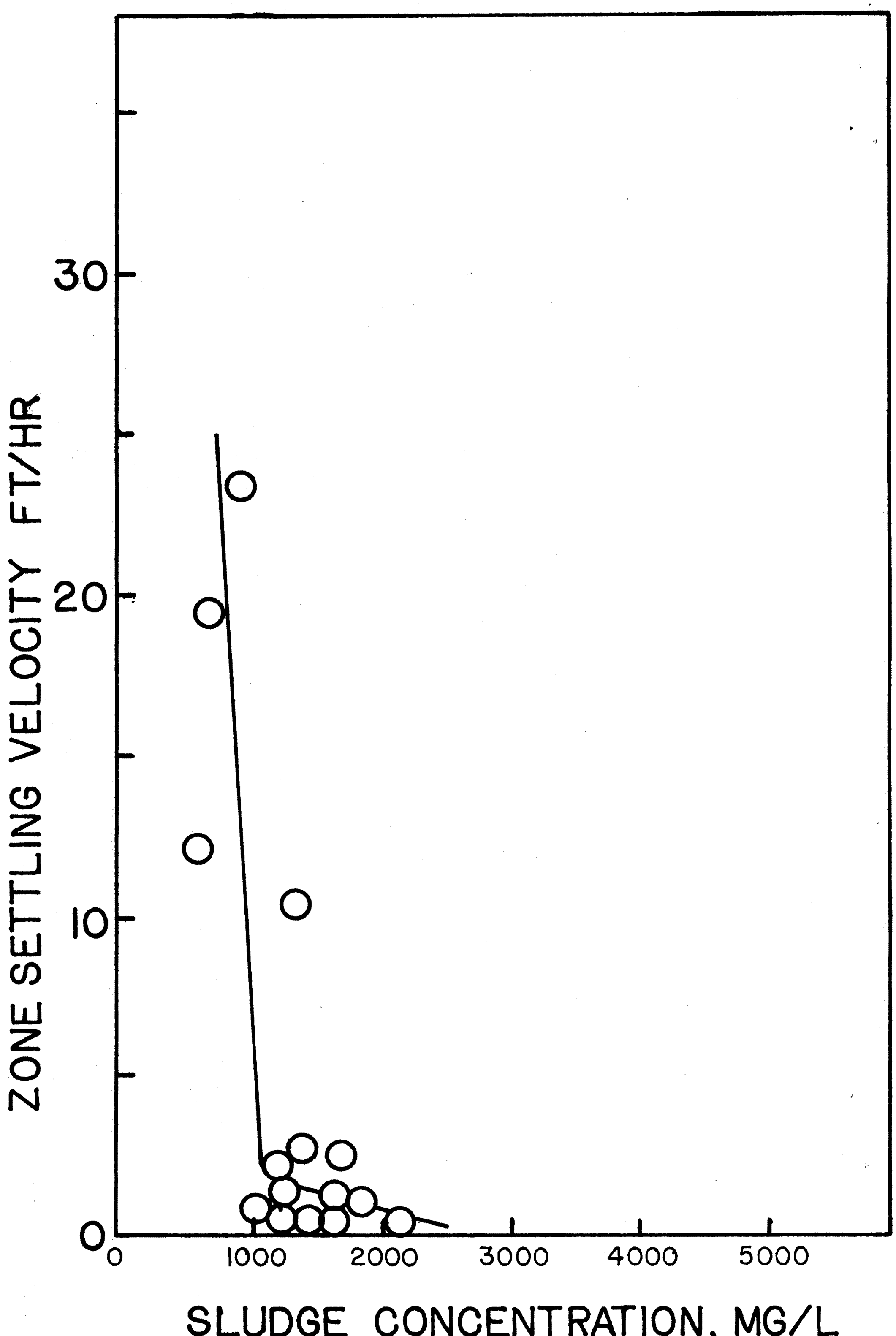
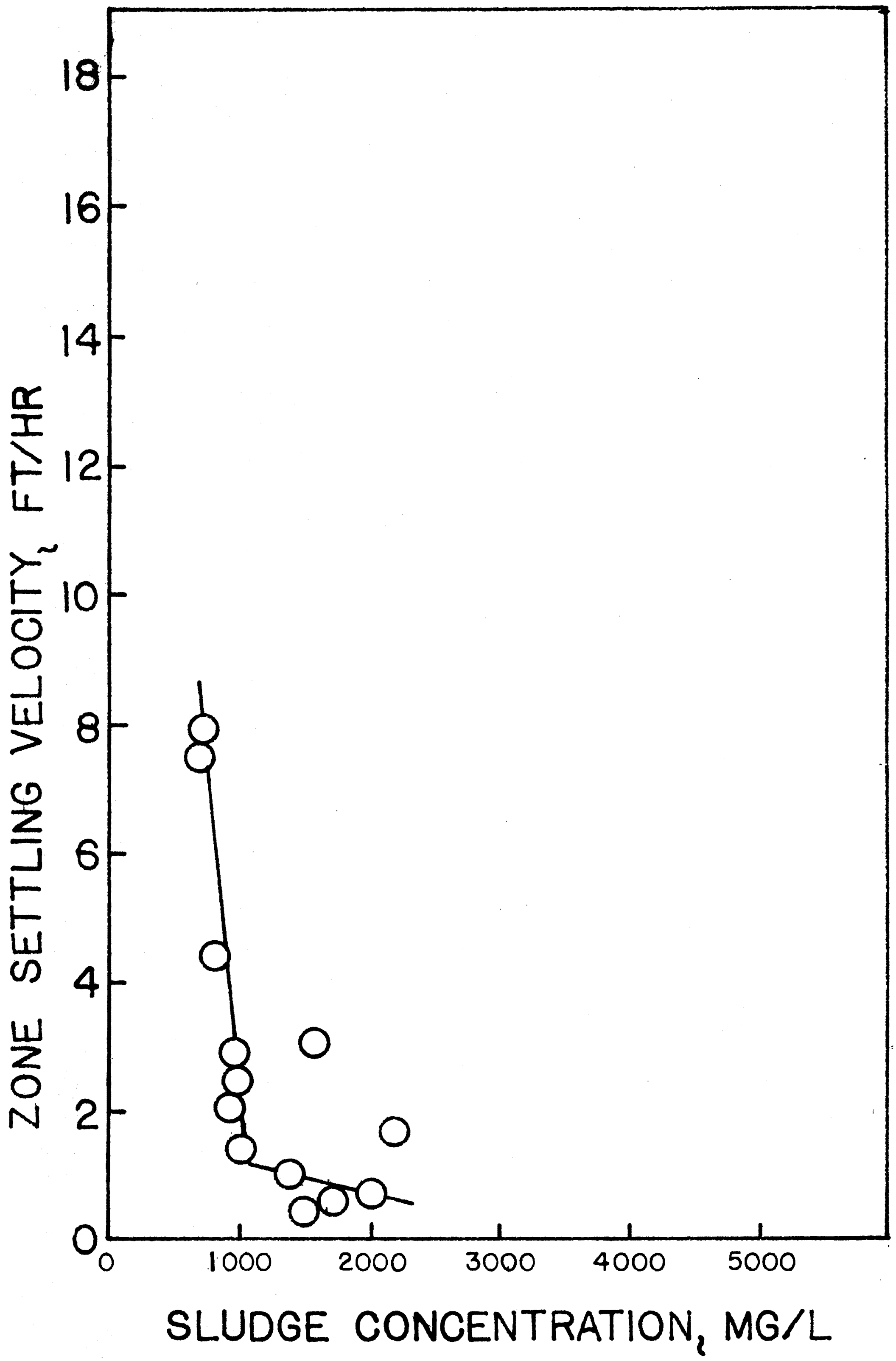

ZONE SETTLING VELOCITY FT/HR
30
20
10
0
0
1000
2000
3000
4000
5000
SLUDGE CONCENTRATION, MG/L

Figure 15. Zone Settling Velocity versus Sludge Concentration at Sludge Age of 2.2 Days


ZONE SETTLING VELOCITY, FT/HR
18
16
14
12
10
8
6
4
2
0
0
1000
2000
3000
4000
5000
SLUDGE CONCENTRATION, MG/L

concentration decreased with decreasing sludge age. Figure 16 presents the sludge concentration versus zone settling velocity curves at all tested sludge ages. The curves from Figures 11 through 15 are presented together in Figure 16. The observed values presented in Figures 11 through 15 are omitted from Figure 16 for clarity. Only the resultant curves (fitted to the data by eye) are presented in Figure 16. Figure 16 clearly shows the decrease in zone settling velocity for a given sludge concentration with decreasing sludge age. Figure 17, which presents the data in a different manner, also show that the zone settling velocity is a function of both the initial solids concentration and the sludge age.

The sludge volume index was also measured at various initial sludge concentrations and sludge ages. The relationship between sludge volume index and initial sludge concentration is presented for the tested sludge ages in Figures 18 through 22. The observed data points are included in Figures 18 through 22. Figure 23 combines the curves (derived from the observed data points by approaching a best fit by eye) from Figures 18 through 22. The data points have been omitted from Figure 23 for clarity. Figure 23 indicates that the sludge volume index at a given initial sludge concentration was found to increase with decreasing sludge age. It should be noted that the curves in Figure 23 seem to approach a limit at their right-hand ends. This is in fact so. If the sludge concentration at time zero is 2000 mg/l, the

Figure 16. Zone Settling Velocity versus Sludge Concentration at All Sludge Ages (composite of Figures 11 thru 15)

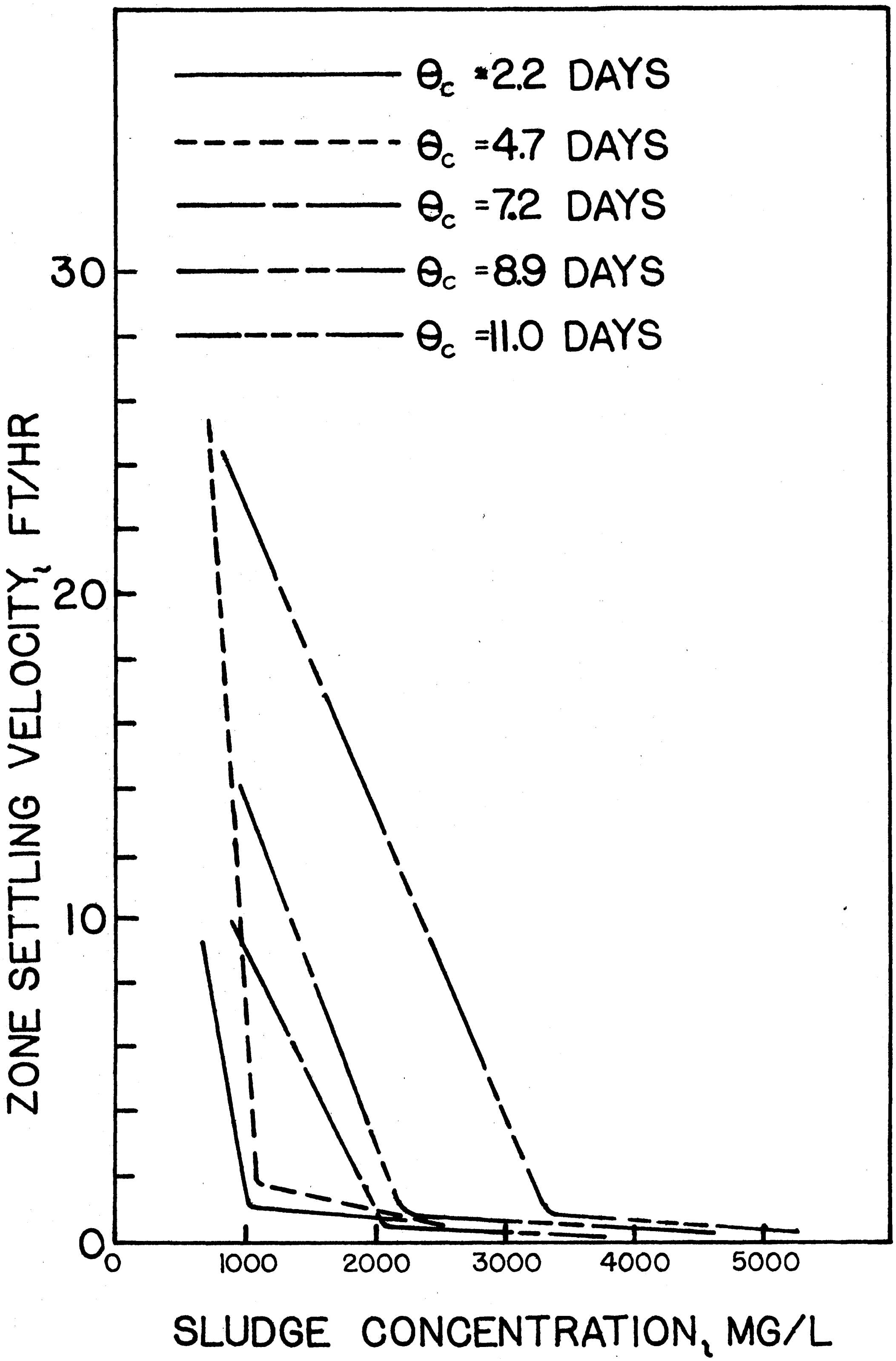

θc =2.2 DAYS
θc =4.7 DAYS
θc =7.2 DAYS
θc =8.9 DAYS
θc =11.0 DAYS
30
20
10
0
0
1000
2000
3000
4000
5000
ZONE SETTLING VELOCITY, FT/HR
SLUDGE CONCENTRATION, MG/L

Figure 17. Zone Settling Velocity versus Sludge Age at Various Sludge Concentrations (from Figures 11 thru 15)

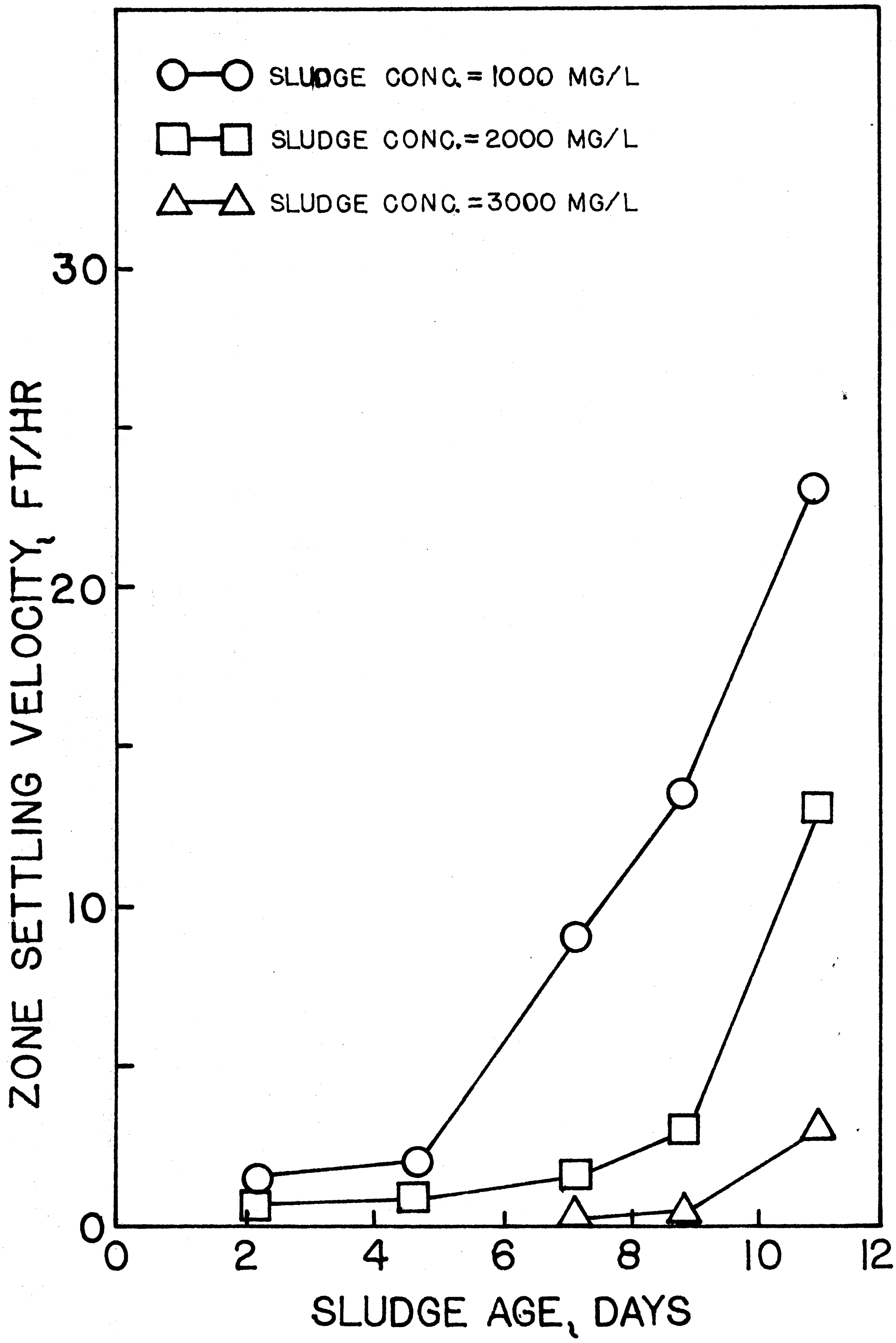

SLUDGE CONC. = 1000 MG/L
SLUDGE CONC. = 2000 MG/L
SLUDGE CONC. = 3000 MG/L
ZONE SETTLING VELOCITY, FT/HR
30
20
10
0
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 18. Sludge Volume Index versus Initial Sludge Concentration at Sludge Age of 11.0 Days

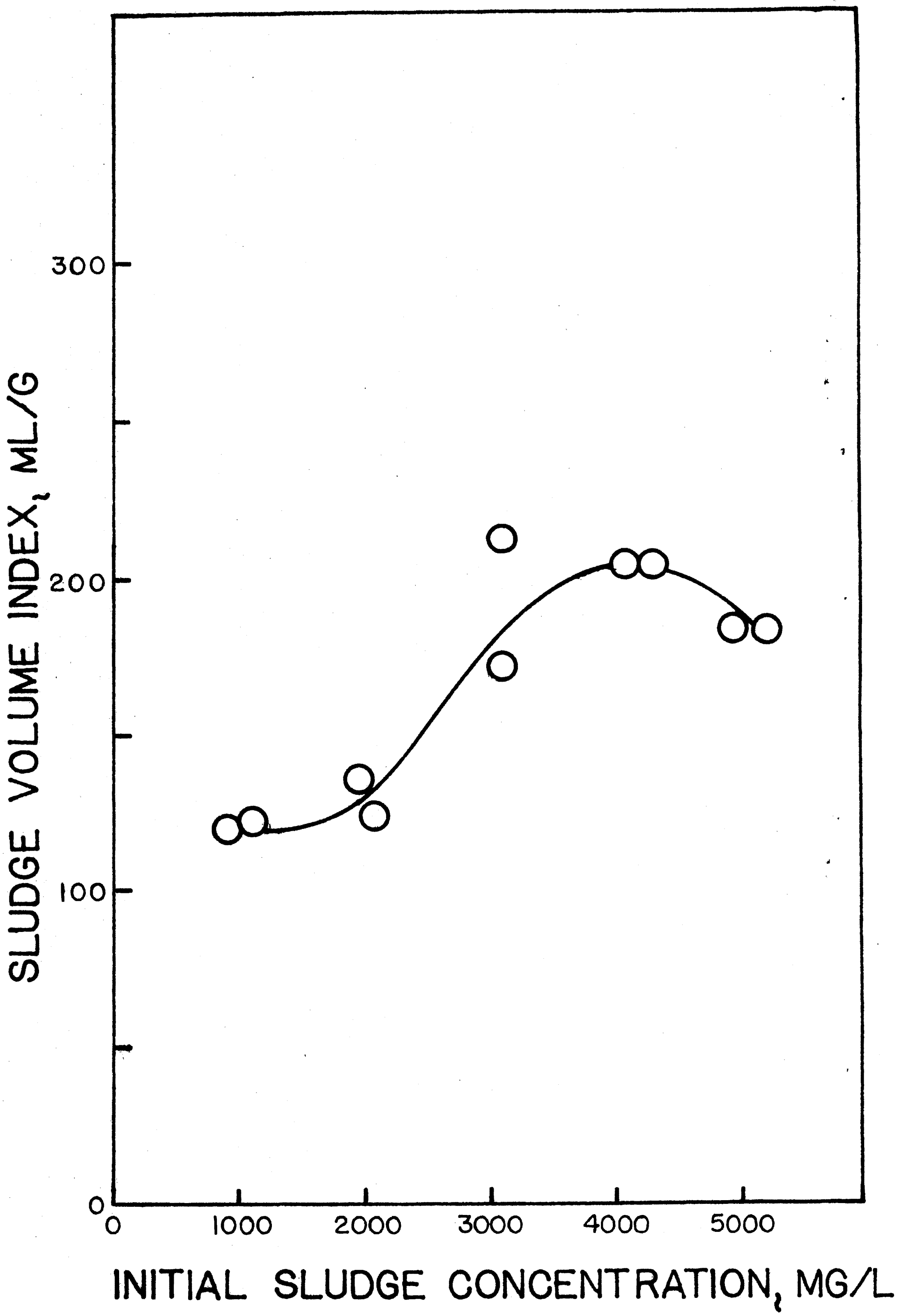

SLUDGE VOLUME INDEX, ML/G
300
200
100
0
0
1000
2000
3000
4000
5000
INITIAL SLUDGE CONCENTRATION, MG/L

Figure 19. Sludge Volume Index versus Initial Concentration at Sludge Age of 8.9 Days

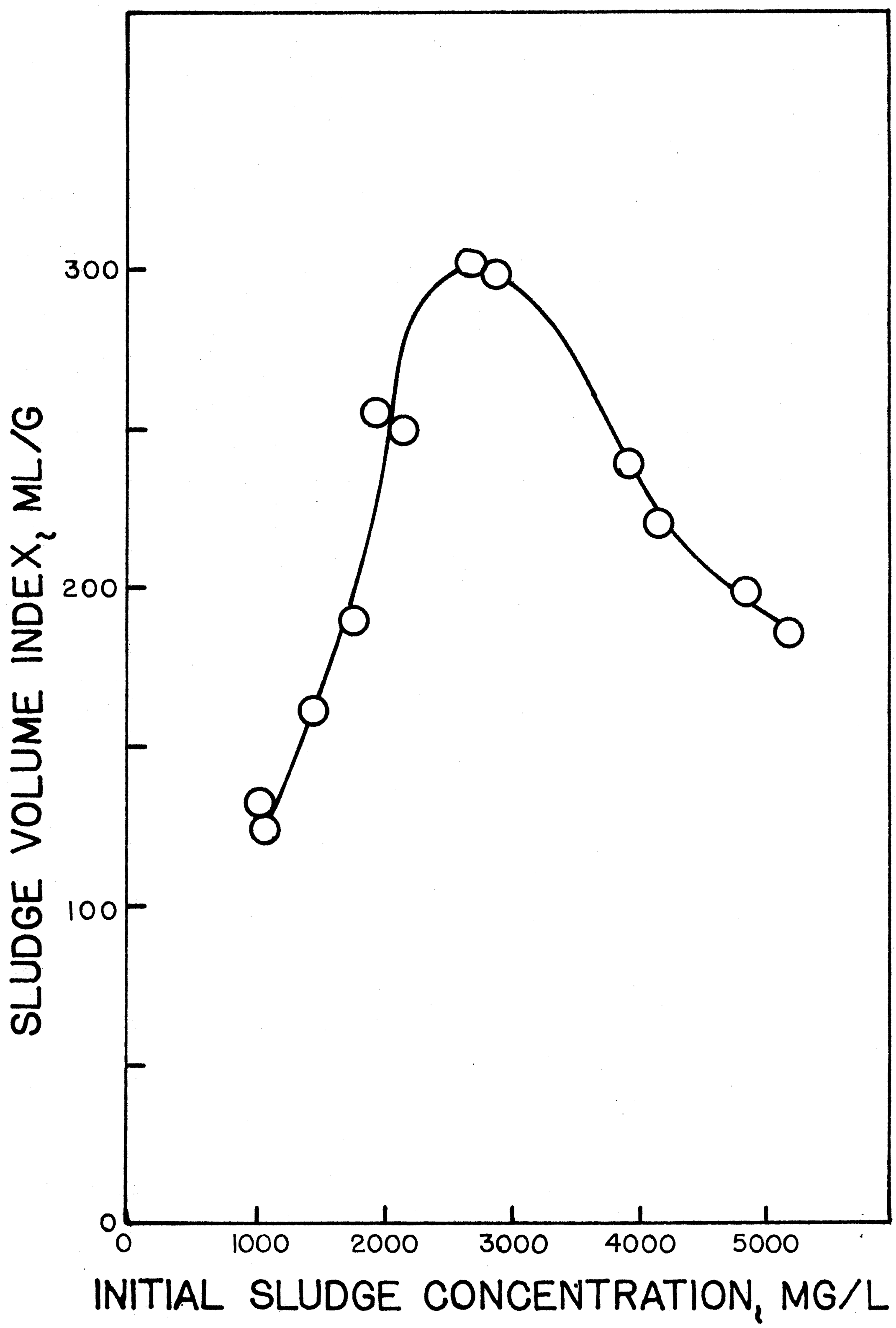

300
200
100
0
SLUDGE VOLUME INDEX, ML/G
0
1000
2000
3000
4000
5000
INITIAL SLUDGE CONCENTRATION, MG/L

Figure 20. Sludge Volume Index versus Initial Sludge Concentration at Sludge Age of 7.2 Days

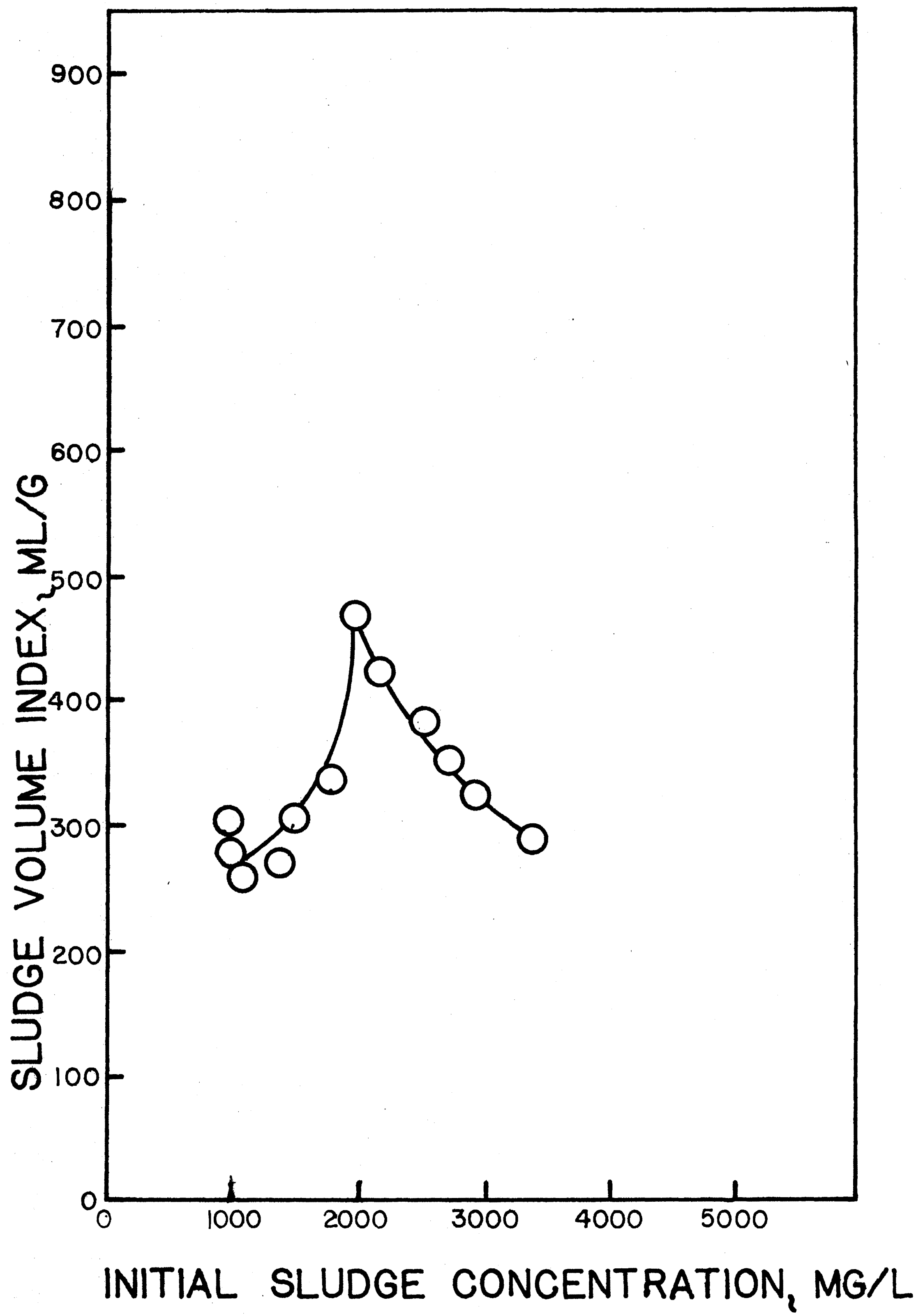
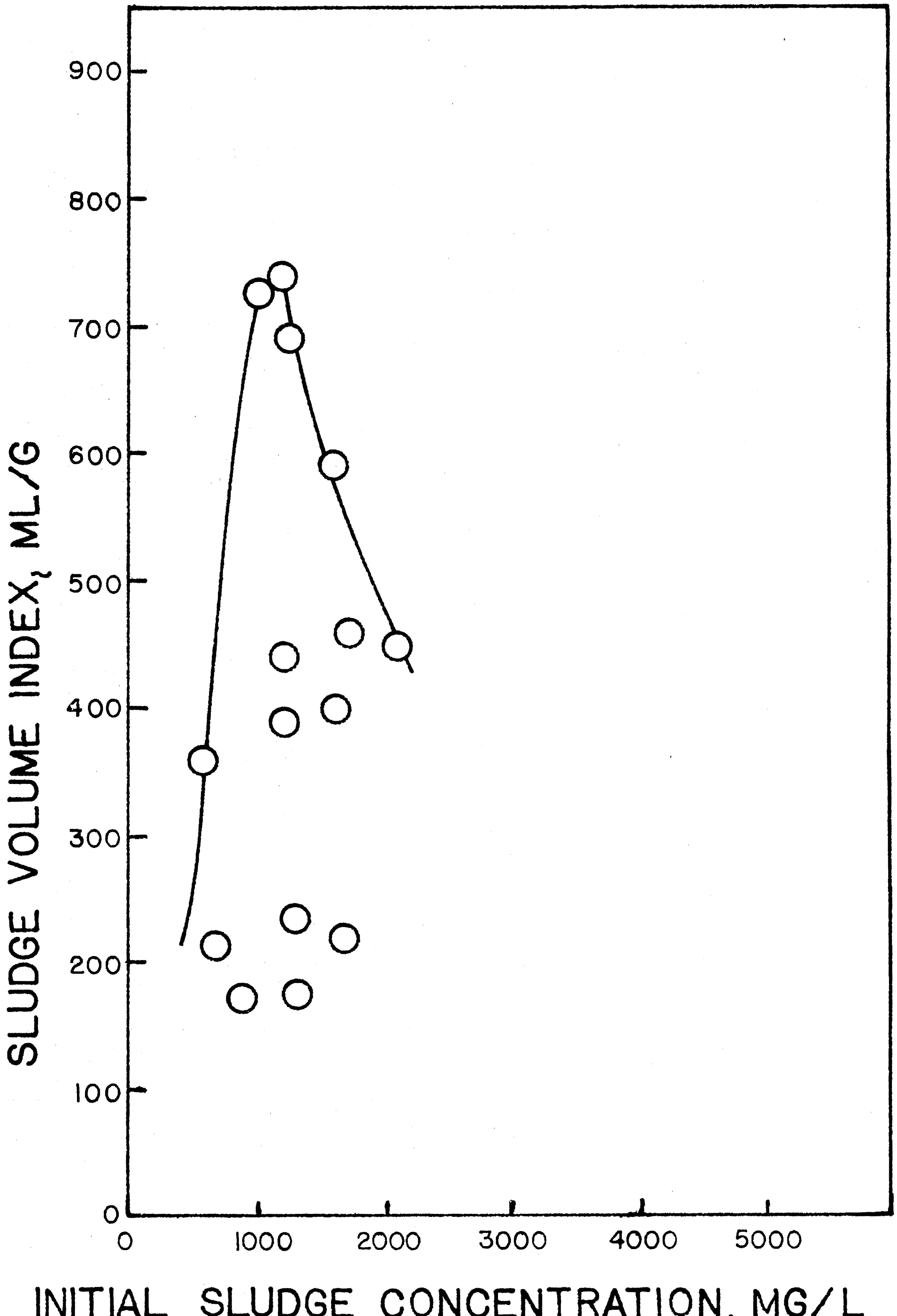

SLUDGE VOLUME INDEX, ML/G
900
800
700
600
500
400
300
200
100
0
0
1000
2000
3000
4000
5000
INITIAL SLUDGE CONCENTRATION, MG/L

Figure 21. Sludge Volume Index versus Initial Sludge Concentration at Sludge Age of 4.7 Days



900
800
700
600
500
400
300
200
100
0
SLUDGE VOLUME INDEX, ML/G
0
1000
2000
3000
4000
5000
INITIAL SLUDGE CONCENTRATION, MG/L

Figure 22. Sludge Volume Index versus Initial Sludge Concentration at Sludge Age of 2.2 Days

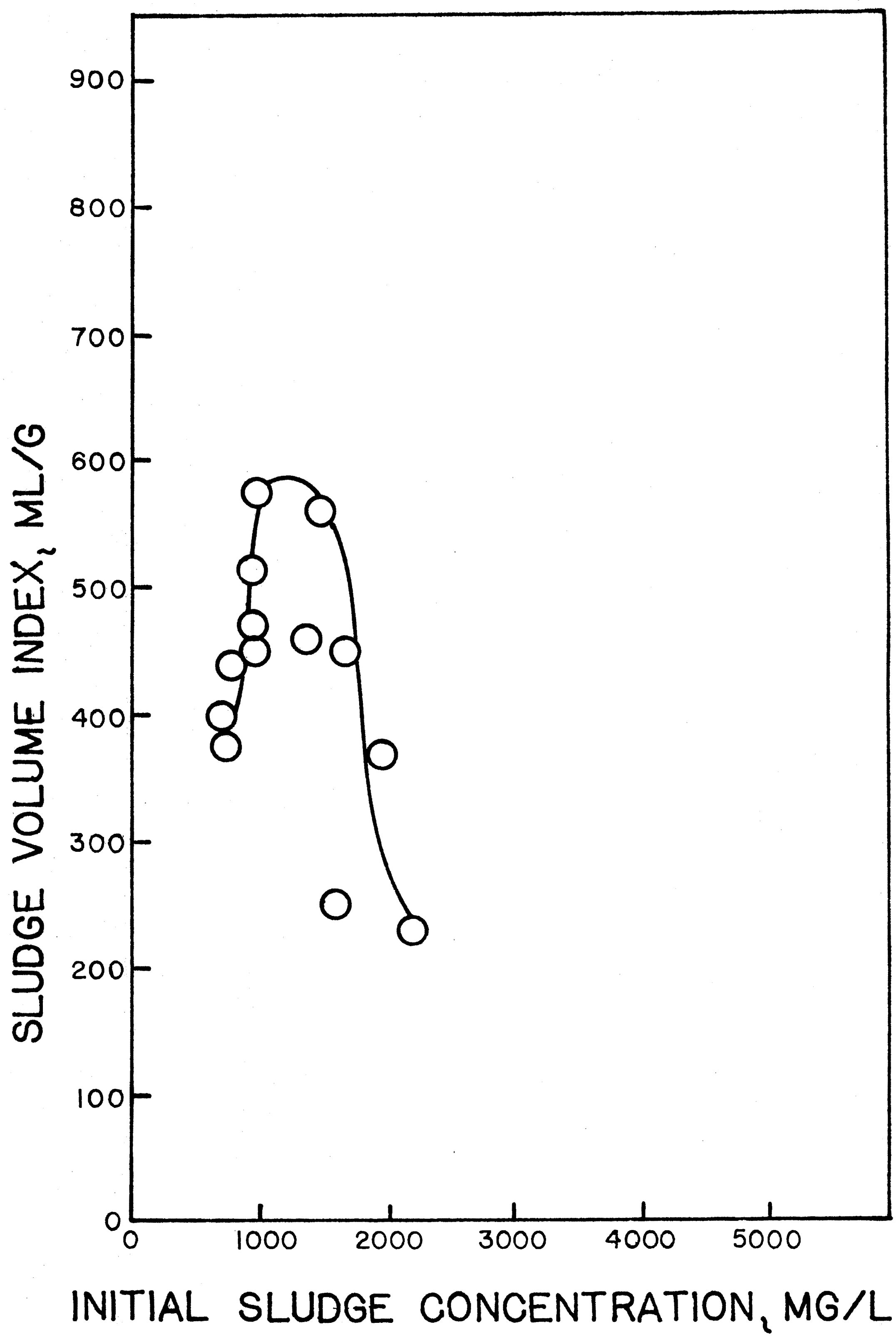
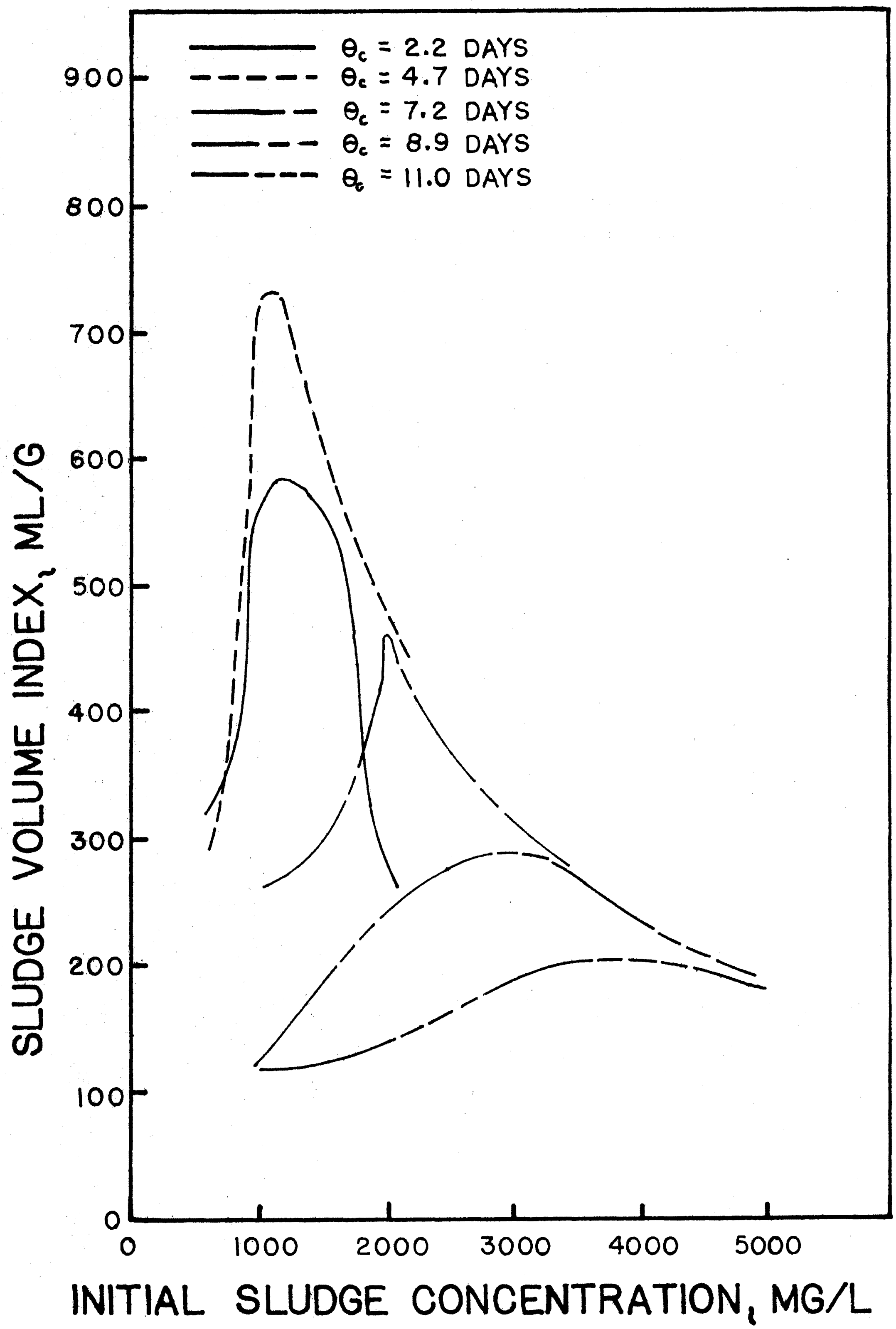

900
800
700
600
500
400
300
200
100
0
SLUDGE VOLUME INDEX, ML/G
0
1000
2000
3000
4000
5000
INITIAL SLUDGE CONCENTRATION, MG/L

Figure 23. Sludge Volume Index versus Initial Sludge Concentration at All Tested Sludge Ages(composite of Figures 18 thru 22)



θc = 2.2 DAYS
θc = 4.7 DAYS
θc = 7.2 DAYS
θc = 8.9 DAYS
θc = 11.0 DAYS
SLUDGE VOLUME INDEX, ML/G
0
100
200
300
400
500
600
700
800
900
0
1000
2000
3000
4000
5000
INITIAL SLUDGE CONCENTRATION, MG/L

maximum sludge volume index attainable is 500 ml/g. The apparent limiting condition, which the curves approach at their right-hand ends, indicates little or no compaction occurred at the relevant initial concentrations. Figures 24 and 25, like Figure 23, present the observed relationships between sludge age, initial solids concentration, and sludge volume index. Figures 24 and 25 present the relationship between sludge volume index and sludge age at different initial concentrations and consequently reveal the relationship between sludge volume index and sludge age more clearly than does Figure 23. From Figures 18 throug 25, it can be said that the greatest sludge volume index occurs at a sludge age between four and six days. Also, at a given sludge age, the sludge volume index first increases with increasing initial sludge concentration and then begins to decrease with increased initial sludge concentration (the latter is a result of the maximum possible sludge volume index decreasing with increasing initial sludge concentration as explained earlier).

In addition to sludge volume index, additional compaction data was collected by allowing sludge to settle for 24 hours. The sludge, in all cases, appeared to have compacted as far as possible after 24 hours. The average concentration achieved after 24 hours of quiescent settling is reported in Figure 26 for all observed sludge ages. The maximum sludge concentration achievable decreased with decreasing sludge age, as can be seen in Figure 26.

Figure 24. Sludge Volume Index versus Sludge Age at Various Initial Concentrations (from Figures 18 thru 22)

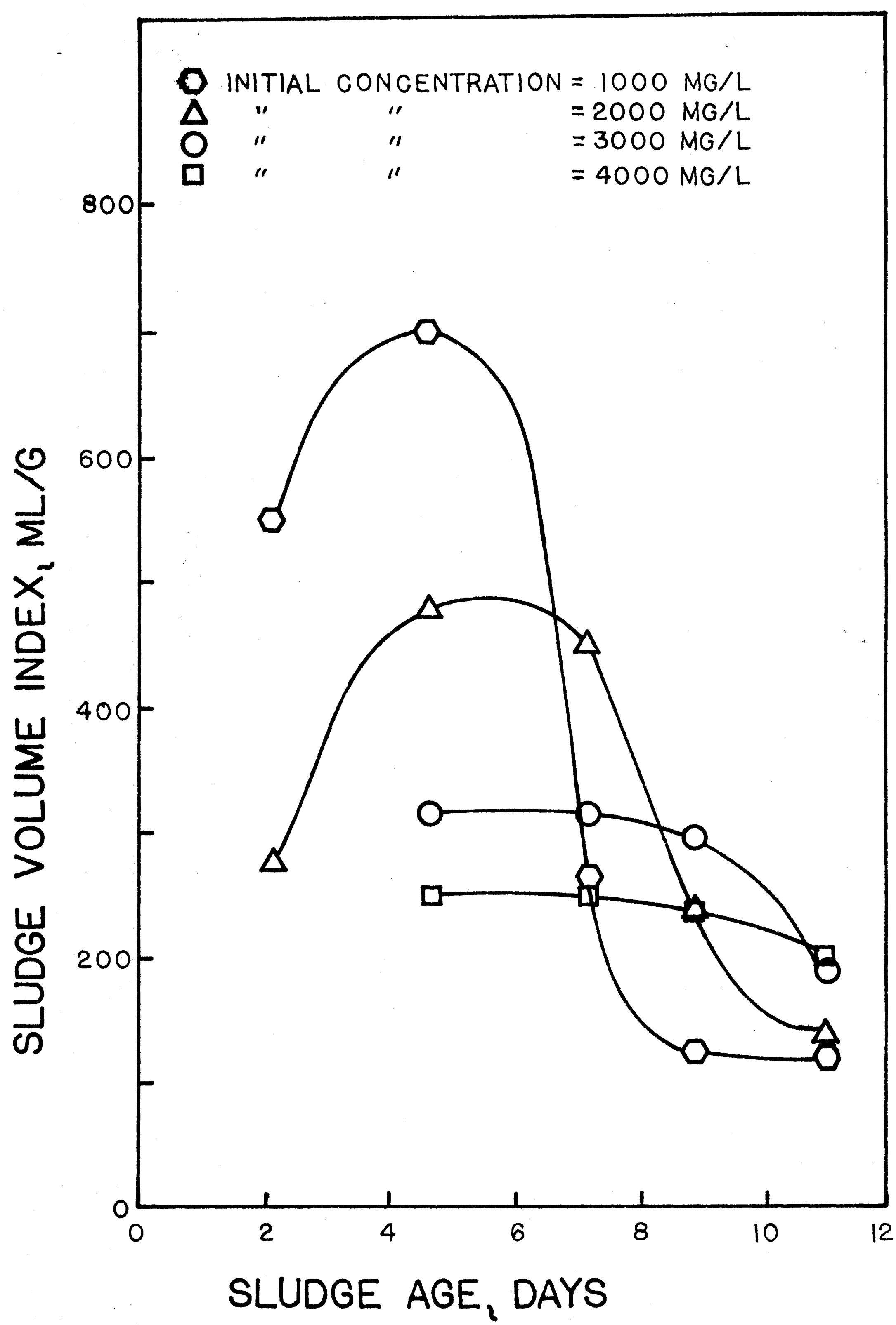

INITIAL CONCENTRATION = 1000 MG/L
" " = 2000 MG/L
" " = 3000 MG/L
" " = 4000 MG/L
SLUDGE VOLUME INDEX, ML/G
0
200
400
600
800
SLUDGE AGE, DAYS
0
2
4
6
8
10
12

Figure 25. Sludge Volume Index versus Sludge Age at Initial Sludge Concentrations Equal to Mixed Liquor Suspended Solids

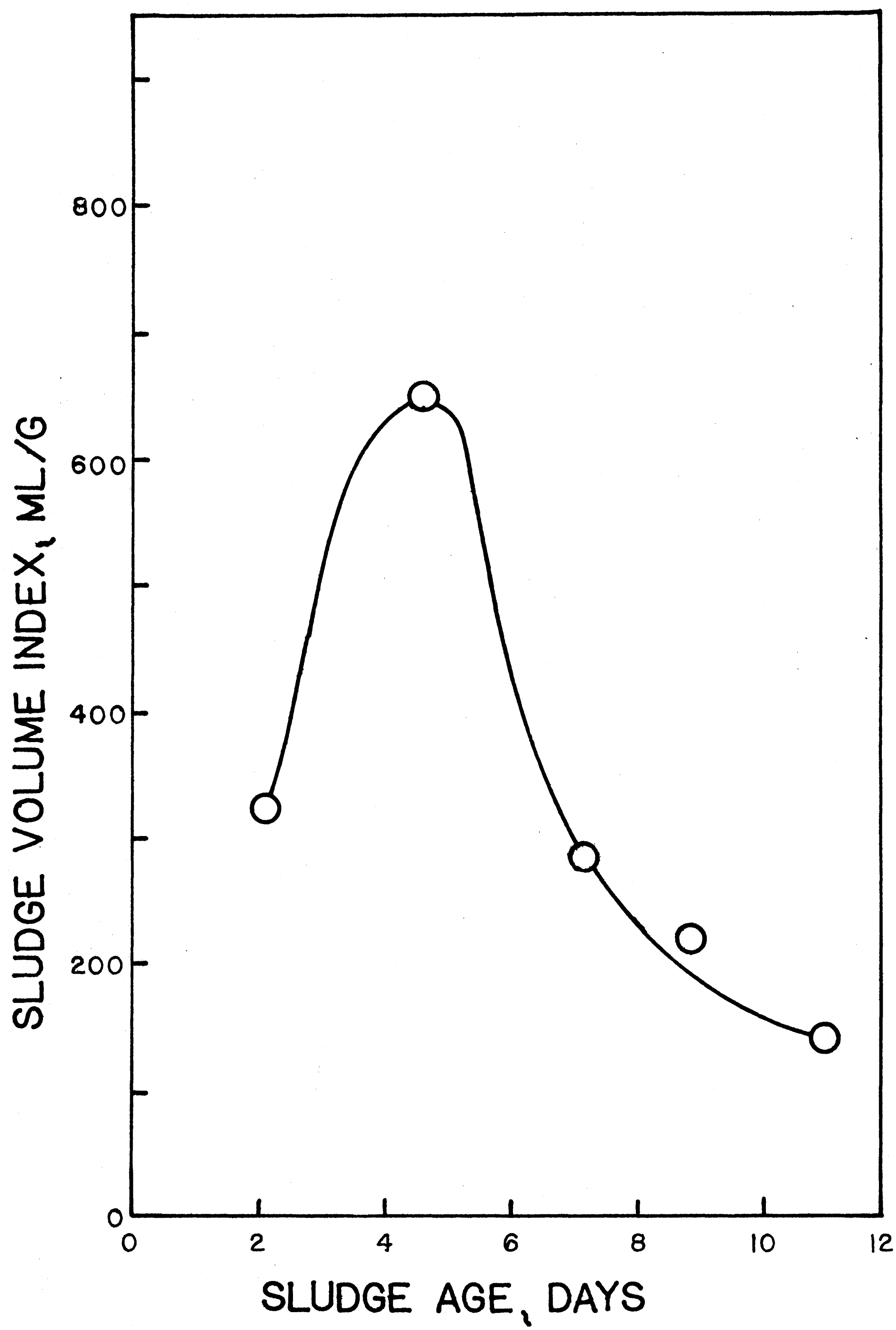

800
600
400
200
0
SLUDGE VOLUME INDEX, ML/G
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 26. Maximum Sludge Concentration versus
Sludge Age

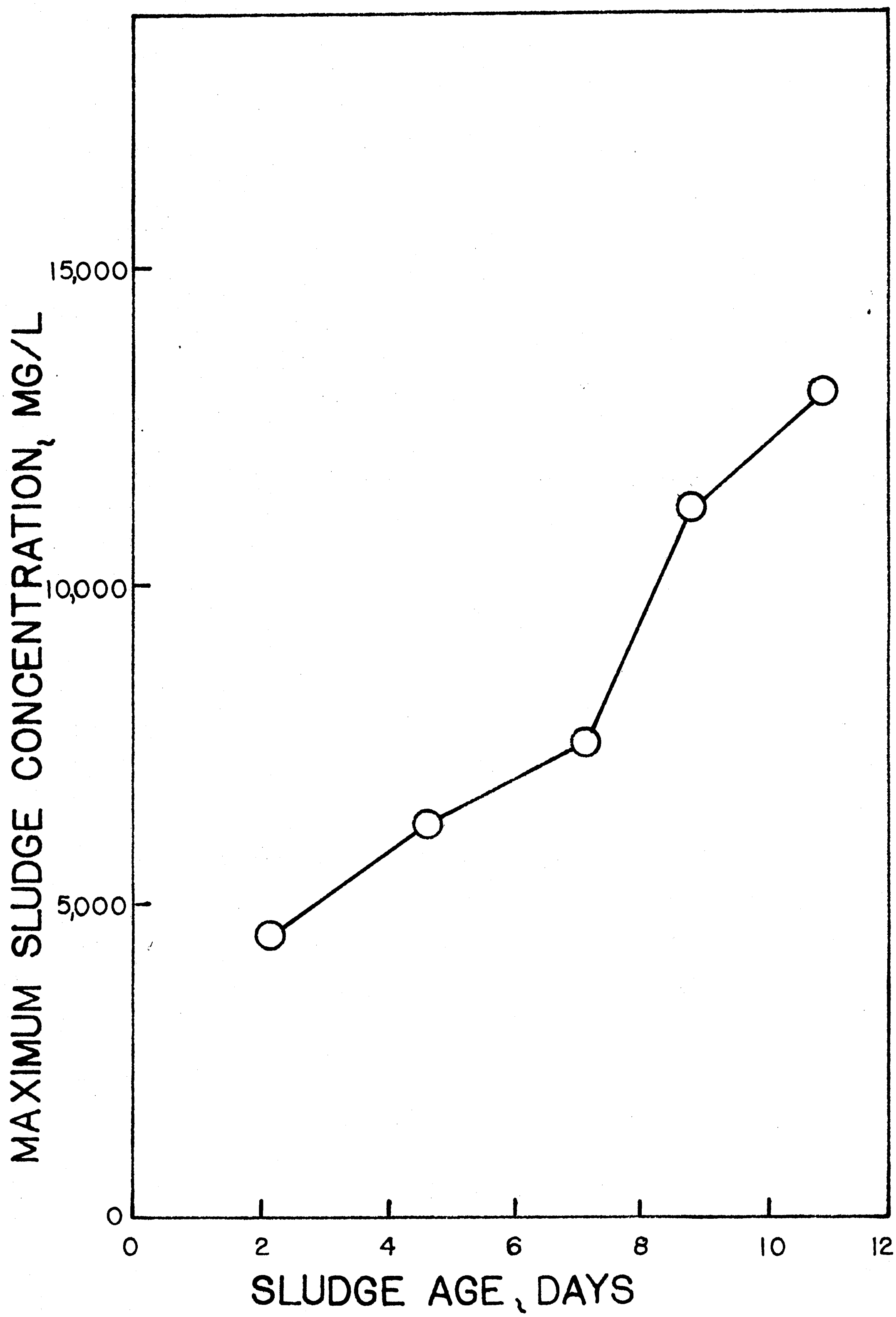
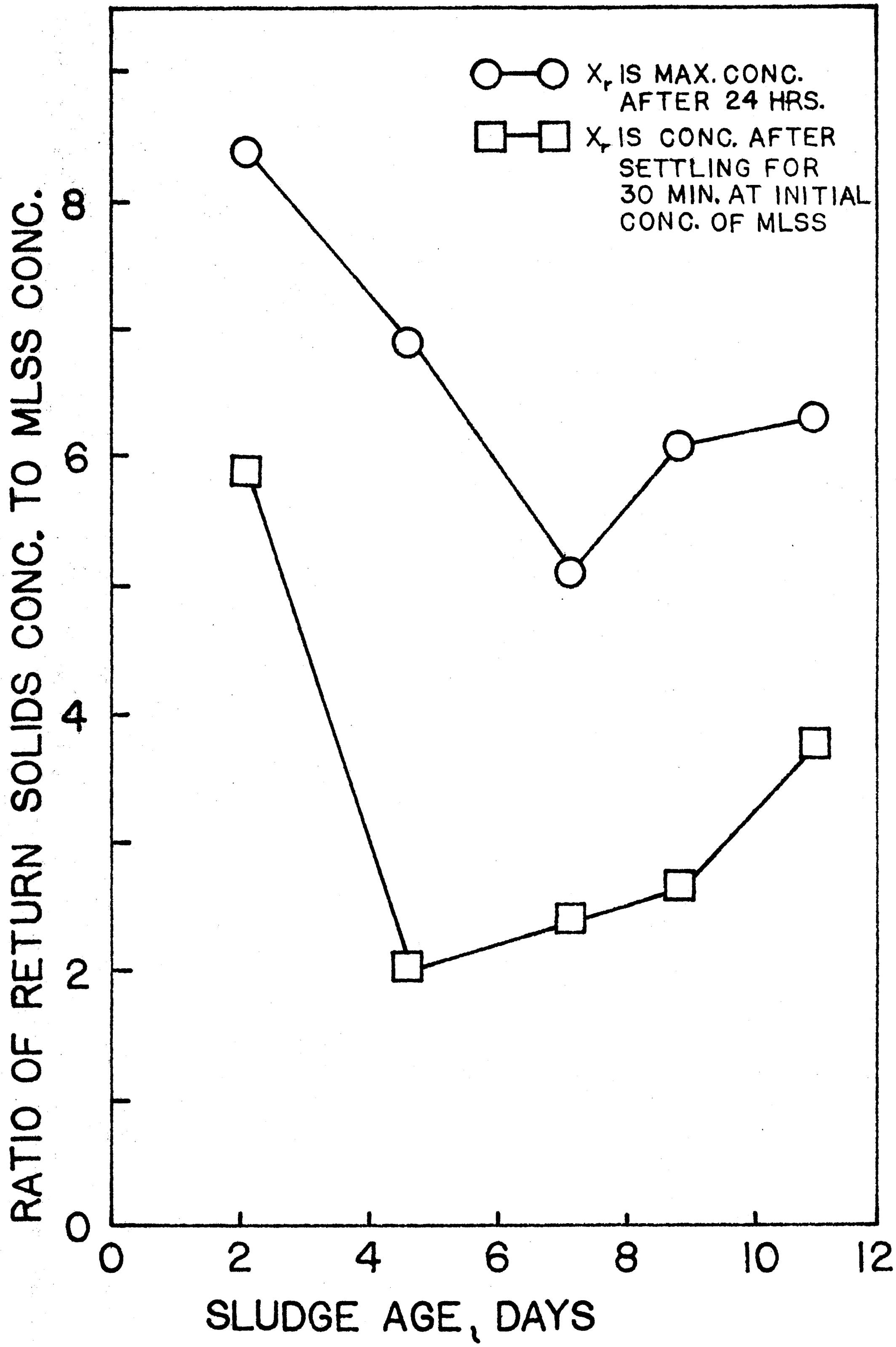

15,000
10,000
5,000
0
MAXIMUM SLUDGE CONCENTRATION, MG/L
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 27 combines the mixed liquor suspended solids concentrations from Figure 8 with sludge volume index data from Figure 23 and maximum concentration data from Figure 26. Both the ratio of mixed liquor suspended solids to the concentration after 30 minutes settling (at an initial concentration equal to mixed liquor suspended solids concentration) and the ratio of mixed liquor suspended solids to the concentration after 24 hours of quiescent settling are compared over the range of observed sludge ages in Figure 27. The value of the ratio between mixed liquor suspended solids and recycled sludge from a secondary clarifier would likely lie somewhere within the indicated range for each sludge age, depending on the clarifier overflow rate and detention time (for this system). The actual value of this ratio for a given activated sludge system would depend on the sludge loading on the clarifier, the individual sludge settling characteristics, the selected recycle flow rate, and the available thickening area according to the Dick analysis (15). As can be seen in Figure 27, both the maximum and minimum ratios possible decreased with decreasing sludge age down to around 5 to 7 days and then both increased. A sludge age of 2.2 days produced the best results with respect to the achievable sludge concentration ratios.

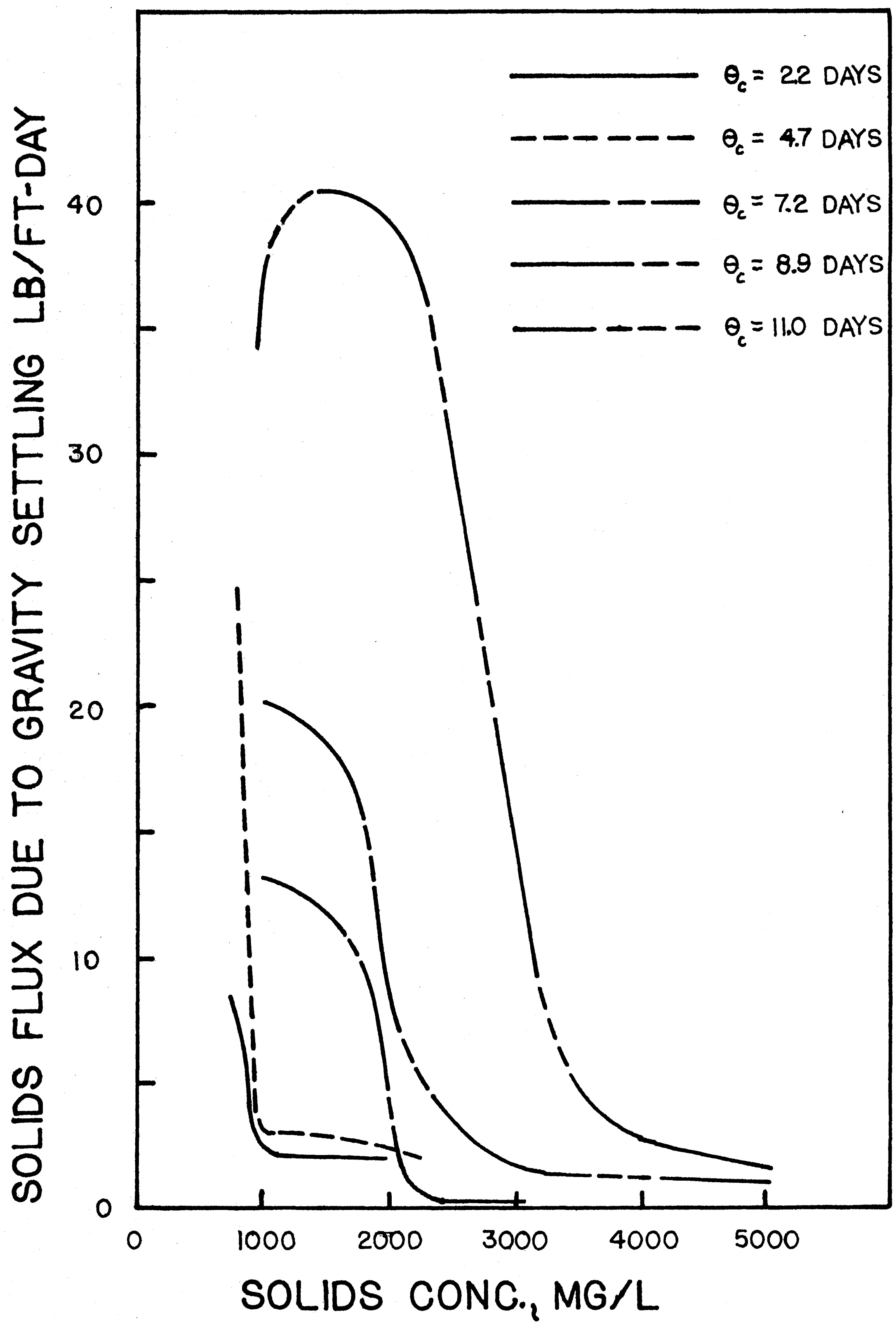
Figure 28 presents the relationship between solids flux due to gravity and initial sludge concentration at each of the observed sludge ages. It can be seen that the solids flux at a given solids concentration decreased with decreasing sludge age.

Figure 27. Ratio of Return Solids to Mixed Liquor Suspended Solids at Tested Sludge Ages



X_r IS MAX. CONC. AFTER 24 HRS.
X_r IS CONC. AFTER SETTLING FOR 30 MIN. AT INITIAL CONC. OF MLSS
RATIO OF RETURN SOLIDS CONC. TO MLSS CONC.
0
2
4
6
8
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 28. Solids Flux versus Solids Concentration at Tested Sludge Ages


θc = 2.2 DAYS
θc = 4.7 DAYS
θc = 7.2 DAYS
θc = 8.9 DAYS
θc = 11.0 DAYS
SOLIDS FLUX DUE TO GRAVITY SETTLING LB/FT-DAY
0
10
20
30
40
0
1000
2000
3000
4000
5000
SOLIDS CONC., MG/L

CHAPTER V

DISCUSSION

A. Operating Data

The data describing the operating characteristics of the bench-scale activated sludge unit used in this study, as presented in Figures 2 through 10, were fit quite well by the mean cell residence time equations. The relationship between the effluent suspended solids and sludge age, as presented in Figure 9, requires further discussion.

An interesting finding with respect to the operating data was the observed relationship between average effluent suspended solids concentration and sludge age. This finding is of interest because sludge age apparently has some effect on the clarification function of a secondary clarifier for activated sludge. The Environmental Protection Agency has set limits on both effluent suspended solids and effluent BOD. Consequently, these are both important design and operation criteria. Effluent suspended solids contribute to both effluent suspended solids and effluent BOD. As represented in Figure 9, the average effluent suspended solids concentration rose from 8.5 mg/l at a sludge age of 11.0 days to a maximum of 21 mg/l at a sludge age of 4.7 days and then dropped to 8.3 mg/l at a sludge age of 2.2 days. The overflow rate and clarifier detention time were constant at all sludge ages. The overflow rate was approximately 20 gal/ft^2-day and the detention time was 15 hours. These are both extreme values and should have produced very good clarification at all sludge ages (the settled sludge was retained in the clarifier no longer than 30 minutes before being recycled). A relationship similar to that found in this study was observed by Bisogni and Lawrence (19), although the absolute values observed in each study were different. This is to be expected. Aside from differences in feed, overflow rate, and mixed liquor suspended solids concentrations; there is the possibility of differing methods of calculating sludge age (this is not specified in the Bisogni and Lawrence study). In this study, activated sludge solids were wasted once per day and the activated sludge solids concentration measured immediately prior to wasting was the value used in calculating sludge age. Since no solids were detained in the secondary clarifier in this study for more than 30 minutes, the solids in the clarifier were insignificant. Another reason for the difference between the values observed in the present study and the values observed by Bisogni and Lawrence is possibly the differing operating procedures. Bisogni and Lawrence simultaneously ran separate units for each sludge age, while a single experimental unit was operated at various sludge ages in descending order in the present study. Regardless of the slight difference between the values observed by Bisogni and Lawrence and values observed in the present study and the reason or reasons for that difference, both studies do suggest that sludge age affects clarification. However, the specific nature of the relationship is not clear at this point and more research needs to be done on the effect of sludge age on clarification of activated sludge.

B. Thickening and Compaction Data

The principal purpose of this study was to investigate the relationship between sludge age and the thickening properties of activated sludge. Zone settling velocity and sludge volume index have both been used extensively as indicators of sludge thickening or compaction characteristics. The effect of sludge age on these two parameters was investigated by Bisogni and Lawrence (19). The results of the Bisogni and Lawrence study were discussed in the literature review of this paper. While answering some questions concerning the relationship between sludge age and sludge volume index, the Bisogni and Lawrence study raised another question. As was pointed out in the literature review of this paper, the Bisogni and Lawrence study reported the effect of sludge age on both zone settling velocity for an initial sludge concentration of 2000 mg/l and sludge volume index at an initial sludge concentration equal to the mixed liquor suspended solids concentration (which varied with sludge age). The question raised by the Bisogni and Lawrence paper, which this study was designed to investigate, concerns the effect of the additional parameter of initial sludge concentration on sludge volume index and zone settling velocity. The effects of both sludge age and initial sludge concentration on both sludge volume index and zone settling velocity will be discussed below with reference to the results of both this study and the Bisogni and Lawrence study.

As indicated in the previous chapter, the zone settling velocity was found to decrease both with increasing sludge concentration and decreasing sludge age (see Figures 16 and 17). The curve in Figure 17, for a sludge concentration of 2000 mg/l, presents a relationship between sludge age and zone settling velocity similar to that reported by Bisogni and Lawrence; that is, at a given sludge concentration, zone settling velocity decreases with decreasing sludge age. However, the absolute values found in this study are different than those found by Bisogni and Lawrence, which is to be expected. The remaining curves in Figure 17, for sludge concentrations of 1000 mg/l and 3000 mg/l, also follow a relationship similar to that found by Bisogni and Lawrence for a sludge concentration of 2000 mg/l; although the absolute values are again different. The results of this study tend to support the relationship between sludge age and zone settling velocity at a sludge concentration of 2000 mg/l reported by Bisogni and Lawrence, although the absolute values differ in the two studies. Additionally, Figures 16 and 17 confirm what one would expect from Bisogni and Lawrence's study - at any given sludge concentration, the zone settling velocity decreases with sludge age.

One conclusion that might be drawn from the above is that the traditional plant operator's strategy of decreasing the mixed liquor suspended solids concentration, in order to deal with an overloaded secondary clarifier, may not always work. This strategy requires wasting more sludge per day, which will result in a decreased sludge age. As pointed out in the previous paragraph, decreasing sludge age also means decreasing the zone settling velocity at all solids concentrations. There are two factors to be considered. Decreasing the mixed liquor suspended solids concentration does decrease the loading on the clarifier; so that the clarifier would no longer be overloaded, if the zone settling velocities at all sludge concentrations - between the mixed liquor suspended solids concentration and the return solids concentration - remained constant despite the resultant change in sludge age. However, this is not so. If the sludge age were reduced, the zone settling velocities at all sludge concentrations of interest would likely decrease. For the strategy to work, the decreased loading would have to more than compensate for the decreased zone settling velocities. Whether this strategy worked or not, the plant operator would certainly have to settle for a decreased underflow concentration (see Figures 26 and 28). One possible advantage of this strategy is that the required return flow might possibly be reduced with reduced sludge age (under certain conditions, apparent in Figure 27). From the above discussion it can be seen that the strategy of increasing sludge wastage may or may not solve the problem of an overloaded clarifier. The most important result, as well as the most undesirable result, of an overloaded secondary clarifier is an increase in effluent suspended solids. Changing the sludge age would also probably result in increased effluent suspended solids - at least, temporarily. The safest strategy in dealing with an overloaded clarifier and what should be the first strategy to be tried is increasing the return flow. Although this will likely decrease the underflow concentration, so will decreasing the sludge age. Adequate capacity for return flow should be designed into treatment plants and should receive careful consideration by the design engineer.

The sludge volume index for a given initial sludge concentration was found to increase with decreasing sludge age, except that the values observed at a sludge age of 2.2 days were smaller than those observed at a sludge age of 4.7 days (see Figure 24). Also, the observed sludge volume index at a given sludge age was found to first increase with increasing initial sludge concentration and to then begin to decrease with increasing initial sludge concentration (see Figure 23). Figure 25 presents the relationship observed in this study between sludge age and sludge volume index for an initial sludge concentration equal to the mixed liquor suspended solids concentration observed at the relevant sludge age. The results reported in Figure 25 are quite similar to those reported by Bisogni and Lawrence (19). That is, the curve in Figure 25 shows a trend similar to that reported by

Bisogni and Lawrence; although the absolute values observed in this study and those reported by Bisogni and Lawrence differ. One would not and should not expect the absolute values to be similar.

As was pointed out in the previous paragraph, the results of this study indicate that both sludge concentration and sludge age influence the observed sludge volume index. This fact can have some significance. Sludge volume index should have little relevance to the design of a secondary clarifier. However, it can be used effectively by the plant operator, if one important point omitted by Standard Methods (23) is kept in mind. The sludge volume index is dependent not only on sludge age and other variables such as oxygen availability which can affect the actual settling and compaction characteristics of an activated sludge, but on initial sludge concentration as well. If the operator is not aware of the effect of initial sludge concentration on sludge volume index and consequently does not standardize his measurements by choosing some standard starting concentration, the operator's sludge volume index measurements will be both meaningless and useless.

An important point which should be considered by the design engineer is ease of operation. In operating an activated sludge plant; it would greatly simplify the operation, if the thickening characteristics of the sludge showed little or no variability. If this were so, both the recycle flow rate and the waste flow rate would require little or no variation to accomodate fluctuations in sludge underflow concentration. In this study, the zone settling velocity at a given concentration varied considerably at sludge ages of 2.2 and 4.7 days (Figures 11 through 15). This was not true at higher sludge ages. The same effect is seen for sludge volume index in Figures 18 through 23. As far as ease of day to day operation is concerned, it would seem that a sludge age greater than about five days is preferable. This value may differ with varying wastes and operating conditions.

A factor which was not controlled for in this study was the mixed liquor suspended solids concentration. That is, while effluent suspended solids concentration, zone settling velocity, and sludge volume index varied with sludge age; these parameters also varied with mixed liquor suspended solids concentration, which varied along with sludge age in this study, Although it seems probable that sludge age is the independent variable of greatest significance; it is possible that the varying mixed liquor suspended solids concentration was either entirely or at least partially responsible for the variations in effluent suspended solids concentration, zone settling velocity, and sludge volume index. The simplest means of determining the effect of mixed liquor suspended solids concentration on the above parameters is to maintain a constant sludge age, while varying the feed concentration.

CHAPTER VI

CONCLUSIONS

This study has led to the conclusions listed below, which are valid only within the range of sludge ages and activated sludge concentrations observed in this study.

1. At a given initial sludge concentration, the sludge volume index first increases to a maximum value with decreasing sludge age and thereafter decreases with decreasing sludge age.

2. At a given sludge age, the sludge volume index first increases to some maximum value with increasing initial sludge concentration and thereafter decreases with increasing sludge concentration.

3. The zone settling velocity of an activated sludge decreases with both decreasing sludge age and increasing initial sludge concentration.

4. The maximum concentration to which an activated sludge will settle decreases with decreasing sludge age.

5. At a constant secondary clarifier overflow rate and secondary clarifier hydraulic detention time, the effluent suspended solids concentration will vary with sludge age.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

1. Study the effect of varied mixed liquor suspended solids concentrations on the zone settling velocity at a constant sludge age, in order to separate the effect of the operating solids concentration in the aerator from the effect of sludge age.

2. Study the effect of varied sludge age on the zone settling velocity at a given initial sludge concentration, while maintaining a constant mixed liquor suspended solids concentration - for the same reason as above.

3. Study the effect of sludge age and mixed liquor suspended solids concentration on the clarification properties of activated sludge via the relevant tests and equations for a class 2 suspension.

4. Compare the observed zone settling velocity data for an activated sludge system with the observed operating parameters of that system via the Coe and Clevenger/Dick equation(s).

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