THE EFFECT OF SLUDGE AGE AND CONCENTRATION ON THE SETTLING VELOCITY OF SLUDGE

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Scope and Method of Study: This laboratory investigation was made to study the effect of both sludge age and concentration on the settling velocity of sludge and to develop a mathematical relationship between these three factors. A laboratory activated sludge unit was used in this investigation and brought to steady state at five different sludge ages, ranging from 4 to 12 days. Settling velocity and sludge volume index were determined at various sludge concentrations at each sludge age.

Findings and Conclusions: It was found that settling velocity and sludge volume index vary with changes in sludge age and concentration. A mathematical relationship for each range of solids concentration was developed, one equation for solids concentration ranging from 1000-3000 mg/l, and the other for 3000-5000 mg/l. Both of these equations are useful only when the sludge ages range from 6 to 12 days.

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TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

II. LITERATURE REVIEW 3

Sedimentation Process Analysis 3
Effect of Sludge Age on the Settling Characteristic of Sludge 6
Clarifier Design 9

III. MATERIALS AND METHODS 16

Laboratory Apparatus 16
Feed Solution 19
Experimental and Analytical Procedures 19
Equations Used in Analysis of Data 22

IV. RESULTS 24

Operating Data 24
Settling Data and Development of a Mathematical Model 33

V. DISCUSSION 91

Operating Data 91
Discussion on Settling Data 92

VI. CONCLUSIONS 97

VII. SUGGESTIONS FOR FUTURE STUDY 99

BIBLIOGRAPHY 100

TABLE

Table Page

I. Composition of Synthetic Wastewater 20

LIST OF FIGURES

Figure		Page
1.	Experimental Activated Sludge Unit With Internal Recycle	18
2.	Percent BOD Removed vs. Sludge Age	26
3.	Soluble Effluent BOD vs. Sludge Age	28
4.	Percent TOC Removed vs. Sludge Age	30
5.	Effluent TOC vs. Sludge Age	32
6.	Effluent Suspended Solids vs. Sludge Age	35
7.	Mixed Liquor Suspended Solids vs Sludge Age	37
8.	Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 4 Days	39
9.	Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 6 Days	41
10.	Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 8 Days	43
11.	Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 10 Days	45
12.	Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 12 Days	47
13.	Zone Settling Velocity vs. Sludge Concentration at All Sludge Ages	49
14.	Zone Settling Velocity vs. Sludge Age at Various Sludge Concentrations	52
15.	Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 4 Days	54
16.	Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 6 Days	56

Figure		Page

17. Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 8 Days 58

18. Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 10 Days 60

19. Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 12 Days 62

20. Sludge Volume Index vs. Initial Sludge Concentration at All Studied Sludge Ages 64

21. Sludge Volume Index vs. Sludge Age at Various Initial Concentrations 66

22. Solids Flux vs. Sludge Concentration at Sludge Age of 4 Days 69

23. Soldis Flux vs. Sludge Concentration at Sludge Age of 6 Days 71

24. Solids Flux vs. Sludge Concentration at Sludge Age of 8 Days 73

25. Solids Flux vs. Sludge Concentration at Sludge Age of 10 Days 75

26. Solids Flux vs. Sludge Concentration at Sludge Age of 12 Days 77

27. Solids Flux vs. Sludge Concentration at All Tested Sludge Ages 79

28. Initial Velocity (from Figure 13) vs. Sludge Age . . . 82

29. Slope (from Figure 13) vs. Sludge Age 84

30. Initial Velocity (from Figure 13) vs. Sludge Age . . . 88

31. Slope (from Figure 13) vs. Sludge Age 90

CHAPTER I

INTRODUCTION

Industrial and population growth have brought about pollution problems which have become one of the major public concerns of our time. Water pollution is one of the common problems which man is facing today. Recognition of this problem has led to the use of different techniques to remove pollutants from water and improve its quality. One way to get rid of the pollutants is by using biological reactors. One type of biological reactor is the activated sludge unit. In the activated sludge treatment plant, the pollutants are converted to suspended solids by biological means. The suspended solids are removed by gravity sedimentation to permit return of treated water to the environment.

Sedimentation basins play an important role in the treatment of waste water. Clarification and thickening of sludge are two significant functions of all sedimentation basins. The effluent from a waste water treatment plant is discharged to the environment; therefore it needs to be clarified from biological solids. For the activated sludge system to function well, a part of the biomass must be returned to the aeration basin.

Gravity settling is the most economical mean of performance for these two functions. The purpose of this study was to investigate the effect of sludge age on the settling characteristics of microorganisms and developing a relationship between the settling velocity of micro-organisms and their retention time.

CHAPTER II

LITERATURE REVIEW

Sedimentation Process Analysis

Sedimentation is one of the most common processes used in the field of water and waste water treatment. Sedimentation is the separation of suspended particles from water. Sedimentation is used for the removal of grit and particulate matter in the primary settling tank, and is used for the removal of biological solids in the secondary clarifier. In addition, in the chemical coagulation process, a sedimentation basin is used to remove chemical floc.

The performance of secondary sedimentation units in biological processes, as Eckenfelder and Melbinger (1) have pointed out, is related to the physical and chemical nature of the sludge and to the hydraulic characteristics of the sedimentation basin.

Settling tanks used in waste water treatment processes have two functions; one is the production of an effluent which is relatively free of settleable solids, and is called clarification. The other is the concentrating of the solids removed into a small volume, which is called thickening. The design of a sedimentation tank requires analysis of both thickening and clarification. Improper design for the clarification and thickening functions of final tanks can lead to direct deterioration of the effluent quality of the waste water treatment plant system.

Particles in a fluid body will settle according to their size, density, and shape. Fitch (2) believes that particles settle in any of four markedly different manners, and all of these different manners are governed by particle interaction. This is determined largely by the dilution of the suspension, and the relative tendency of the particles to cohere. He believes that at high dilutions there exists a regime which is called "clarification." Particles in this regime may settle either individually (classified as class I clarification), or by collecting into separated floccules (designed as class II clarification). In this class, flocculation takes place as a result of the collision of particles. Camp (3) believes that collision can be brought about in three ways: 1) Brownian motion of particles, 2) differential settling velocities whereby faster settling particles overtake and collide with those that are slower settling, and 3) differential velocities or shear in the suspending fluid, which causes particles centered in one flow filament to sideswipe particles in adjacent filaments. Fitch (2) says one of the characteristics of the clarification regime is that there will be no clear line of demarcation. Faster particles settle out ahead of slower particles.

As dilution decreases, the particles are crowded closer together, and Fitch (2) believes their settling behavior undergoes a marked change. Here, particles enter a regime which is called "zone settling." The solids settle as a more or less consolidated mass, and there will be a clear line between the suspension particles and supernatant.

At lower dilution, the particles enter another regime, which is called "compression." According to Coe and Clevenger (4), this regime will occur when the weight of suspended particles is no longer borne completely by hydrodynamic force. They attributed this regime to mechanical support of layers of floc.

Eckenfelder and Melbinger (1) divided the settling process into three distinguished zones. They believe that during the initial settling period the sludge floc settles at a constant velocity under existing conditions of hindered settling. The magnitude of this velocity is a function of the initial solids concentration. The concentration of solids in the hindered settling zone will remain constant until solids enter the next zone.

As the layer of settled sludge increases, the settling floc begins to press on layers below, and at this time the transition zone occurs. Through the transition zone the settling velocity is not constant but will decrease due to the increasing density and viscosity of the suspension surrounding the particles.

When the floc concentration becomes so great as to be mechanically supported by the floc layers below, a compression zone will occur. The solid concentration in this zone is related to the depth of sludge and the detention of solids in this zone. Cummings (5) reported that for a given detention time, a shallow compression zone depth will yield a higher underflow concentration than will a greater depth. He reports that as the depth of the sludge blanket is increased, the sludge detention in the compression zone must also be increased for a specified underflow concentration.

The clarifier in biological treatment has dual functions. These two functions are clarifying the supernatant and thickening the sludge underflow. According to Eckenfelder and Melbinger (1), the clarification capacity of the unit is related to the settling velocity of the sludge in which the velocity of the sludge interface must be greater than the vertical rise of the liquid at any level. They reported that the thickening capacity is related to the depth of sludge in the basin and the time the sludge is in the compression zone. Thickening is enhanced by the hydraulic movement of the sludge blanket and the action of the rakes which break up stratification of the settled sludge.

Effect of Sludge Age on the Settling Characteristic of Sludge

In the activated sludge unit the separation of biomass and water will occur via gravity and bioflocculation. As Bisogni and Lawrence (6) have reported, the effectiveness of this biomass separation depends on the settling characteristics and bioflocculation of the activated sludge. Settling characteristics of the sludge are defined by its sludge volume index (SVI), zone settling velocity, and the percent of microorganism which remain dispersed after a long settling period.

The first step in biomass-liquid separation as Bisogni and Lawrence (6) note, is the formation of floc or bioflocculation. If the first step does not occur, the second step which is gravity settling and compaction of the biomass, will not occur. They believe the formation of floc will not necessarily result in good settling. If the floc has low density, a bulking floc will be formed. Lack of bioflocculation can result in a dispersed growth system.

Many attempts have been made to recognize bioflocculation and sludge bulking. In 1968, Boyle et al. (7) summarized the major theories of bioflocculation, but the exact mechanism is not known. It is believed there is a relationship between degree of bioflocculation and growth rate of sludge. In 1956, Heukelekian and Weisburg (8) tried to find a relatioship between zoogloeal sludge bulking and bound water content of the sludge. They found that as the bound water content of the sludge increased, the sludge volume index also increased. Later, they noted that in activated sludge, bound water was a function of the loading factor.

In 1967, Eckenfelder and Ford (9) used pilot plant studies to investigate the settling characteristics of three different waste waters. The types they used were domestic, brewery, and petrochemical waste waters. They used different F/M ratios with the range of 0 to 2 in their study. The settling characteristics of the biological sludge were determined by using stirred settling columns. They found that the sludge volume index in all three types of wastes decreased at a range of F/M from 0 to 0.3, and that the sludge volume index increased as the F/M ration increased from 0.3 to 2. They got an inverse result for the settling velocity for all three types of waste water. In all three types of wastes, the settling velocity at first increased for a F/M ratio of 0 to 0.3, and then as the F/M ratio was increased above 0.3, the settling velocity decreased. The organic loading rate has a direct relationship with the growth phase of microorganisms. With respect to the work of Boyle et al. (7), it seems that microbial growth rate should have a direct effect on both sludge bioflocculation and sludge settling. The inverse of the biological solids retention time as Lawrence and McCarty (1) reported in 1970 is equal to the net specific growth rate. Therefore, settling characteristics of the biological solids are related to the solids retention time.

An investigation by Bisogni and Lawrence (6) concerned the relationship between sludge age and the settling characteristics of microorganisms. They ran a series of bench scale laboratory aerobic reactors of the Ludzack type. The sludge age studied varied from 0.25 days to 12 days. In their experiment they attempted to eliminate concentration as a factor affecting settling velocity by diluting or concentrating all samples to 2000 mg/l. They found that as the sludge age decreased from 12 days to 4 days, the settling velocity decreased linearly, and from 4 days to 2 days of sludge age, the settling velocity decreased slightly more.

They also found that as the sludge ages decreased from 12 days Θ_c to 4 days Θ_c, the sludge volume index increased slowly. These changes in sludge volume index for sludge ages decreased rapidly from 4 days to 0.25 days. They also measured the amount of suspended solids in the effluent at different sludge ages. They found that the effluent suspended solids decreased from a maximum sludge age equal to 0.25 to a minimum at one day Θ_c and from one day Θ_c suspended solids increased rapidly to a maximum at almost 3 days Θ_c, then they decreased to a minimum at 6 days Θ_c and finally from 6 days Θ_c they increased again.

The experiment of Bisogni and Lawrence (6) covered only a 2000 mg/l concentration of biological solids. They did not present a model which described the relationship between sludge ages and the settling characteristics of microorganisms.

Another effort to find the relationship between sludge ages and settling characteristics of microorganisms was made by Roper and Grady (11). They used the Vesilind equation (12) to express this relationship:

$$V_i = V_o \, e^{-B_o C_i}$$

in which V_i = zone settling velocity of the sludge is dependent on the sludge concentration, C_i. The parameters B_o and V_o depend on the sludge settling characteristics. According to the settling data reported by Bisogni and Lawrence (6), V_o is highly dependent on the sludge age.

$$V_o = 0.0835 \;\; \Theta_c - 0.24 \text{ ft/min}$$

$$\text{when} \quad 3 \leq \Theta_c \leq 12 \text{ days}$$

Roper and Grady (11) also used these equations in Dick's equation (13) to show the limit of solid flux in which settling failure occurs. They believe their equation is a general equation which can show the relationship between sludge age and solids concentration, and settling velocity. They also believe that the constants in their equation stay the same in all cases.

The effect of sludge age on the settling velocity of different sludges was rarely considered in a few cases for most models encountered in research. Even though most models relate the settling velocity to the sludge concentration, only one or two models consider the relationship between sludge age and settling velocity.

Although very few models consider the relationship of sludge age with settling characteristics, additional research is necessary. Obviously, the relationship between sludge age and settling velocity of sludges affects the design of thickeners significantly.

Clarifier Design

To make sure that a final clarifier accomplishes its job, both clarification and the thickening function of a settling tank should be considered in the design. As Dick (13) reported, when the size of the settling tank for a desired degree of clarification exceeds the size needed for a desired degree of thickening, then the clarification function governs sizing of the final clarifier. However, if the thickening requirement is greater, thickening will be predominant and will govern the size of the tank.

According to Eckenfelder and Melbinger (1) in designing a settling tank, three design factors should be considered. The first design factor to be considered is allowing sufficient area for the purpose of clarification over the operating mixed liquor suspendid solids range. This is related to the overflow rate in which the vertical rise of liquid should not exceed the solids subsistence rate at any level. The second design factor is related to the area and volume requirements to produce by thickening an underflow of a desired concentration. The third design factor to consider is the permissible retention time of sludge in the bottom of the settling tank.

Improper design of a settling tank for thickening and clarification as reported by Dick (13) can lead to direct deterioration of effluent quality. Improper design of the settling tank which does not provide a desired underflow concentration can lead to a decrease of the mixed liquor suspended solids which, in turn, will cause an increase in specific organic loading. Eckenfelder and Edde (14) reported that an increase in the intensity of organic loading can cause an adverse effect on the flocculating and settling characteristics of the sludge, and make it even more difficult to obtain a desired underflow concentration. Dick (13) reported that with an adequate design of the final clarifier, the size and cost of the aeration tank can be reduced. The reason for this, as he mentioned, is that when the solids return to the aeration tank in a sufficiently high concentration, the required amount under aeration can be contained in a smaller aeration tank.

In the past, the designing of most settling tanks was based on the standard detention time which was required by the local health department. In 1904, Hazen (15) presented a new idea--that removal of suspended solids depends on the surface area of the tank and not upon the volume of the settling tank. At this time, the settling characteristics of the suspended materials which should be clarified was not a consideration. But the concept of surface area as a requirement in the design of a settling tank was originated by Coe and Clevenger (4) in 1916. To show the requirement of this factor in the design, they ran a batch unit and concluded that for a given slurry, settling velocity is a function only of the solids concentration. Based on the batch tests and by using a solids balance, Coe and Clevenger could develop an equation for this purpose:

$$G = \frac{V}{\frac{1}{C} - \frac{1}{C_u}}$$

where

G = solids flux, gr solids/min/sq cm

C = concentration, gr solids/cm^3 slurry

V = velocity of solids for each concentration

C_u = underflow concentration, gr solids/cm^3 slurry

They pointed out that because the solids flux must be constant throughout the thickener, they let G be equal to the influent solids flux:

$$G = \frac{Q_o\ C_o}{A}$$

where Q_o and C_o are the influent flow rate (cm^3 slurry/min) and concentration (gr solids/cm^3 slurry), and A is the area required in sq cm. If this relationship is substituted in the first equation, a new equation will be developed:

$$A = \frac{Q_o\ C_o}{V} \left[\frac{1}{C} - \frac{1}{C_u}\right]$$

After conducting a series of batch tests, one can get a series of data of settling velocity corresponding to each solids concentration used. Substituting different terms in the above equation, the required area can be calculated for each test. Of course, in the design of a clarifier, the maximum area calculated should be considered because if the design of the settling tank is based on the smaller area calculated, some of the solids will escape in the overflow.

The purpose of mentioning the equation offered by Coe and Clevenger (4) here is to show the importance of their work and because they are pioneers in presenting a new method for the design. Subsequent work by other researchers achieved approximately the same results.

To eliminate the repetitive solution of the Coe and Clevenger equation, Yoshioka et al. (16) from Japan presented a graphical solution. Again, a series of batch tests must be conducted and solids flux plotted against the concentration. A straight line is drawn from the desired underflow concentration tangent to the under side of the flux curve. This line will intersect the ordinate at a point which is the minimum flux which the system can handle. For this minimum flux an area can be developed. This graphical procedure developed by Yoshioka will yield the same numerical result as does the equation of Coe and Clevenger.

Another experiment was conducted in the designing of the settling tank by Hassett (17). His work is based on the concept that the total solids flux in a continuous thickener consists of two components. One of these components is induced flux due to the removal of solids in the underflow, and the other is the solids flux due to settling velocity of the sludge. The total flux curve obtained by the Hassett method, as the previous method, has a minimum at some concentration. Again the result of this method is identical to the result obtained by the Coe and Clevenger equation.

The method presented by researchers Behn (18), Eckenfelder and Melbinger (1), Cole (19), and Vesilind (20) was a direct method. The reason for presenting this method was because of some disadvantages which the Coe and Clevenger (4) and Hassett (17) methods encountered, such as requiring a repetitive calculation and need for an accurate flux curve. This method is based on the plotting of results from batch settling tests in an activated sludge unit. From plotting of the settling velocity versus solids concentration in a semilog paper, a relationship between settling velocity and solids concentration can be developed. Then, using the relationship between settling velocity and solids concentration, and substituting these terms in the equation developed by Hassett, a new equation, identical to the Coe and Clevenger equation can be obtained.

In 1952, Kynch (21) presented a new concept in thickening analysis; his work was followed by Fitch and Talmadge (22). This work allows the determination of settling velocity for different concentration of solids. Although his idea was to bring a new concept in the designing of the settling tank, it has been found inapplicable for flocculant particles like biological solids. Later, the work of Kynch (21) was modified to a better and usable form for a thickener design by Talmage and Fitch. Another method which should be considered is volume design method which is based on experience. For this purpose, two experimental methods have been developed. One of these methods is the Roberts (23) method and is based on the analysis of the height-time curve in the compression range. This method originally developed by Michaels and Bolger (24) and advocated by Fitch (25) is based on a mathematical model of compression zone thickening.

Dick (26) used the Hassett (17) equation and the Yoshioka (16) graphical solution and introduced a new design method. In his analysis, he obtained the same result as did Coe and Clevenger (4), except his equation needs less computation. Plotting settling velocity of sludge versus sludge concentration, Richard Dick (26) developed a new model. Zone settling velocity reported by Dick is a function of only solids concentration; he did not consider sludge retention time in his model. He reported that solids retention time or sludge volume were not a factor controlling continuous thickener performance, but that it has influenced thickening performance indirectly. In 1974, Roper and Grady (11) came up with a new model for designing a secondary clarifier. Originally, they used the biooxidation modeled by Lawrence and

McCarty (10) in which they tried to bring the design of aeration more in line with the clarifier. In their model, Roper and Grady (11) used the theory of Dick (13) about the limiting flux and failure point of the settler. Dick's theory maintains that the maximum capacity of a settling tank to pass solids downward depends on a limiting flux. In this case, if the applied flux exceeds this limit, it will result in failure of the settler. Roper and Grady used Dick's total flux equation, then used the equation by Vesilind (12), and substituted velocity from this equation in the total flux equation, deriving a new equation which has already been presented. The new equation devised by combining the settling velocity equation and total flux equation is as follows:

$$G_t = C_i(0.0835\ \Theta_c - 0.24)e^{-B_o C_i} + C_i\left(\frac{\alpha F_0 + F_w}{A}\right)$$

where

G_t = total flux, lbs/day/ft^2

C_i = solids concentration, mg/l

B_0 = sludge constant = 4.5 x 10^{-4} l/mg

V_0 = settling velocity of individual sludge particles, ft/min

A = settler area, ft^2

α = recycle ratio

F_0 = return flow, mgd

F_w = flow rate, mgd, and

Θ_c = sludge age, day

CHAPTER III

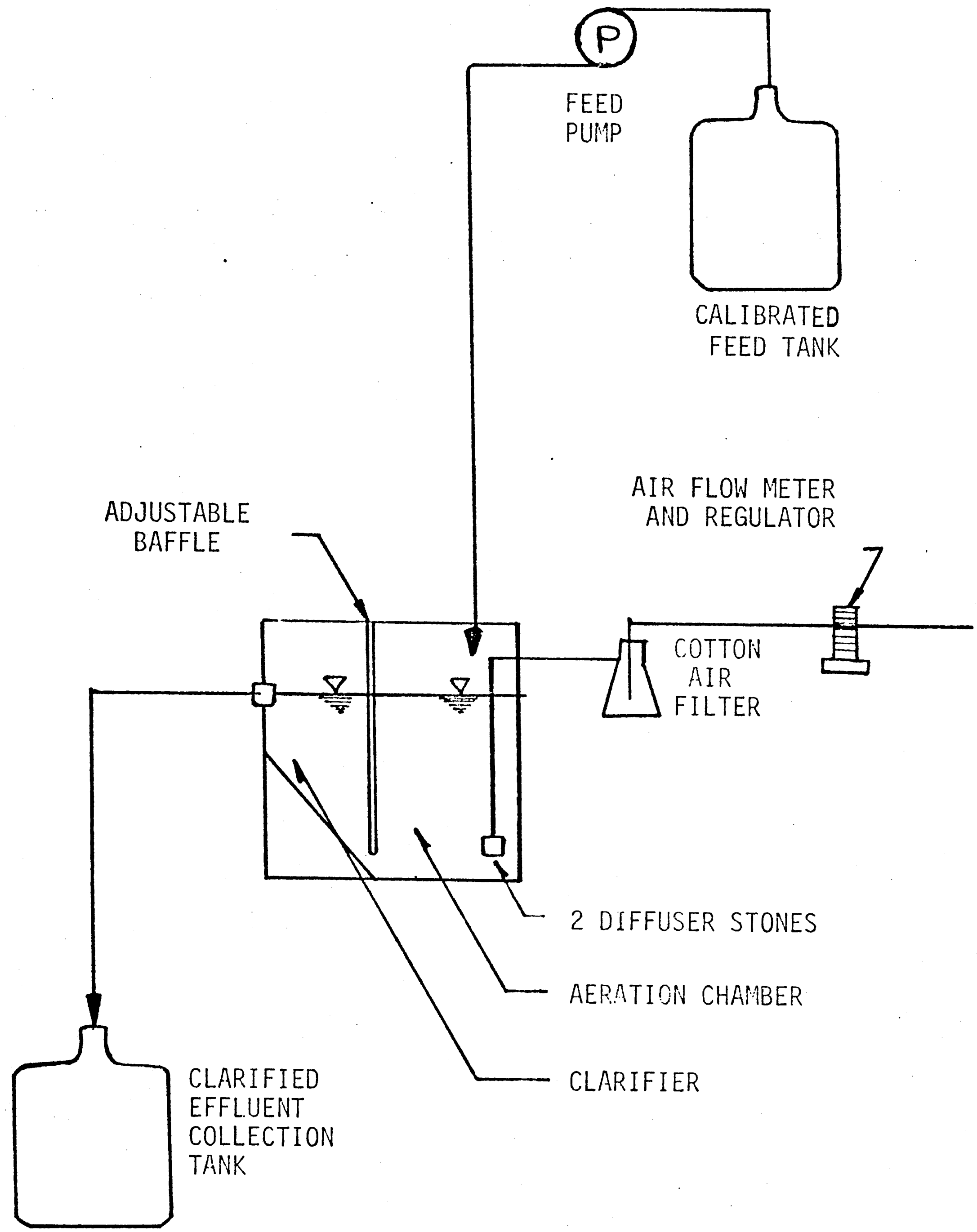
MATERIALS AND METHODS

In order to study the effect of sludge age on the settling characteristics of microorganisms, a laboratory bench scale continuous flow activated sludge was operated under controlled conditions for seven months.

Laboratory Apparatus

A diagram of the laboratory apparatus used in this study is shown in Figure 1. A plexiglass internal recycle reactor was used in which aeration and clarifier volumes were 2.9 and 1.1 liters, respectively. A feed rate of 6 ml/min was supplied to the reactor by means of a Milton Roy "mini-pump." Aeration and clarifier compartments were separated by an adjustable baffle. Air was supplied at a rate of 3 liters/min through two sintered glass diffusers. A Gelman airflow meter was used to monitor the air flow. The influent flow rate was checked every day by means of a 10-ml graduated cylinder and a timer. Feed was prepared every other day in a 5-gallon glass bottle. The feed bottle was marked for 18 liters and was used for two days. pH of the system was monitored every day and maintained in the range of 7.2 - 7.5 by means of a buffer solution. Temperature also was kept at a constant rate. The effluent flowed by gravity from the clarifier compartment to an effluent bottle. All lines in the system were cleaned by an acid wash,

Figure 1. Experimental Activated Sludge Unit With Internal Recycle


FEED
PUMP
CALIBRATED
FEED TANK
ADJUSTABLE
BAFFLE
AIR FLOW METER
AND REGULATOR
COTTON
AIR
FILTER
2 DIFFUSER STONES
AERATION CHAMBER
CLARIFIER
CLARIFIED
EFFLUENT
COLLECTION
TANK

which was a mixture of sulfuric acid and potassium dicromate to prevent biological growth in the lines.

Feed Solution

The chemical composition of the feed solution which was used in this study is listed in Table I. This type of stock solution, which included organic and inorganic chemicals, was made in two bottles. In fixing the feed solution, 13.5 mililiters of each was added to sufficient tap water in a 5-gallon glass bottle to make 18 liters of feed.

Experimental and Analytical Procedures

The microorganism seed used in this study was obtained from the Ponca City municipal wastewater treatment plant. The system was operated as a continuous flow activated sludge reactor. Sludge age was the means by which the operation was controlled. Five different sludge ages were used, starting with 8 days sludge age, then 10 days, and 12 days. The sludge age was then decreased from 12 days to 6 days, and finally to 4 days. To maintain a certain sludge age, biological solids were wasted daily. After removing the baffle between the aeration and clarification compartments, the wastage for each different sludge age was removed. Biological solids in the reactor and in the clarifier effluent bottle were measured daily to monitor for sludge age and for steady state. Suspended solids measurements were made according to Standard Methods, in which a glass filter was used. After reaching steady state condition, the data gathering process began.

To monitor for substrate concentration in the feed and in the clarifier effluent, BOD and TOC tests were made three times per week.

TABLE I

COMPOSITION OF SYNTHETIC WASTEWATER

Organic Component	Amount in 1 liter of Stock Solution
1. Ethylene glycol	113 ml/l
2. Ethyl alcohol	113 ml/l
3. Acetic acid	113 ml/l
4. Glutamic acid	113 gm/l
5. Glucose	113 gm/l
6. Phenol	22.6 gm/l
Add enough tap water to bring it to 1 liter	
Inorganic Component	
1. $(NH_4)_2SO_4$	200 gm/l
2. $MgSO_4 \cdot 7H_2O$	80 gm/l
3. K_2HPO_4	48 gm/l
4. $CaCl_2$	8 gm/l
5. $FeCl_3 \cdot 6H_2O$	0.4 gm/l
6. $MnSO_4 \cdot H_2O$	8 gm/l
Add enough tap water to bring it to 1 liter	

The other types of data which were measured included settling velocity of sludge and sludge volume index for different values of sludge ages.

To measure the settling velocity of the mixed liquor suspended solids, take a sample volume of the mixture for given concentrations with regard to the concentration in the reactor. Measure the given concentrations in a one-liter (1000 ml) graduated cylinder. If the mixture's concentration in the reactor is less than that of the sample concentration, then the sample should be concentrated. However, if the concentration in the reactor is greater than that of the sample concentration, then the sample should be diluted. In any case, the volume should be brought to one liter. When the concentration of suspended solids necessary to run the test was less than that of the mixed liquor suspended solids, the dilution was achieved by using the clarifier effluent. The measurement of settling velocity at each sludge age was begun when the system reached a steady state condition. The settling velocity test was made at each sludge age and with various solids concentrations. The sludge ages ranged from 4 to 12 days, and biological solids concentration from 1000 mg/l to 5000 mg/l.

Only one measurement was made daily per concentration per sludge age. Three one-liter graduated cylinders were used, but only one of them which was clear glass was marked from zero to 36 cm. The diameter of the cylinder was 6.3 cm. Before the test was begun, the sludge content of the graduated cylinder was mixed by slowly pouring back and forth between two cylinders several times. After mixing sufficiently, the suspension was allowed to settle and the position of solids-liquid interface for different time intervals was recorded. The time intervals ranged from 0 to 30 minutes. For the first ten minutes, the solids-liquid interface was recorded for each 30 seconds, but from 10 to 30 minutes it was recorded for each minute. The sludge volume index also was measured during the settling velocity test. This test was also made in accordance with Standard Methods.

After the settling velocity and sludge volume index tests were made, the settled sludge was returned to the reactor to maintain a certain amount of mixed liquor suspended solids in the reactor.

Equations Used in Analysis of Data

The data analysis was accomplished by means of the following equations, and cell residence time or sludge age was determined:

$$\Theta_c = \frac{V \cdot X}{F_w X + (F - F_w) X_e}$$

where

Θ_c = sludge age, day

X = suspended solids concentration, mg/l

V = volume of aeration tank, liter

F = flow rate, liter/day

F_w = waste flowrate, liter/day

X_e = effluent suspended solids concentration, mg/l

BOD and TOC removal efficiency was determined by means of the removal efficiency equation, which is expressed as:

$$E = \frac{(S_i - S_o)}{S_i} \times 100$$

where

E = BOD or TOC removal efficiency, %

S_i = influent BOD or TOC concentration, mg/l

S_0 = effluent BOD or TOC concentration, mg/l

In determination of solids flux due to gravity, this relationship was used:

$$G_g = X \cdot V_i$$

where

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

X = concentration of biological solids, lb/ft^3

V_i = zone settling velocity at C_i, ft/day

CHAPTER IV

RESULTS

The results of this investigation will be presented in two parts. The first part is the data concerned with the removal efficiency of the activated sludge process, and the second part concerns the data related to the settling characteristics of the sludge.

Operating Data

The purpose of presenting the operating data is to show that the reactor performed well during this study. The BOD removal efficiencies at different ranges of sludge age in a continuous flow activated sludge unit are presented in Figure 2. The percentage removal of BOD as it is shown in this figure increases slightly as the sludge age increases.

The soluble effluent BOD as a function of sludge age is presented in Figure 3. As shown in this figure, the soluble effluent BOD decreased as the sludge age increased.

The TOC removal efficiencies at different ranges of sludge age are presented in Figure 4. As can be seen in this figure, the percentage of TOC removal increases as the sludge age increases.

The effluent TOC is shown in Figure 5 as a function of sludge age. This figure shows that the effluent TOC decreases as the sludge ages increase.

Figure 2. Percent BOD Removed vs. Sludge Age

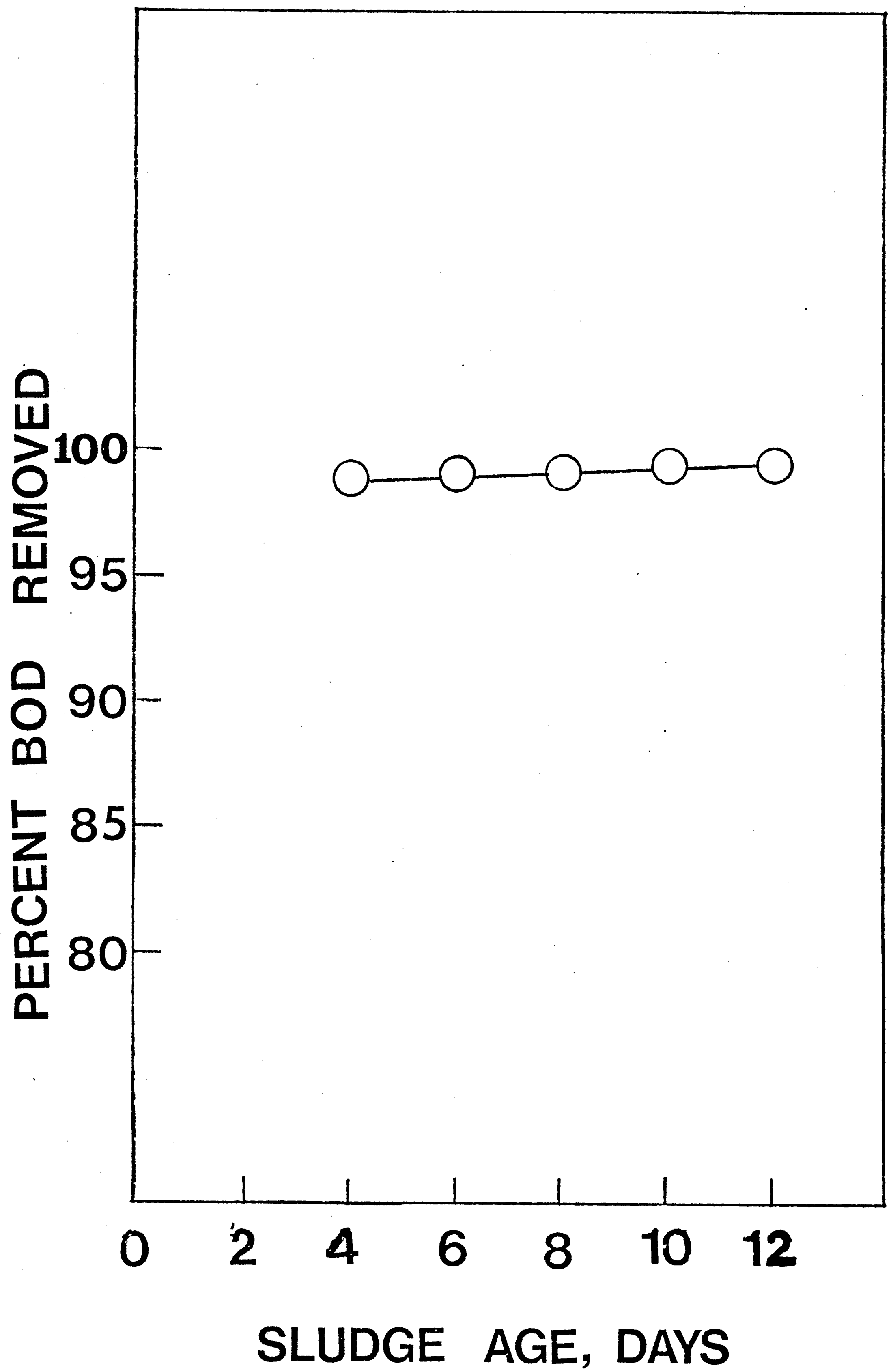

PERCENT BOD REMOVED
100
95
90
85
80
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 3. Soluble Effluent BOD vs. Sludge Age

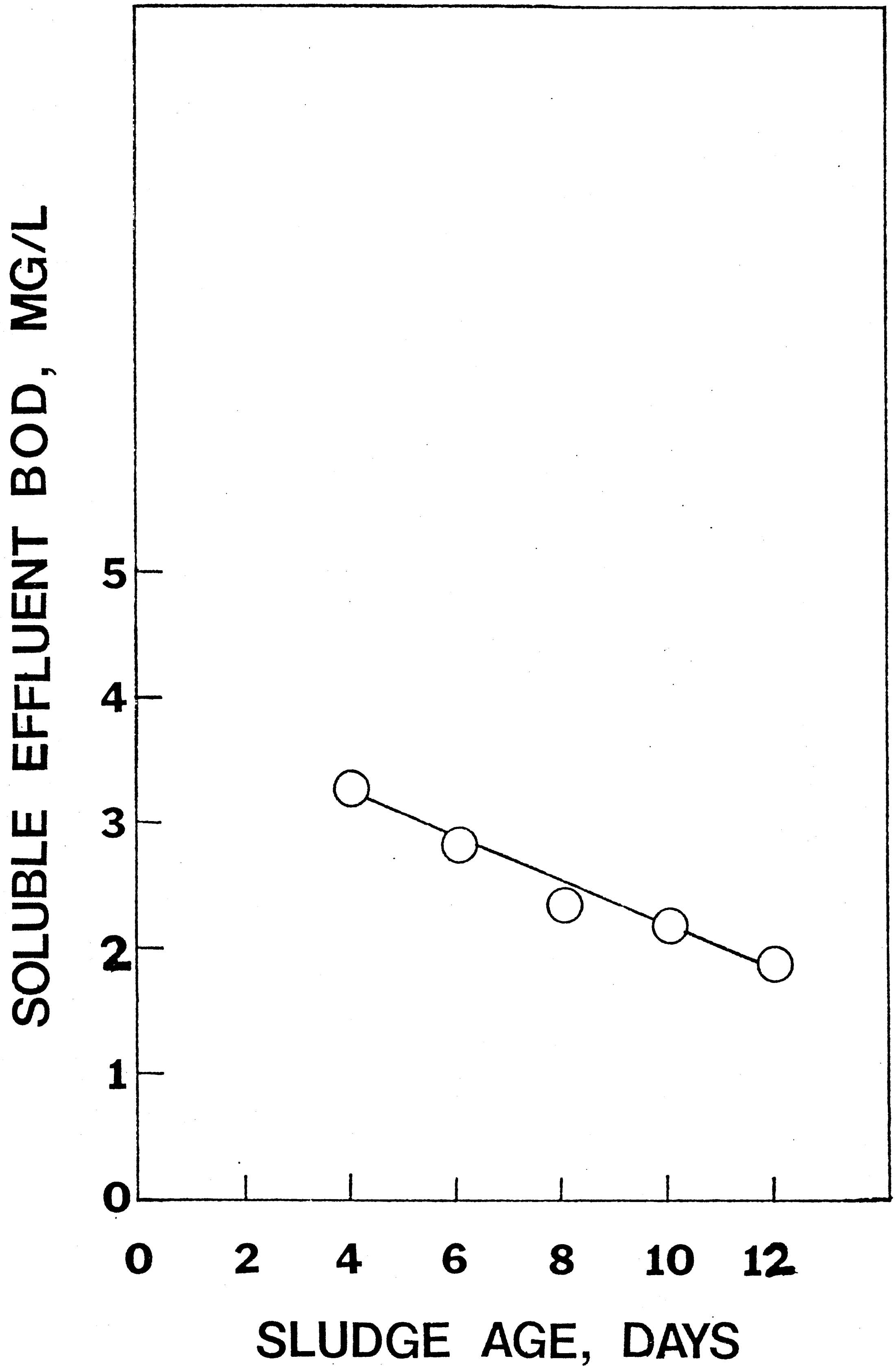

SOLUBLE EFFLUENT BOD, MG/L
0
1
2
3
4
5
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 4. Percent TOC Removed vs. Sludge Age

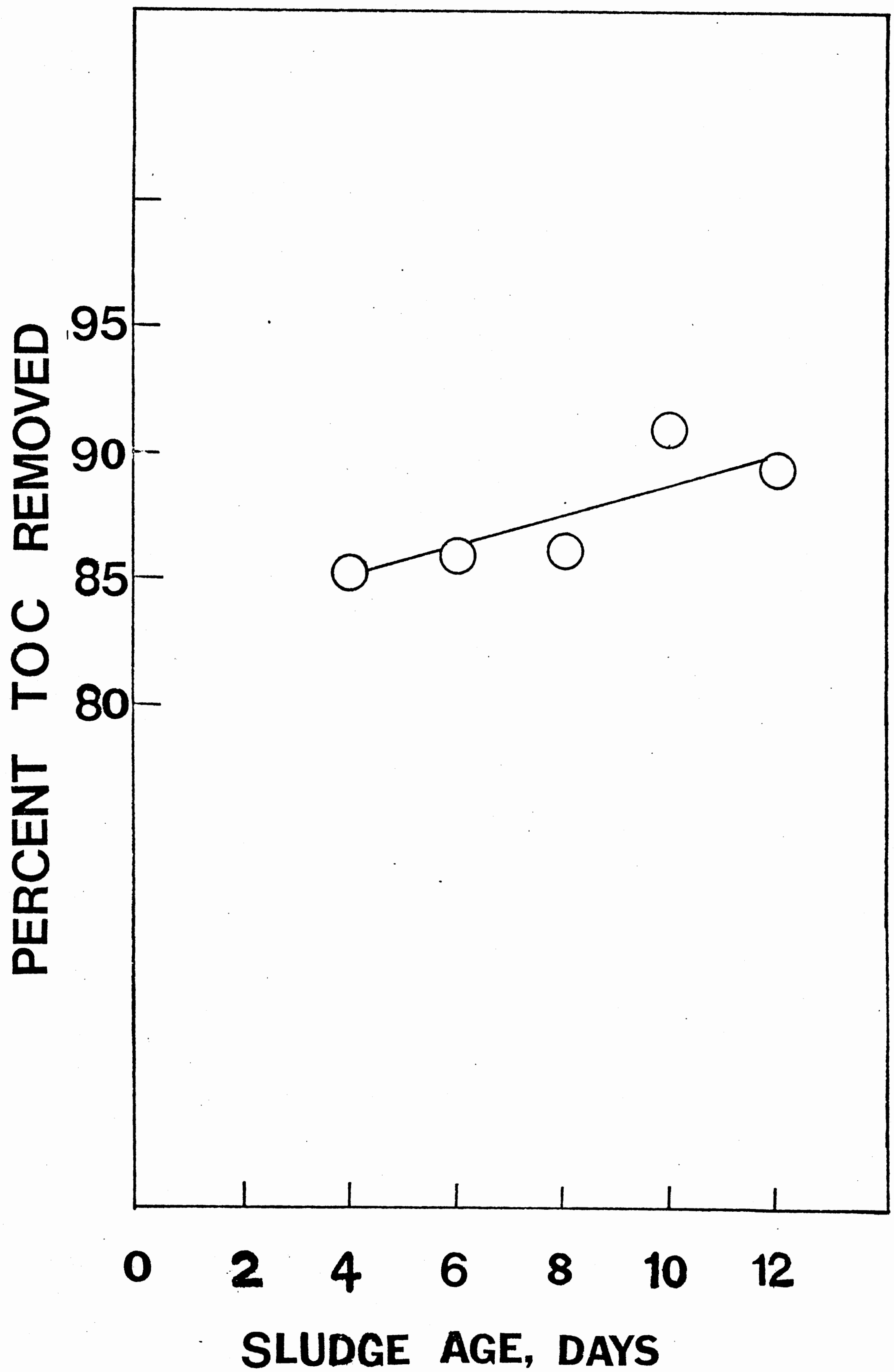
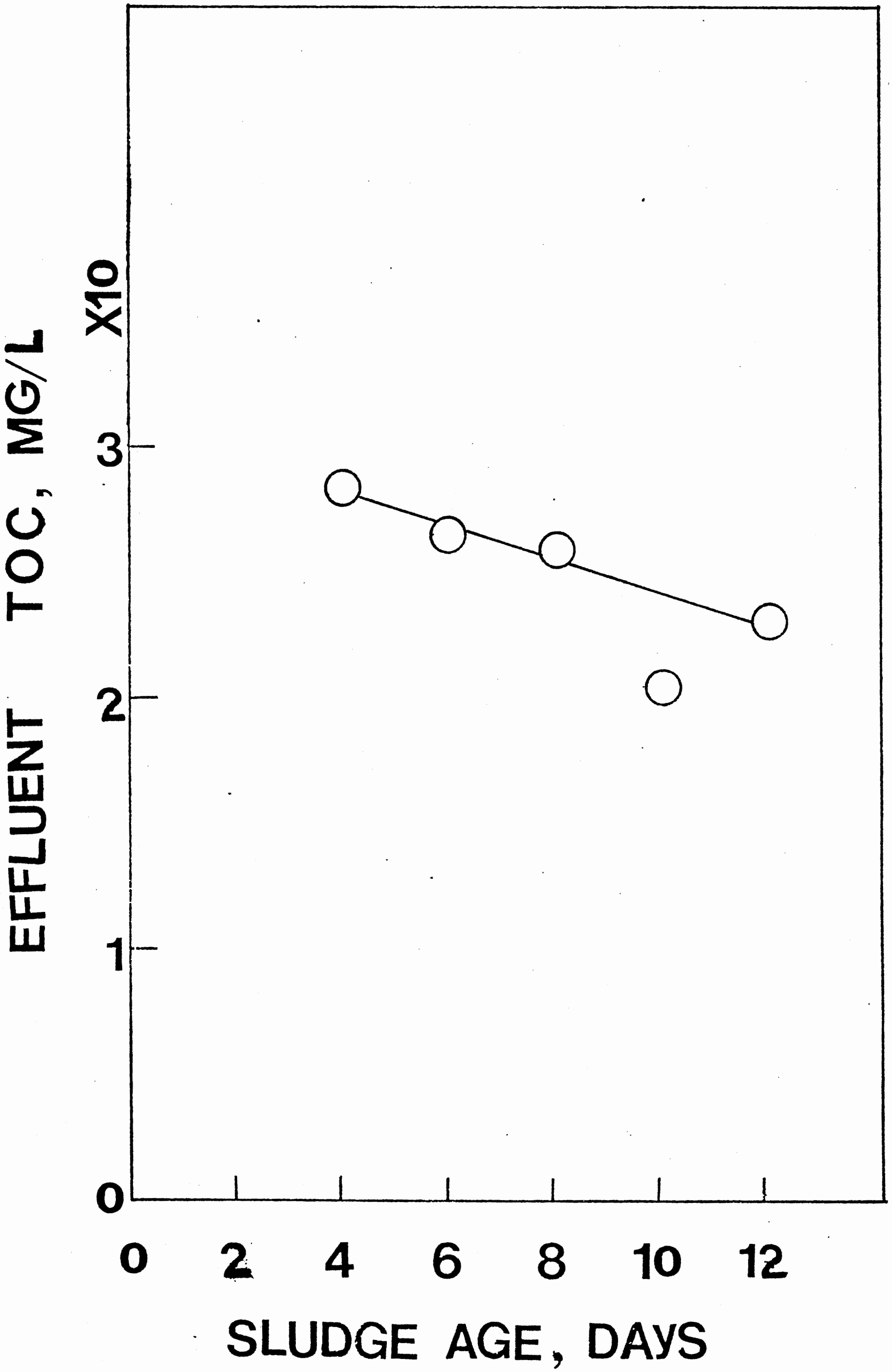

PERCENT TOC REMOVED
95
90
85
80
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 5. Effluent TOC vs. Sludge Age



EFFLUENT TOC, MG/L X10
3
2
1
0
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

It is seen that high removal efficiencies of BOD and TOC were achieved by the activated sludge unit.

The relationship between effluent suspended solids and various sludge ages studied is presented in Figure 6. Effluent suspended solids varied over the range of sludge ages. The average effluent suspended solids were maximum at 6-day sludge age and were minimum at 10-day sludge age.

Figure 7 describes the relationship between the mixed liquor suspended solids concentration at various sludge ages. As can be seen, the amount of solids increases with the increasing sludge age.

Settling Data and Development of a Mathematical Model

When a volume of homogeneous mixed liquor suspended solids is placed in a graduated cylinder, the solids start to settle. After a short period of time, the settling will be at a constant rate. The velocity during this constant rate is called "zone settling velocity." This zone settling velocity is a function of initial solids concentration and as will be seen later, it is also a function of sludge age. The zone settling velocity of different solids concentrations at various sludge ages was studied during this investigation. The relationship between the zone settling velocity and initial sludge concentration at various sludge ages is shown in Figures 8 through 12.

Figure 8 shows this relationship at a sludge age equal to 4 days, and Figures 9, 10, 11, and 12 show this relationship at sludge ages of 6, 8, 10, and 12 days, respectively. Figure 13 shows the zone settling velocity versus sludge concentration for all different sludge ages

Figure 6. Effluent Suspended Solids vs. Sludge Age

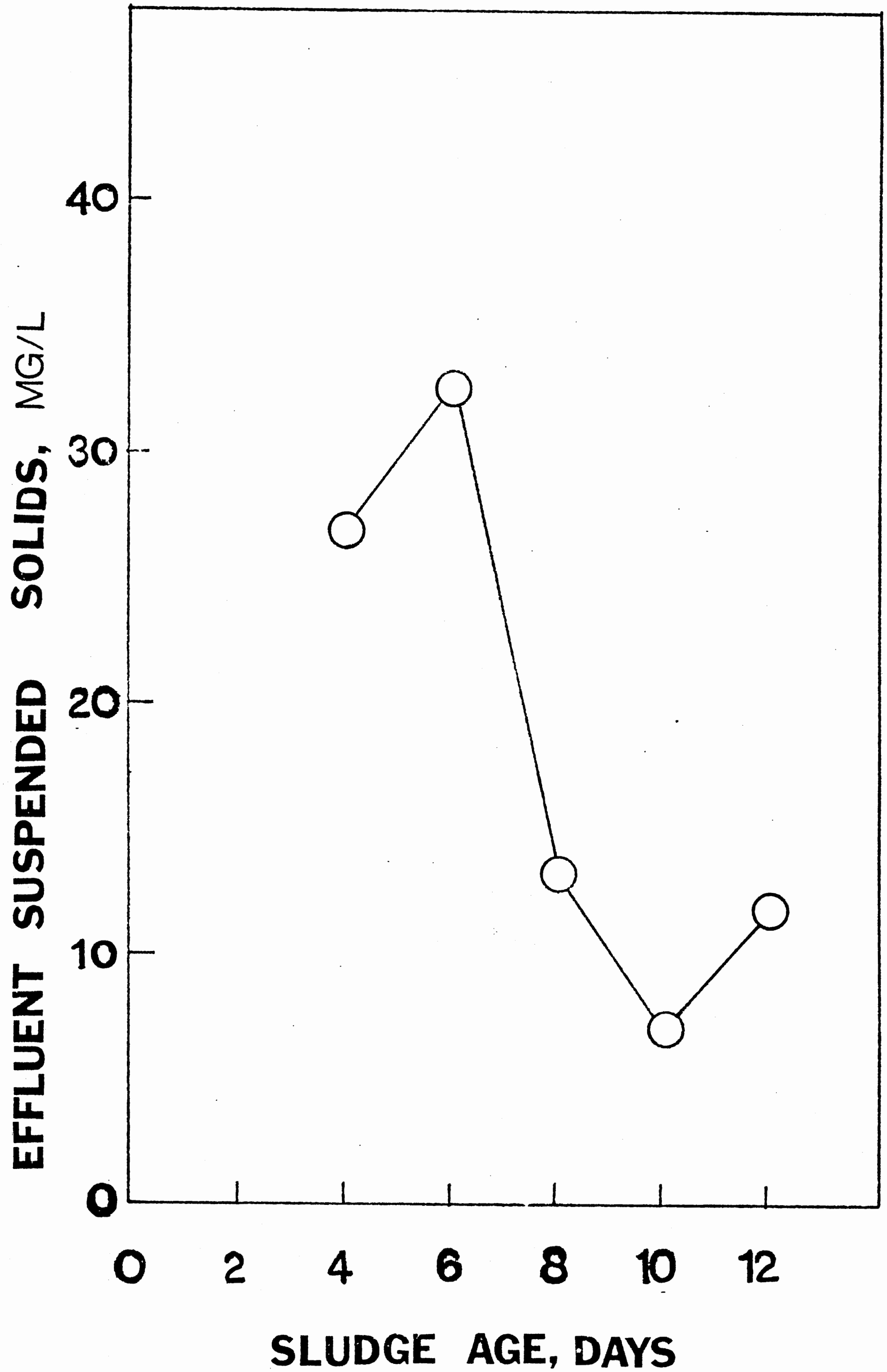

EFFLUENT SUSPENDED SOLIDS, MG/L
40
30
20
10
0
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 9. Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 6 Days

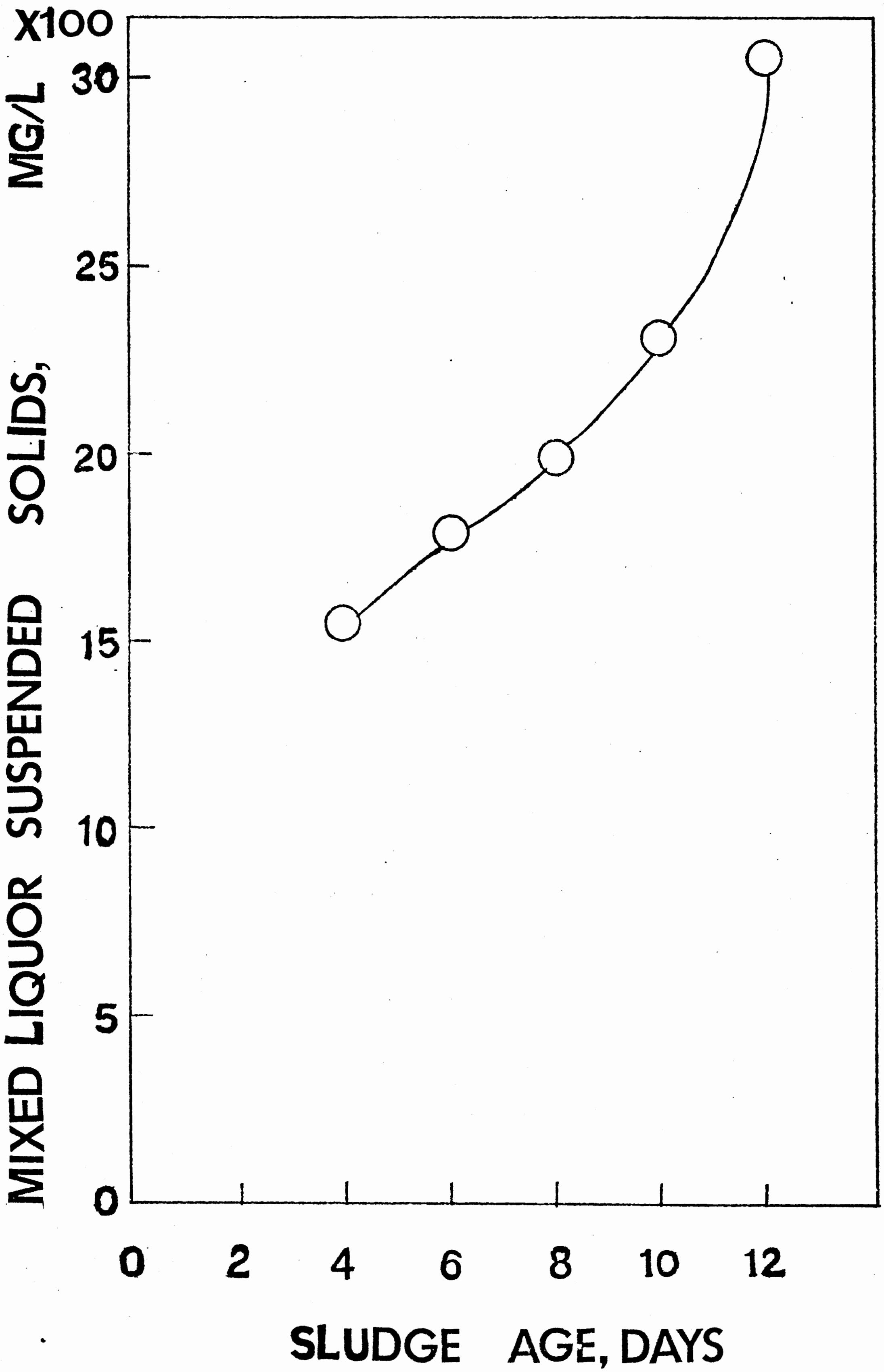

X100
MIXED LIQUOR SUSPENDED SOLIDS, MG/L
30
25
20
15
10
5
0
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 8. Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 4 Days

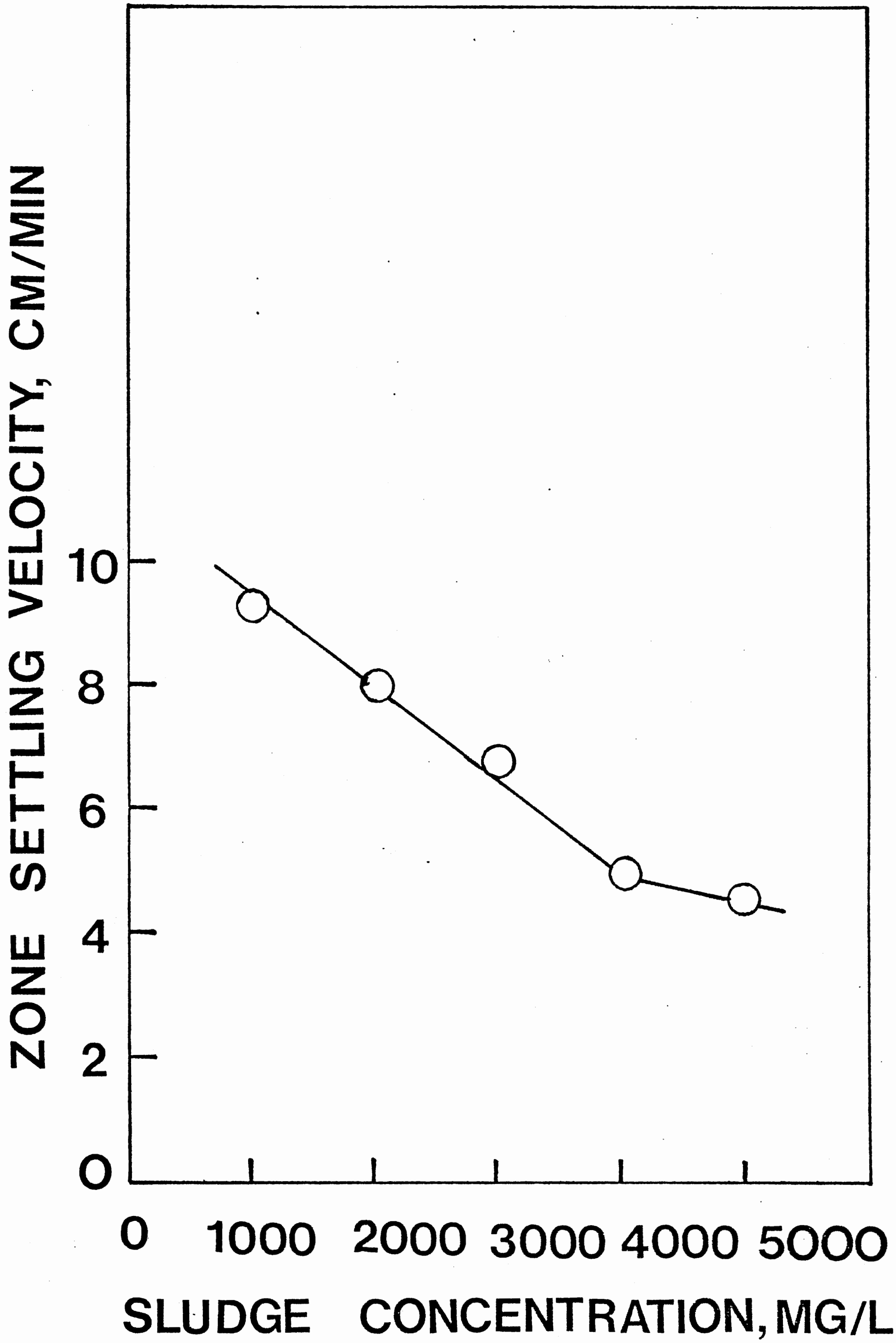

ZONE SETTLING VELOCITY, CM/MIN
10
8
6
4
2
0
0
1000
2000
3000
4000
5000
SLUDGE CONCENTRATION, MG/L

Figure 7. Mixed Liquor Suspended Solids vs. Sludge Age

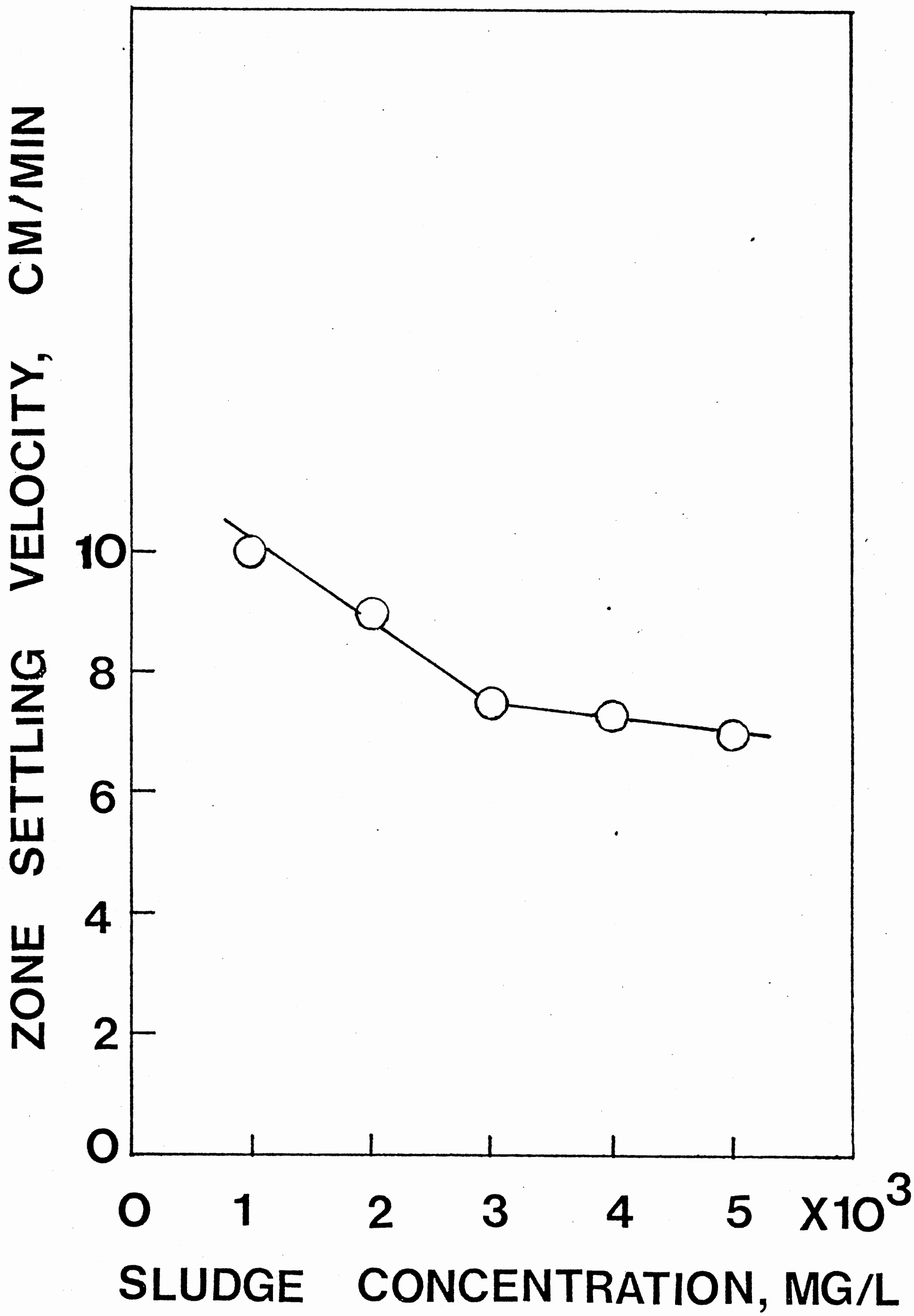

ZONE SETTLING VELOCITY, CM/MIN
10
8
6
4
2
0
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 10. Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 8 Days

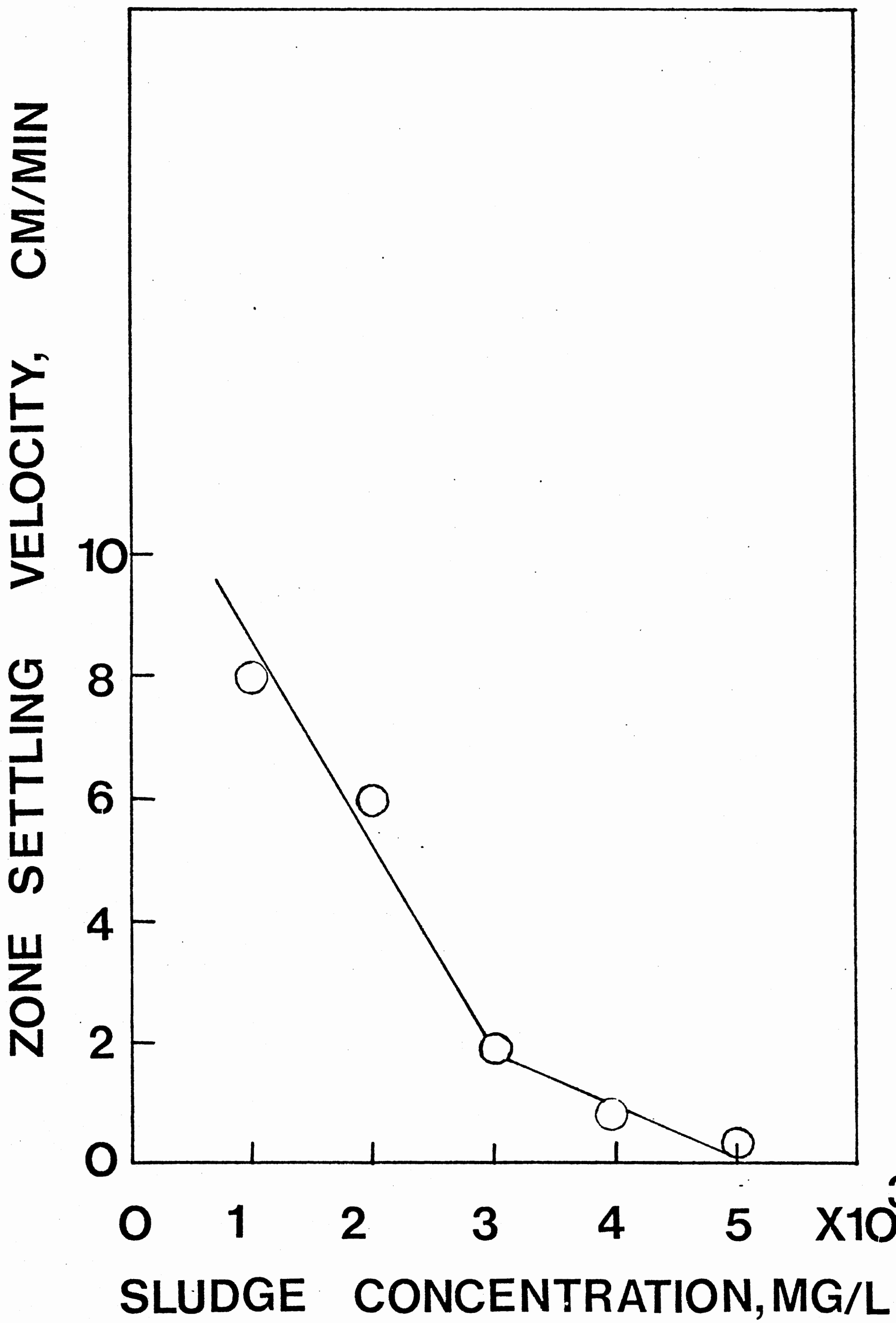

ZONE SETTLING VELOCITY, CM/MIN
10
8
6
4
2
0
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 11. Zone Settling Velocity vs. Sludge Concentration at Sludge Age of 10 Days

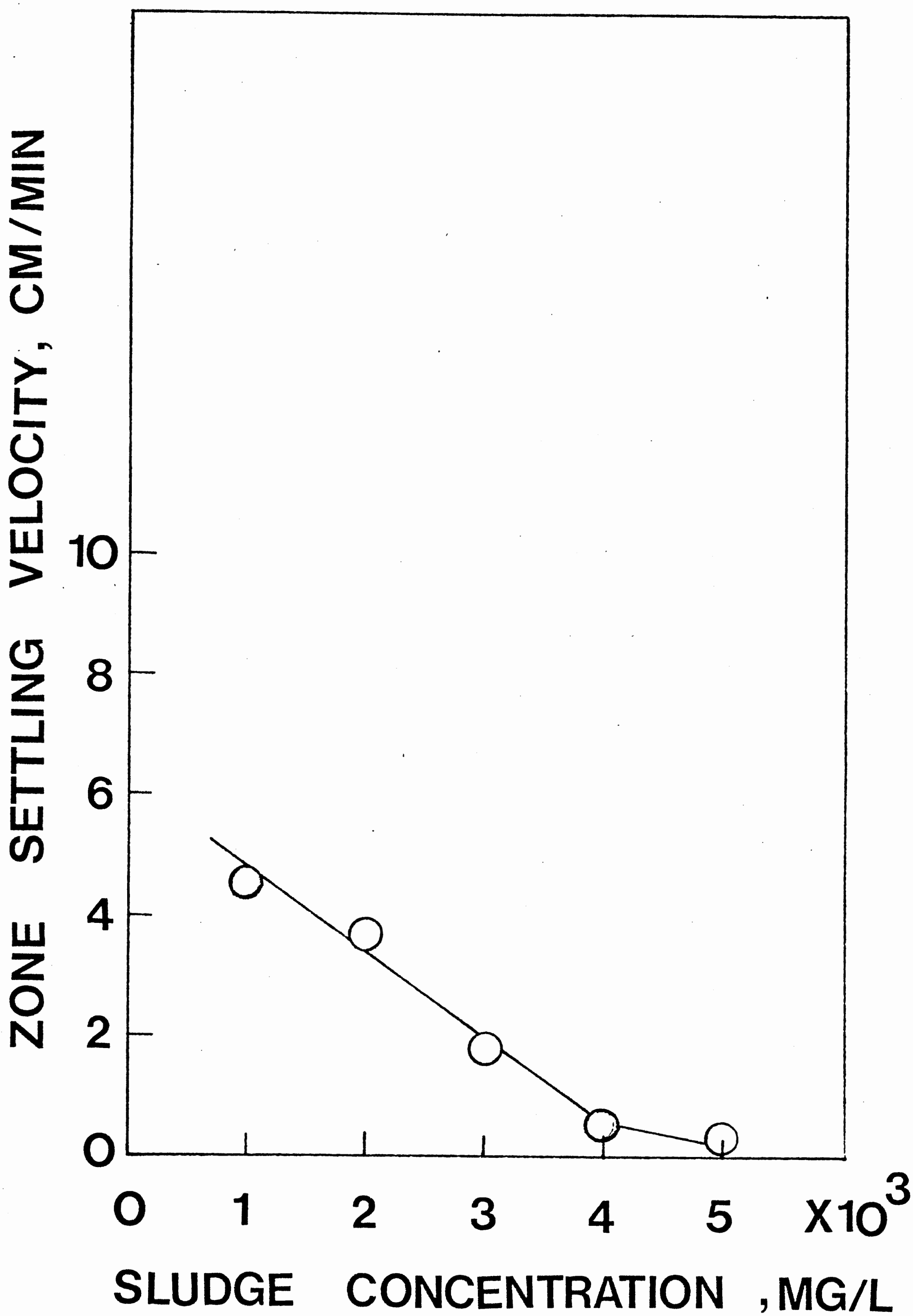

ZONE SETTLING VELOCITY, CM/MIN
10
8
6
4
2
0
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION ,MG/L

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

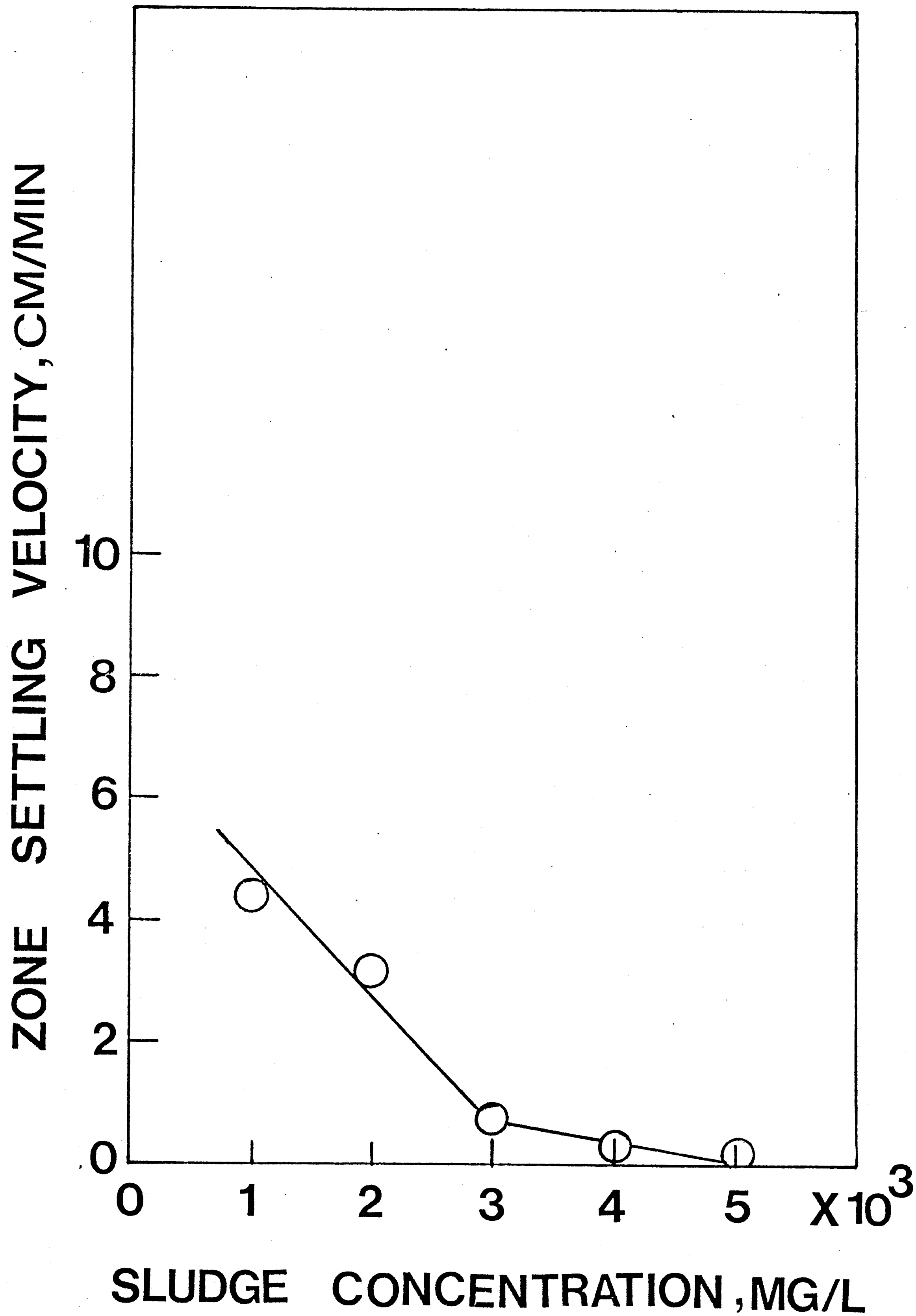
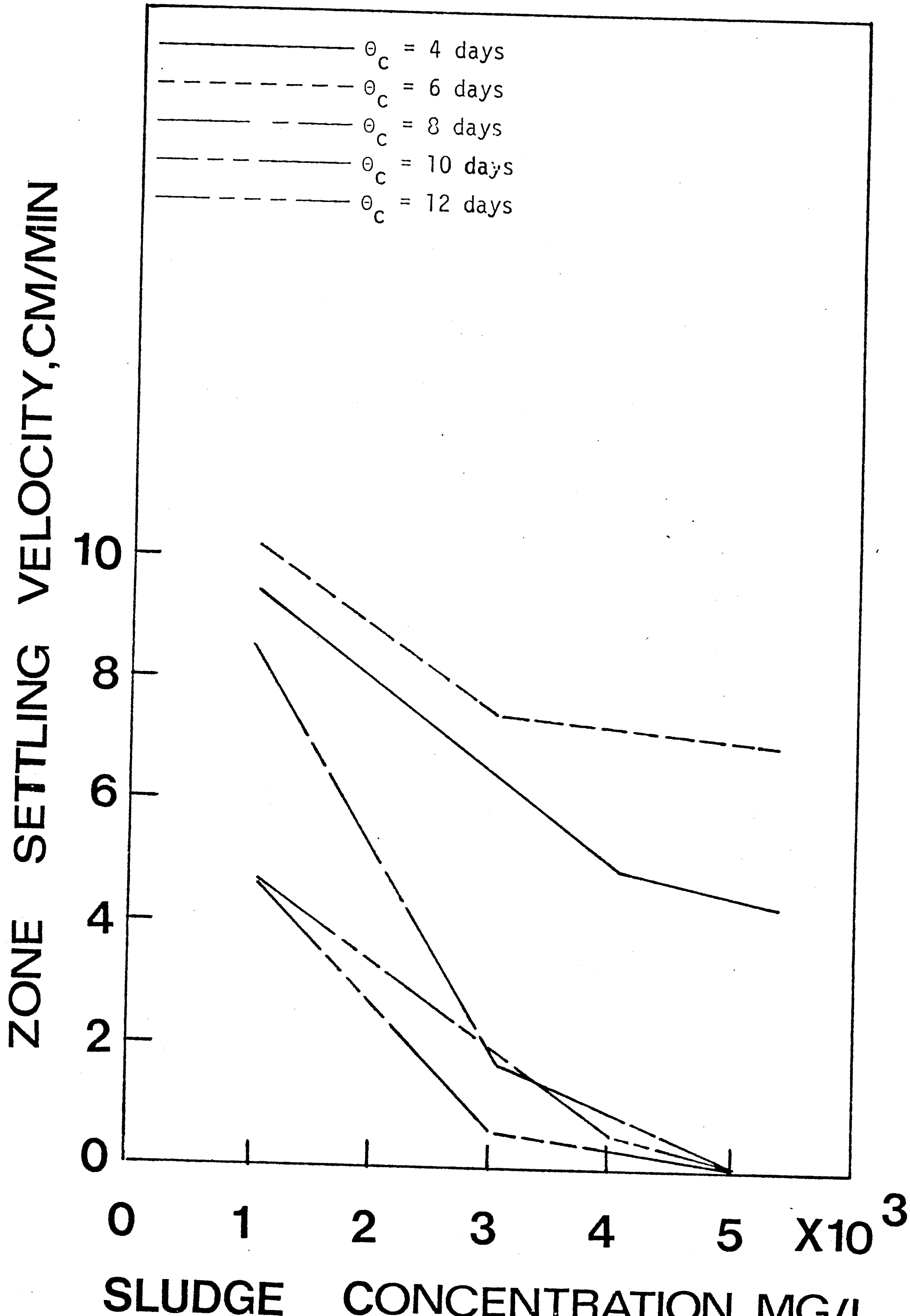

ZONE SETTLING VELOCITY, CM/MIN
10
8
6
4
2
0
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 13. Zone Settling Velocity vs. Sludge Concentration at All Sludge Ages



Θ_c = 4 days
Θ_c = 6 days
Θ_c = 8 days
Θ_c = 10 days
Θ_c = 12 days
ZONE SETTLING VELOCITY, CM/MIN
10
8
6
4
2
0
0
1
2
3
4
5
X10 3
SLUDGE CONCENTRATION, MG/L

studied in this investigation. Figure 13 is the collection of Figures 8 through 12. As can be seen in these figures, zone settling velocity at a given initial solids concentration decreases with increasing sludge age; the exception is for 4-day sludge age in which settling velocity decreases at all solids concentrations tested compared to 6-day sludge age. Figure 14 represents the relationship between zone settling velocity and sludge age at different initial solids concentrations. This figure shows that zone settling velocity is a function of both initial solids concentration and sludge age.

Sludge volume index is another type of measurement which has been taken to describe the settleability of sludge. Sludge volume index was also measured for different values of initial solids concentration at various sludge ages. This type of measurement was made in accordance with Standard Methods. The relationship between sludge volume index and initial solids concentration is shown in Figures 15 through 19. Figure 20 is a combination of all curves from Figures 15 through 19. The sludge volume index at 4- and 6-day sludge age appears to be almost constant over the range of initial solids concentration. At 8-day sludge age, as the concentration varies from 1000 mg/l to 2000 mg/l, the sludge volume index decreases proportionally. However, as the concentration varies from 2000 mg/l to 5000 mg/l, the sludge volume index increases proportionally. At 10-day sludge age, the sludge volume index increases constantly; but at 12-day sludge age, it has a minimum at 2000 mg/l solids concentration, then it increases at a maximum of 4000 mg/l, and again it decreases.

Figure 21 presents the relationship between sludge volume index and sludge age at various initial solids concentrations. This figure

Figure 14. Zone Settling Velocity vs. Sludge Age at Various Sludge Concentrations

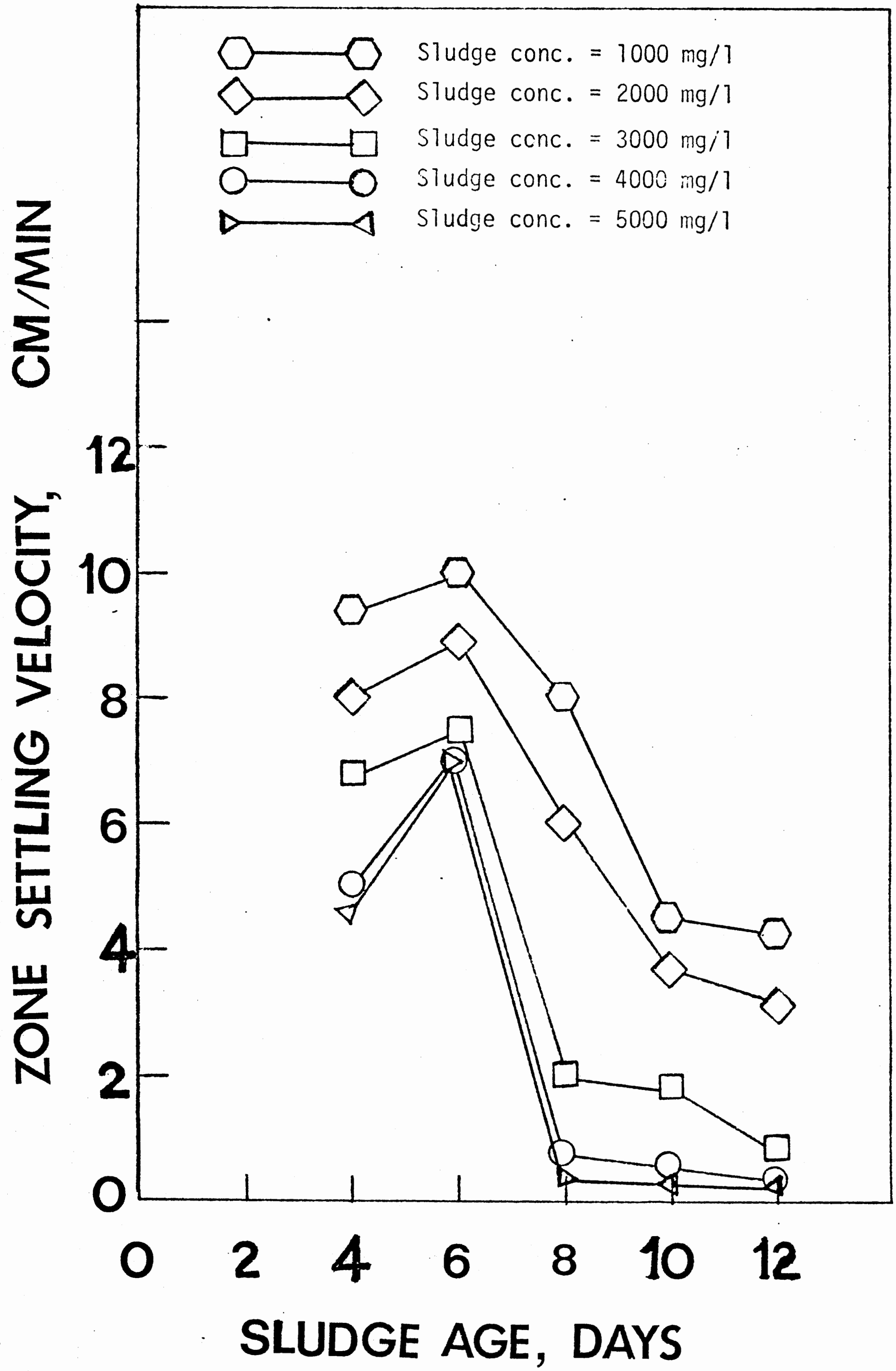

Sludge conc. = 1000 mg/l
Sludge conc. = 2000 mg/l
Sludge conc. = 3000 mg/l
Sludge conc. = 4000 mg/l
Sludge conc. = 5000 mg/l
ZONE SETTLING VELOCITY, CM/MIN
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 15. Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 4 Days

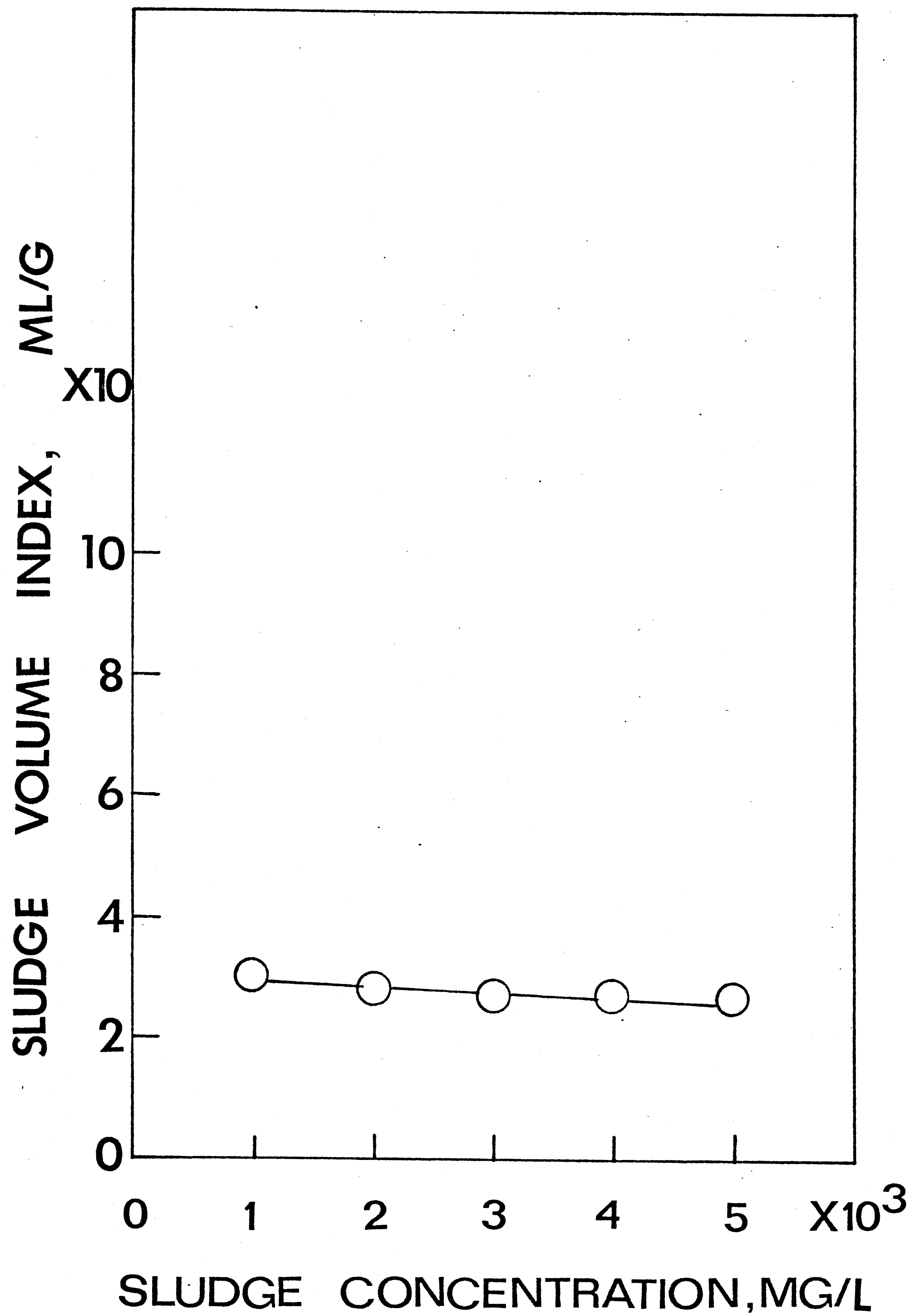

SLUDGE VOLUME INDEX, X10 ML/G
0
2
4
6
8
10
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 16. Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 6 Days

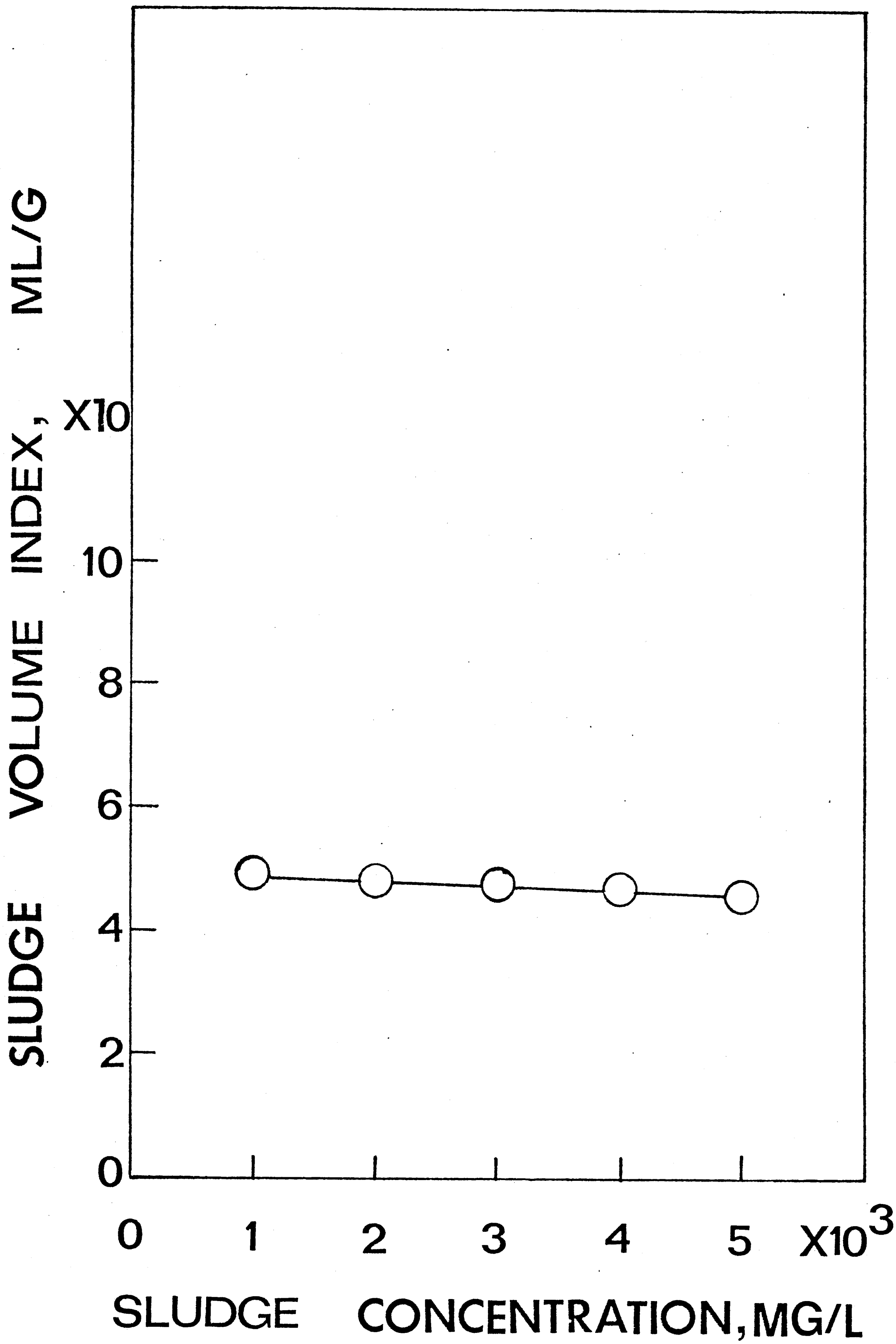

SLUDGE VOLUME INDEX, X10 ML/G
0
2
4
6
8
10
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 17. Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 8 Days

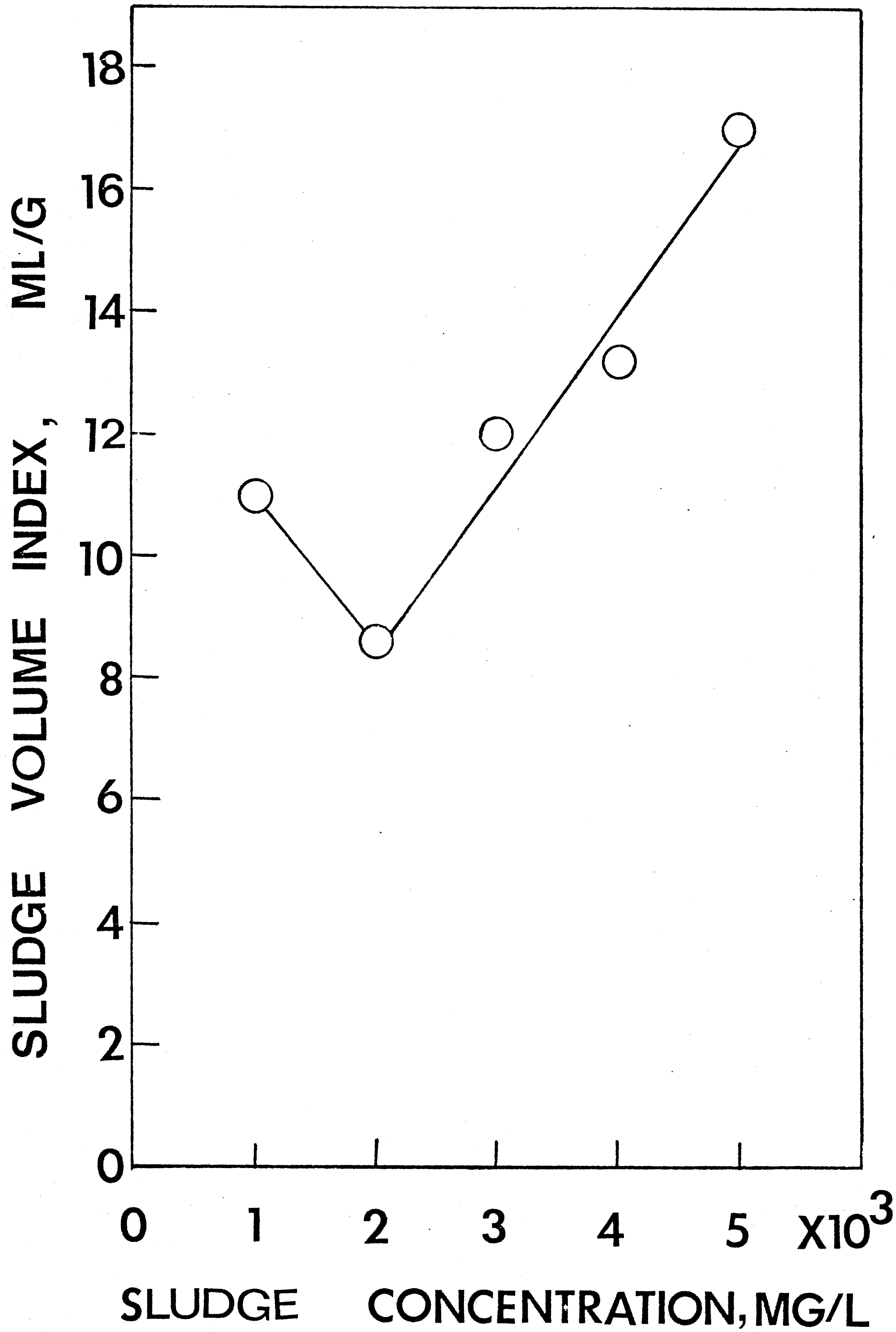

SLUDGE VOLUME INDEX, ML/G
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 18. Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 10 Days

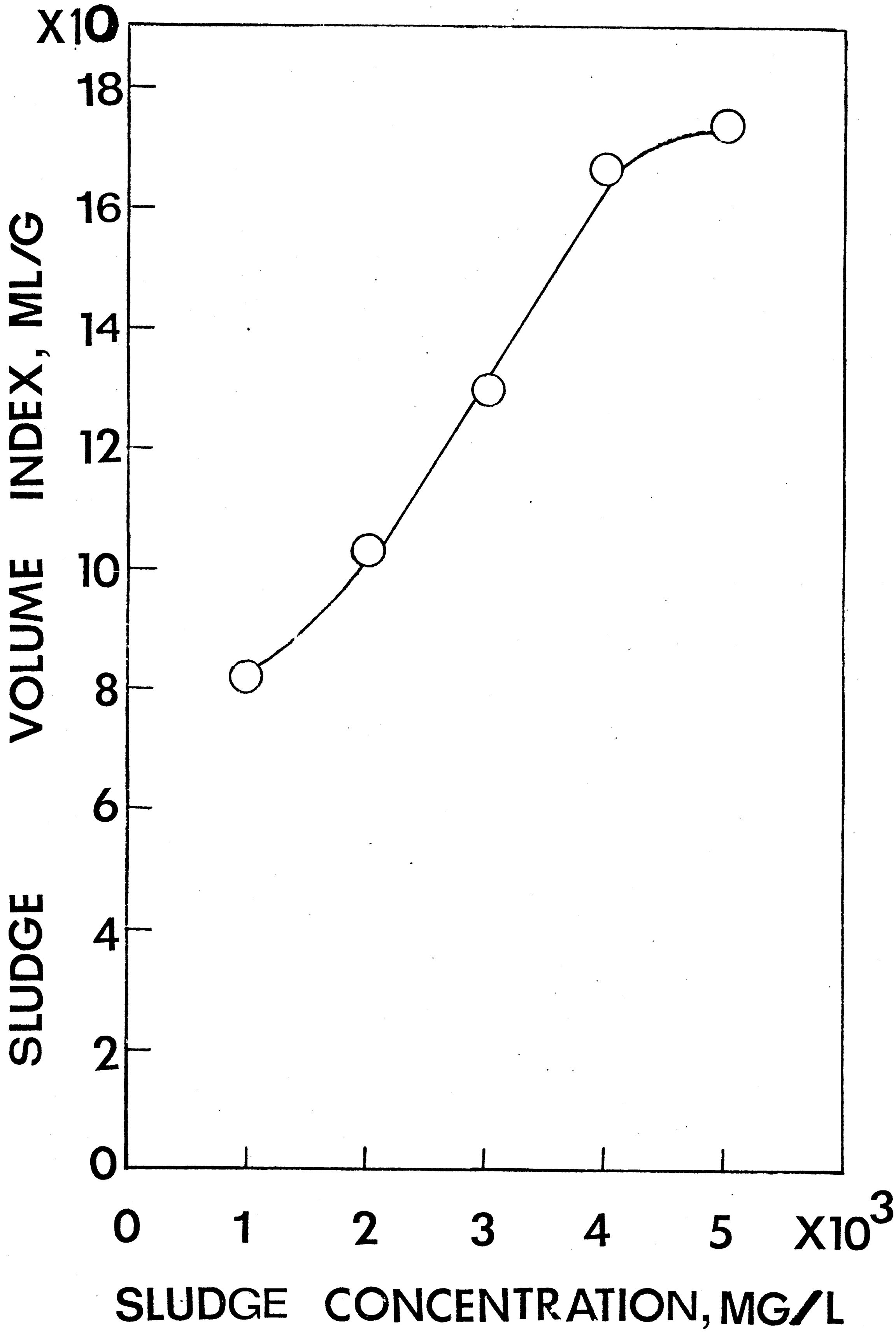

X10
18
16
14
12
10
8
6
4
2
0
SLUDGE VOLUME INDEX, ML/G
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 19. Sludge Volume Index vs. Initial Sludge Concentration at Sludge Age of 12 Days

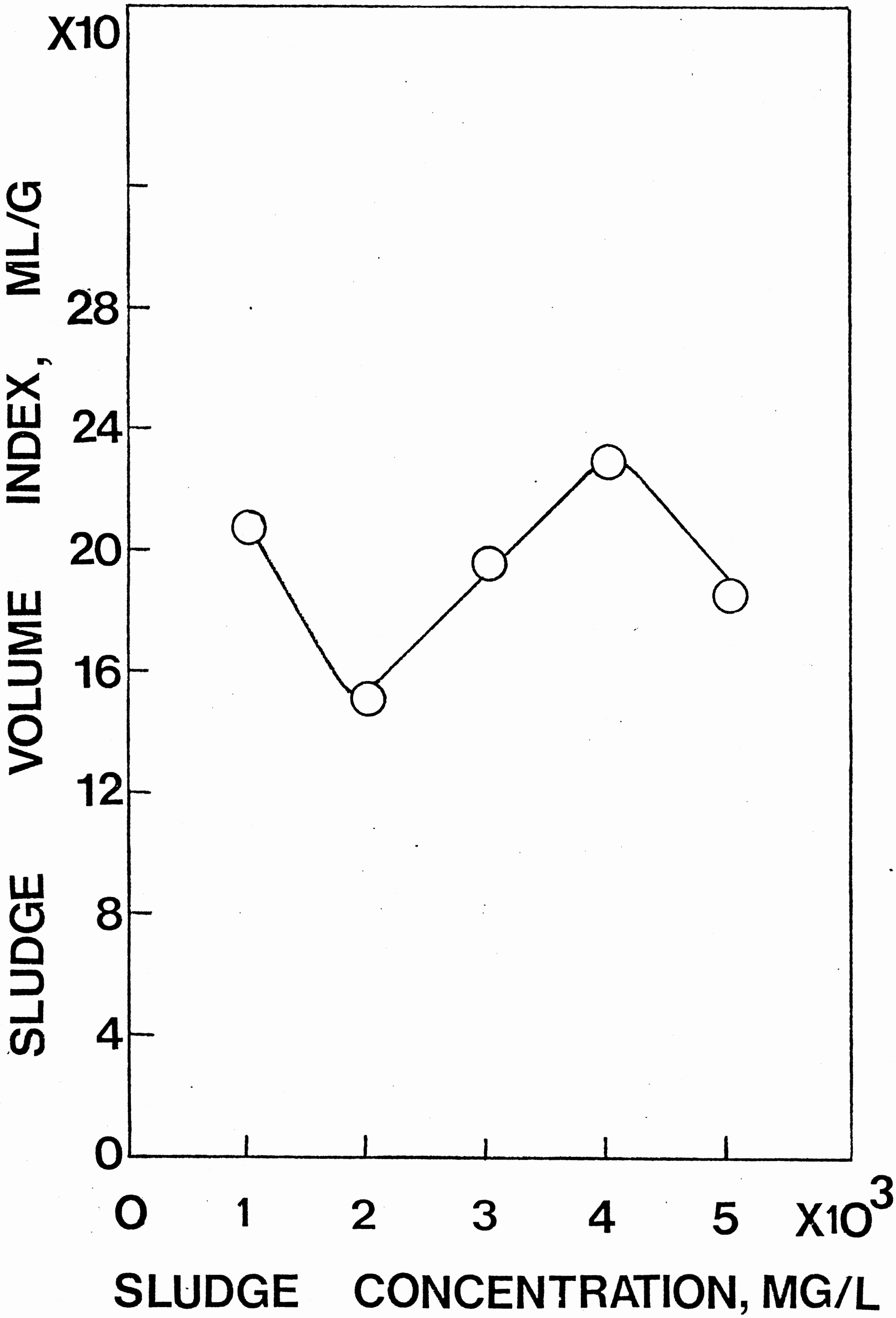
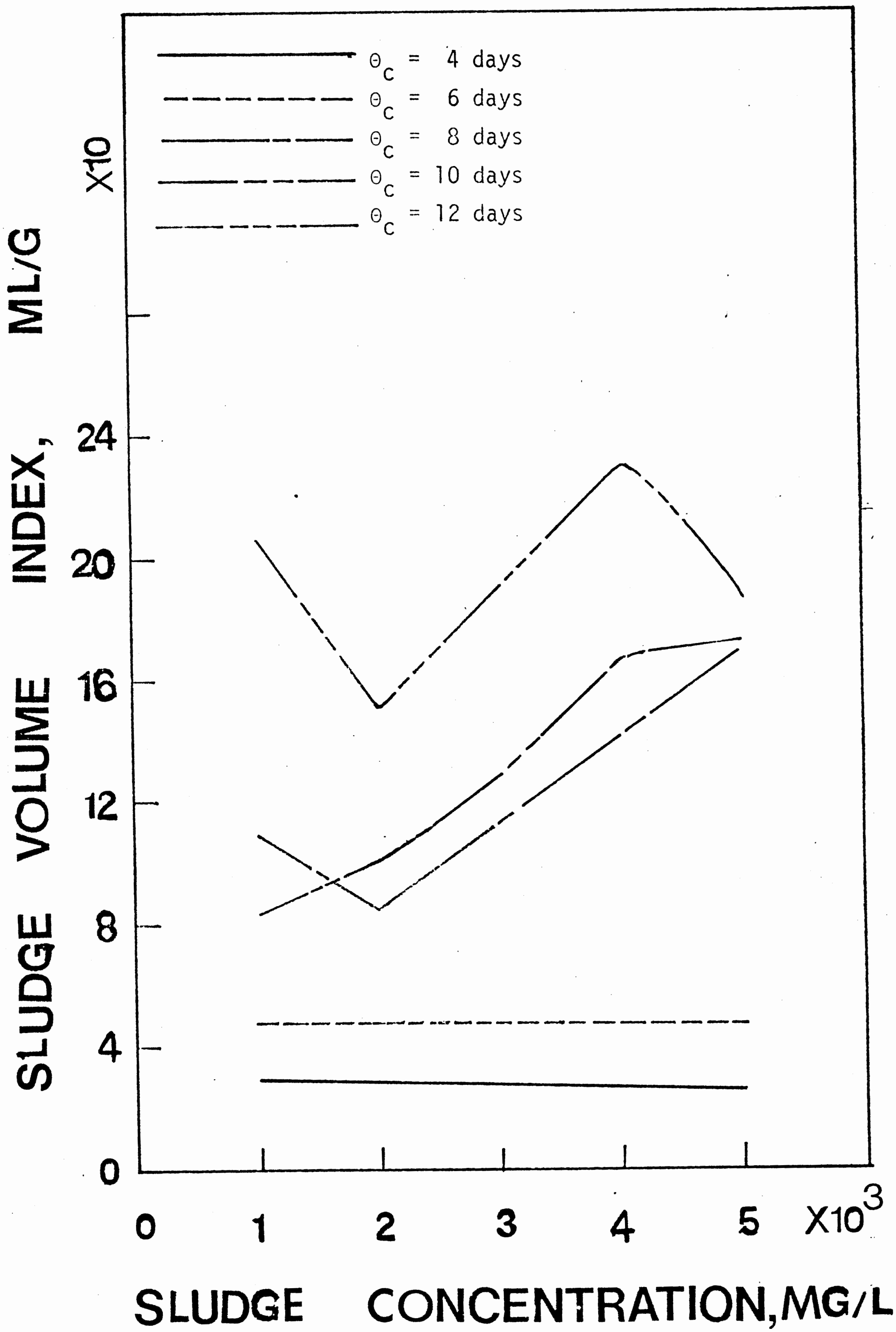
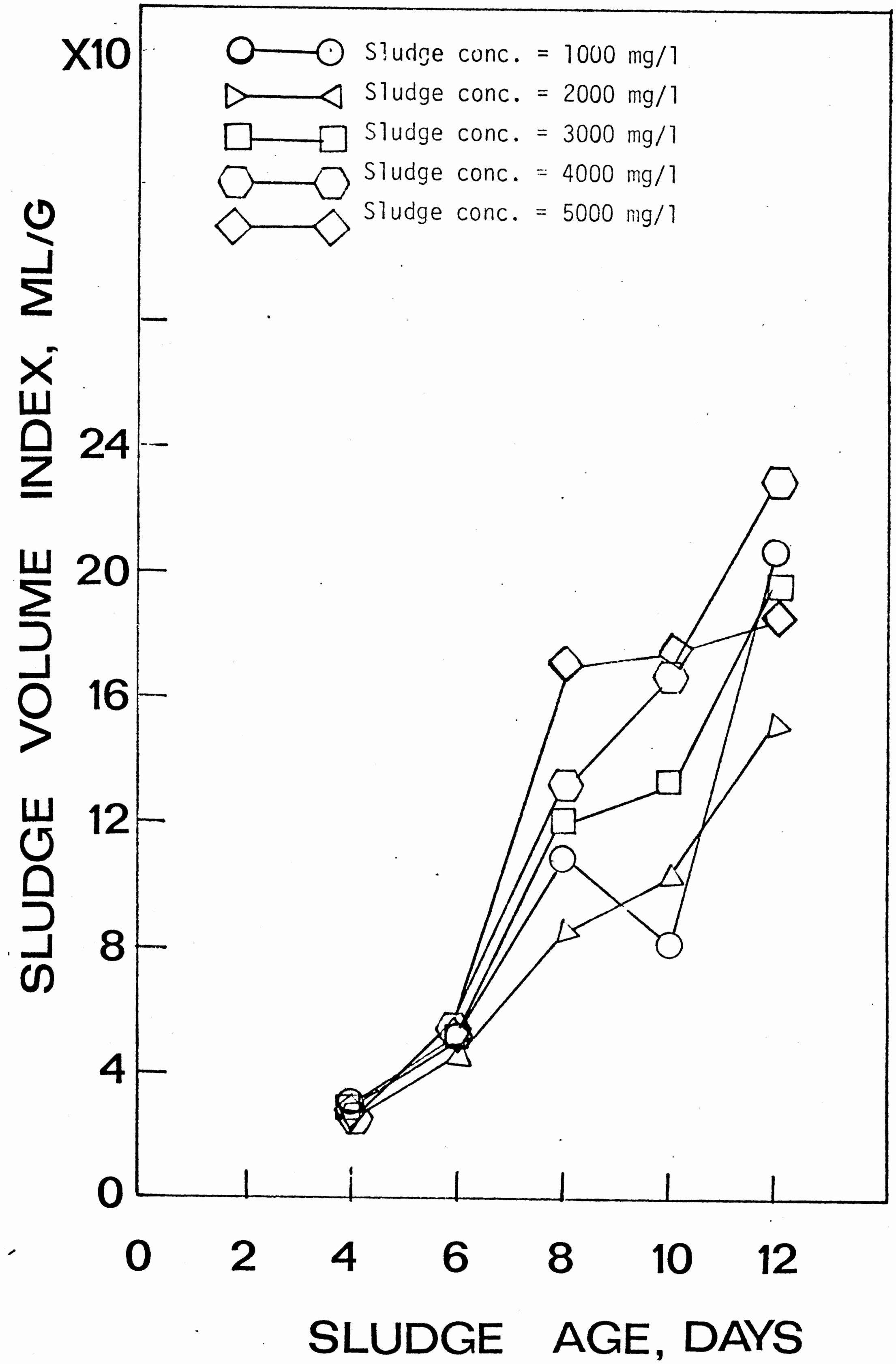

X10
SLUDGE VOLUME INDEX, ML/G
0
4
8
12
16
20
24
28
O
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 20. Sludge Volume Index vs. Initial Sludge Concentration at All Studied Sludge Ages



Θ_c = 4 days
Θ_c = 6 days
Θ_c = 8 days
Θ_c = 10 days
Θ_c = 12 days
SLUDGE VOLUME INDEX, ML/G X10
0
4
8
12
16
20
24
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION,MG/L

Figure 21. Sludge Volume Index vs. Sludge Age at Various Initial Concentrations


X10
Sludge conc. = 1000 mg/l
Sludge conc. = 2000 mg/l
Sludge conc. = 3000 mg/l
Sludge conc. = 4000 mg/l
Sludge conc. = 5000 mg/l
SLUDGE VOLUME INDEX, ML/G
0
4
8
12
16
20
24
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

shows a clearer relationship between the sludge volume index and sludge age. From the above figures it can be seen that the 12 day sludge age has the greatest sludge volume index. In other words, the sludge volume index is going to increase from 4-day to 12-day sludge ages. As seen in Chapter II, increasing sludge volume index will result in lower settleability of sludge. In other words, with higher sludge volume index, the zone settling velocity will decrease.

Figures 22 through 26 describe the relationship between solids flux and initial solids concentrations at various sludge ages. Figure 27 is a combination of all of these figures; Figure 27 compares the relationship between solids flux and solids concentrations for all sludge ages studied in this investigation. As can be seen in this figure, except for 4-day sludge age in which the solids flux decreases compared to 6-day sludge age, the solids flux due to gravity increased as the sludge age decreased from 12-day to 6-day sludge ages. In this case, 6-day sludge age has the greatest solids flux, and 12-day sludge age has the least solids flux.

The main purpose of this study was to develop a mathematical model for zone settling velocity of microorganisms at various sludge ages over different initial solids concentrations. Only a few mathematical relations have been developed to relate the zone settling velocity to the initial solids concentration. In most studies in the literature, the settling velocity of sludge is considered to be only a function of initial suspended solids. Therefore, except for probably one model, which was originated by Vesilind (12) and developed by other researchers like Bisogni and Lawrence (6) and Roper and Grady (11) considers sludge age indirectly. The other models relate the zone settling velocity

Figure 22. Solids Flux vs. Sludge Concentration at Sludge Age of 4 Days

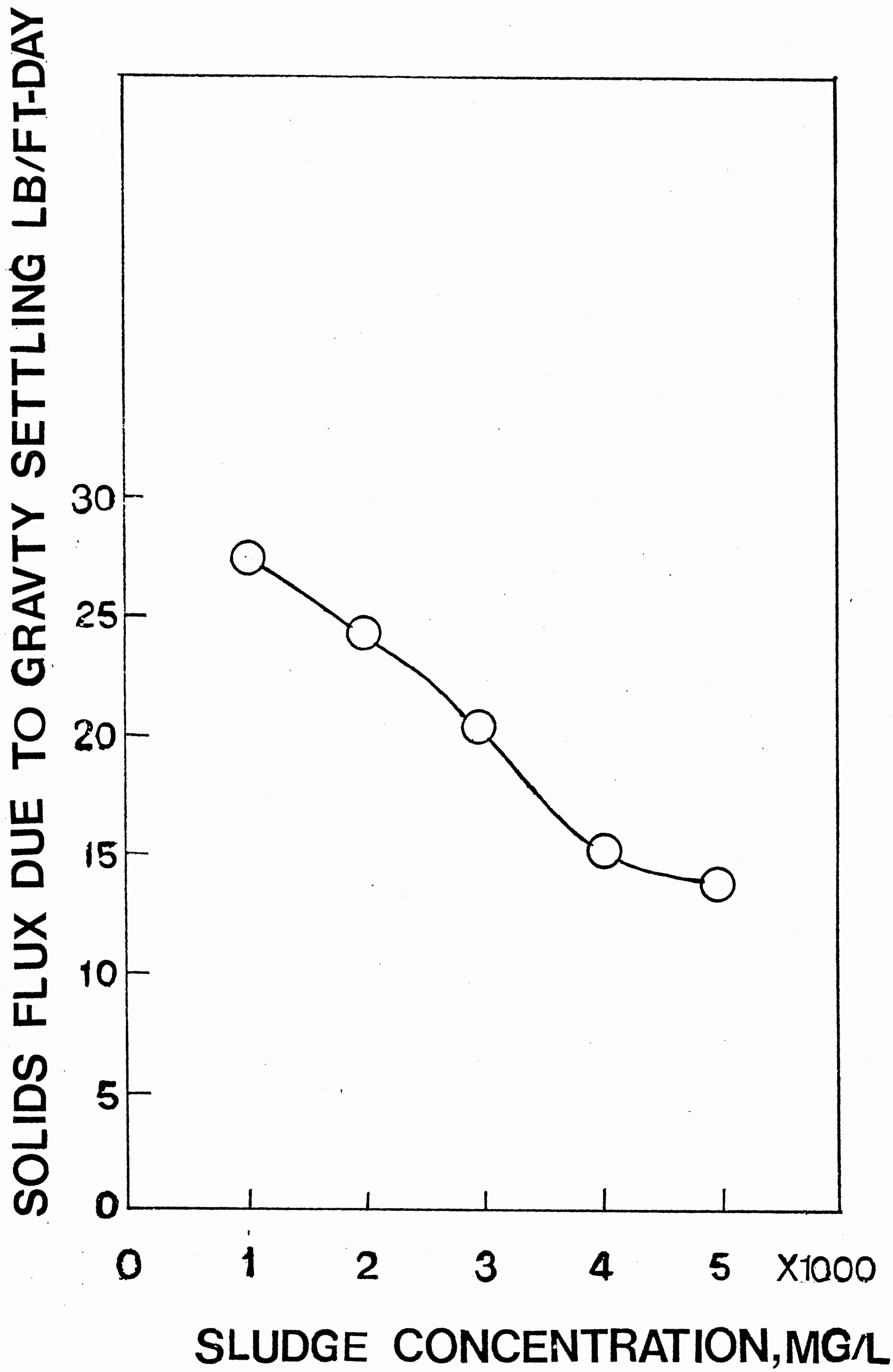

SOLIDS FLUX DUE TO GRAVTY SETTLING LB/FT-DAY
30
25
20
15
10
5
0
0
1
2
3
4
5
X1000
SLUDGE CONCENTRATION,MG/L

Figure 23. Solids Flux vs. Sludge Concentration at Sludge Age of 6 Days

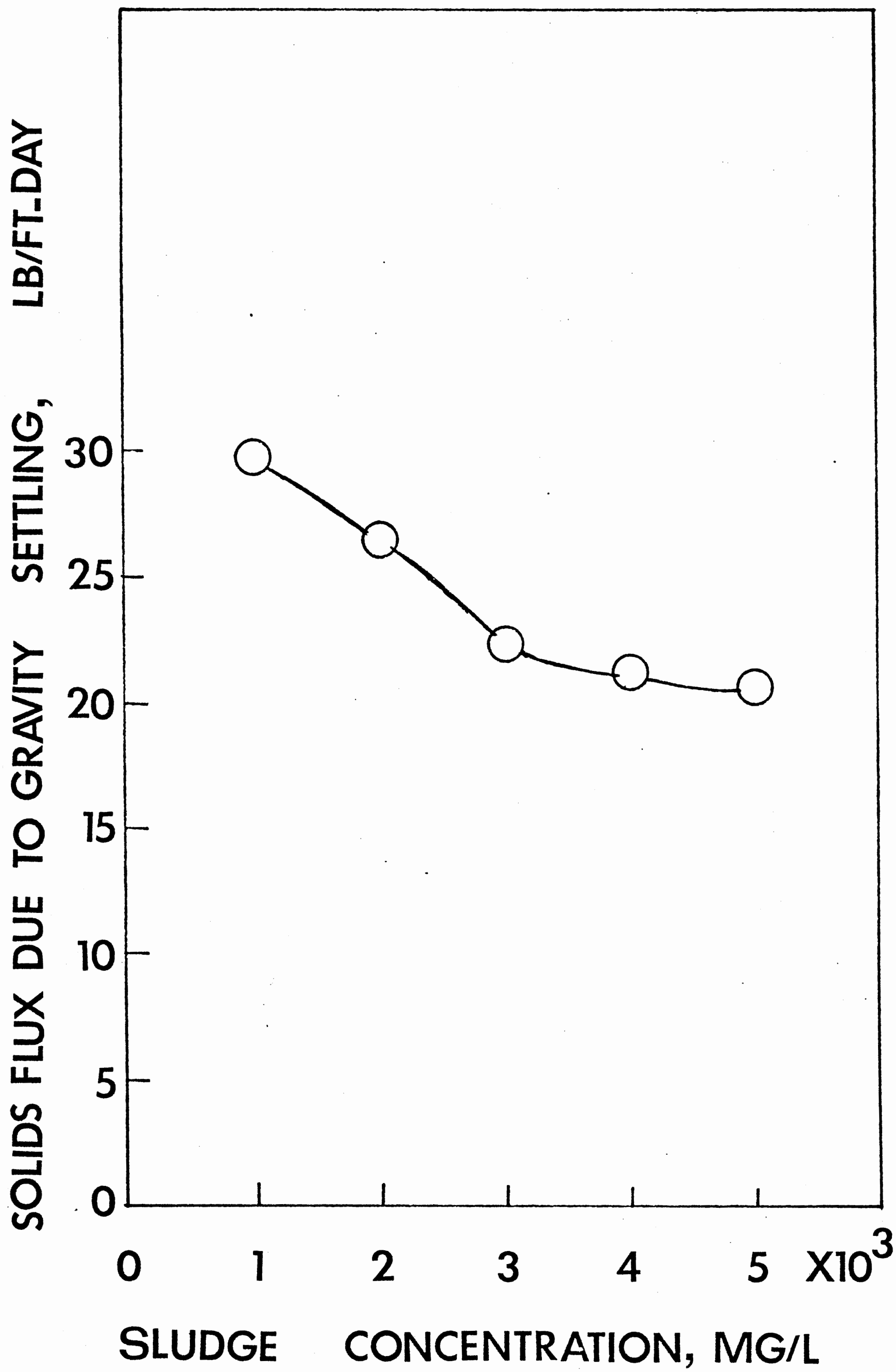

SOLIDS FLUX DUE TO GRAVITY SETTLING, LB/FT.-DAY
30
25
20
15
10
5
0
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 24. Solids Flux vs. Sludge Concentration at Sludge Age of 8 Days

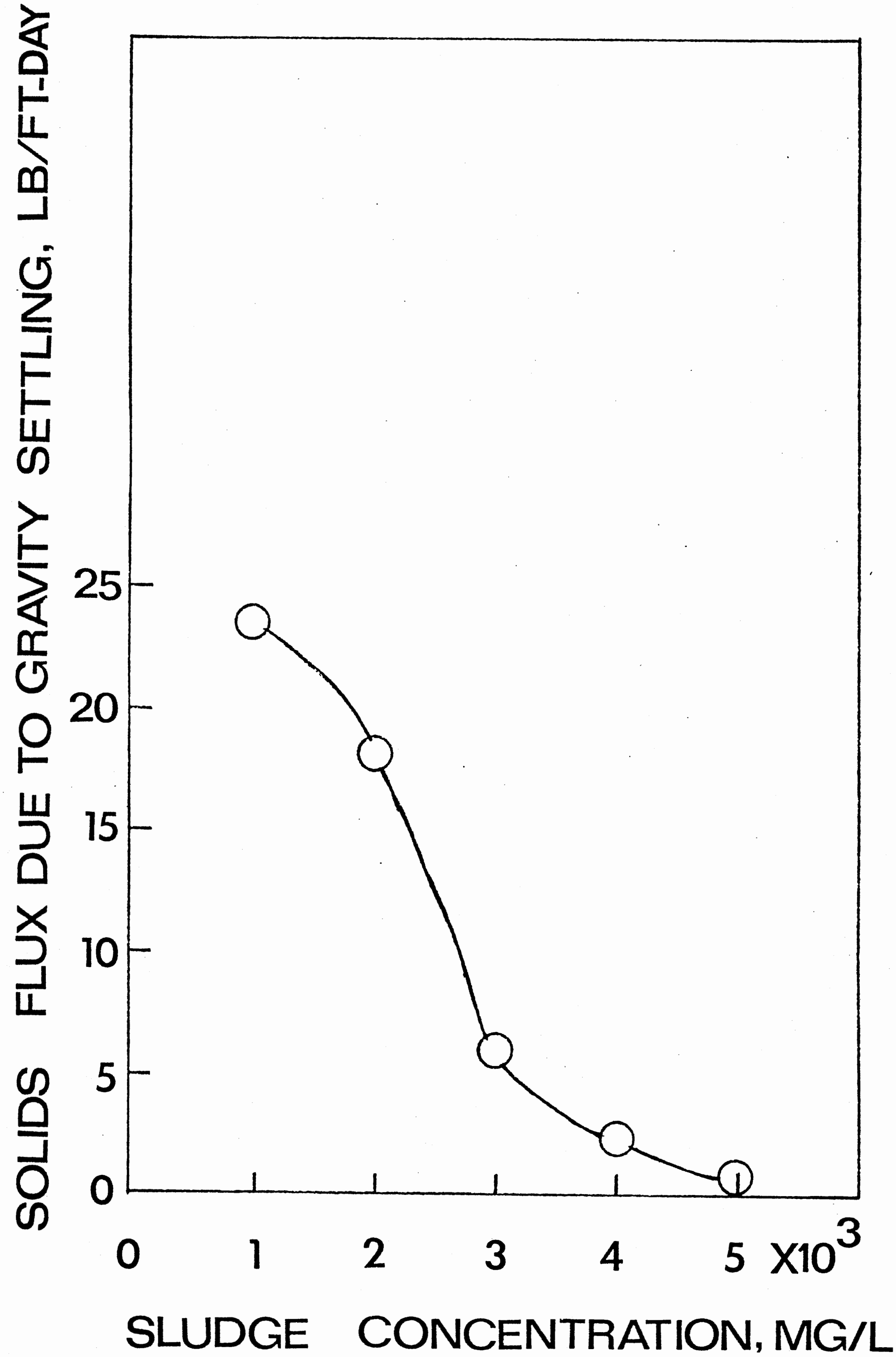

SOLIDS FLUX DUE TO GRAVITY SETTLING, LB/FT-DAY
25
20
15
10
5
0
0
1
2
3
4
5 X10^3
SLUDGE CONCENTRATION, MG/L

Figure 25. Solids Flux vs. Sludge Concentration at Sludge Age of 10 Days

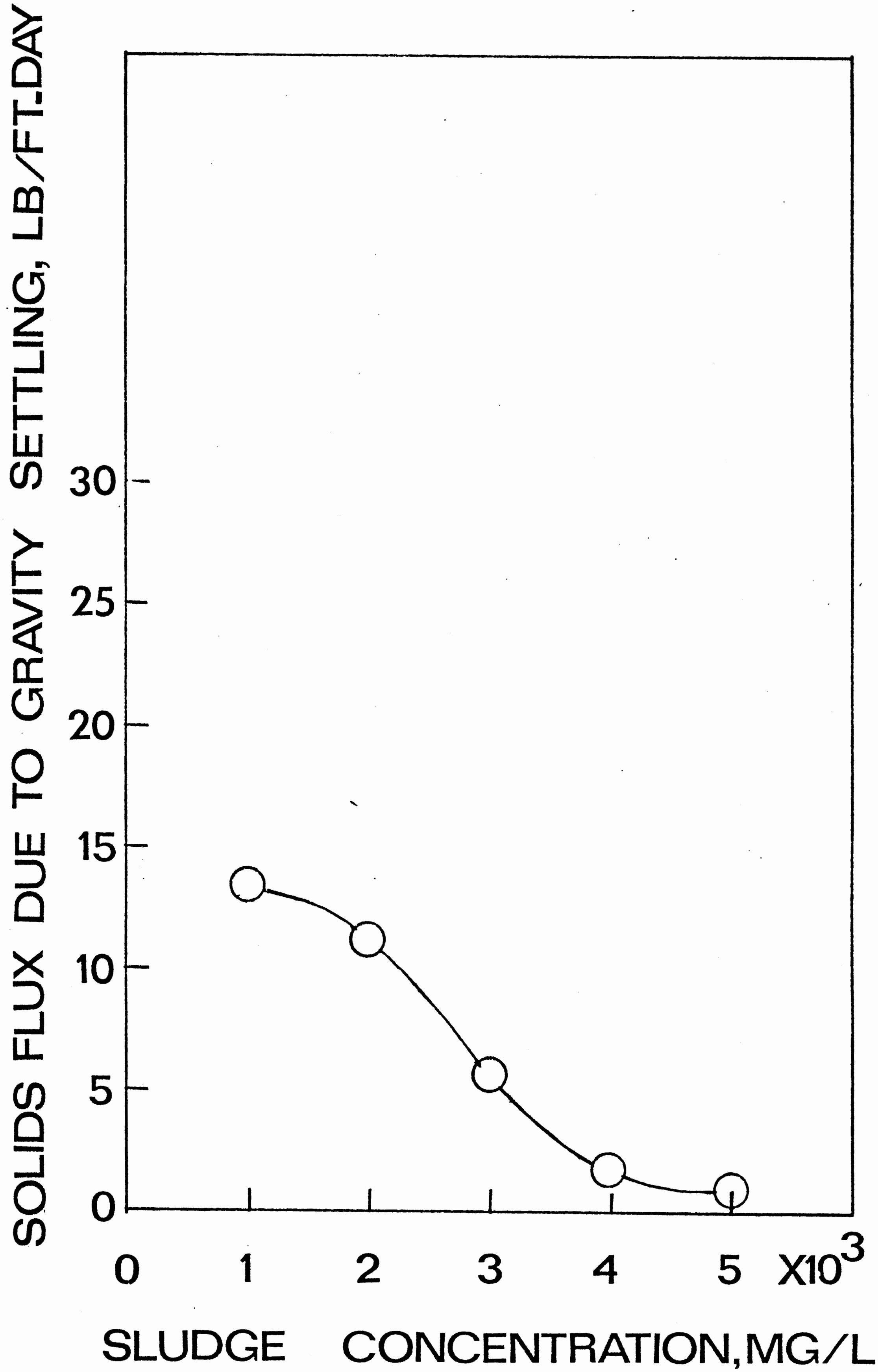
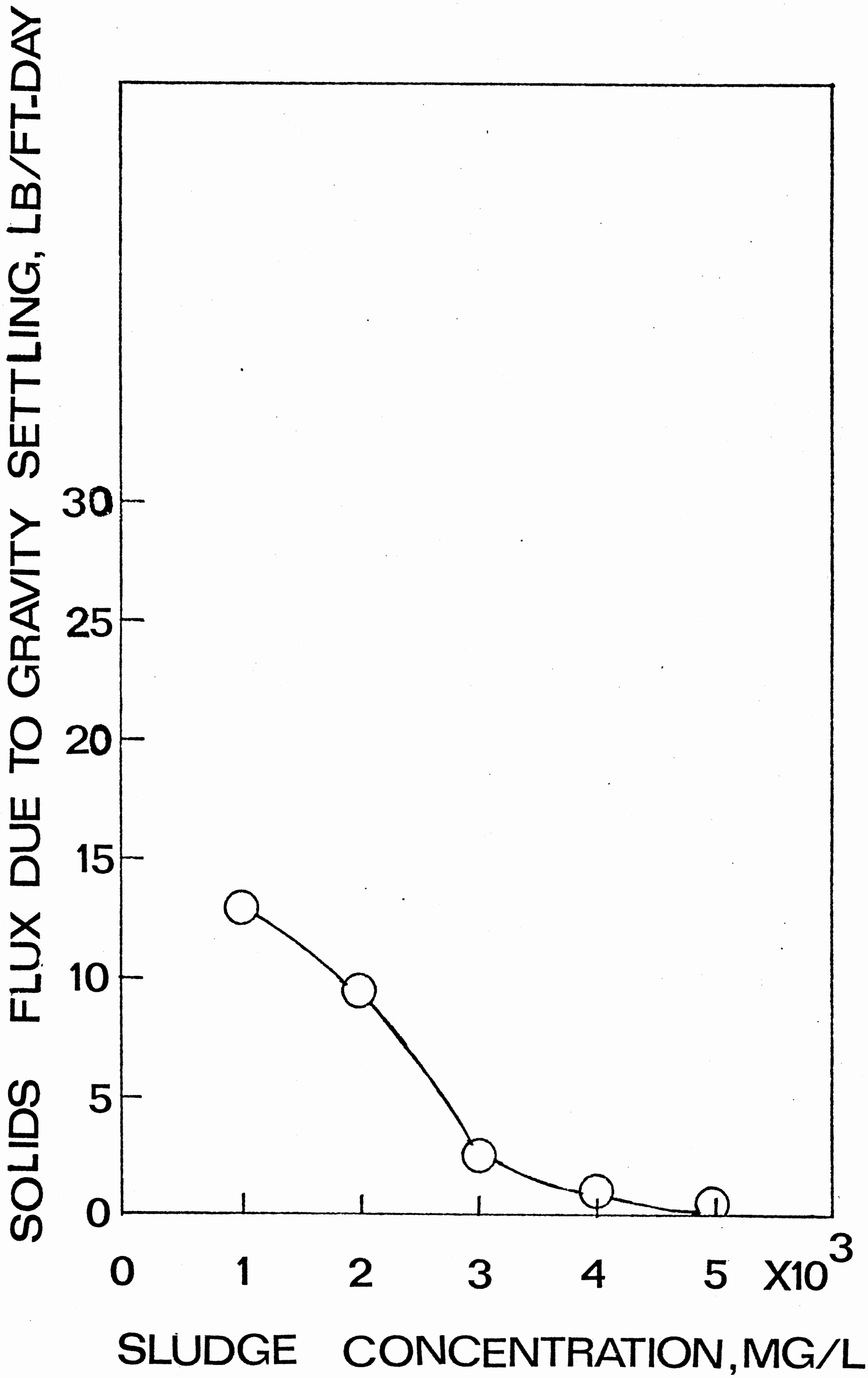
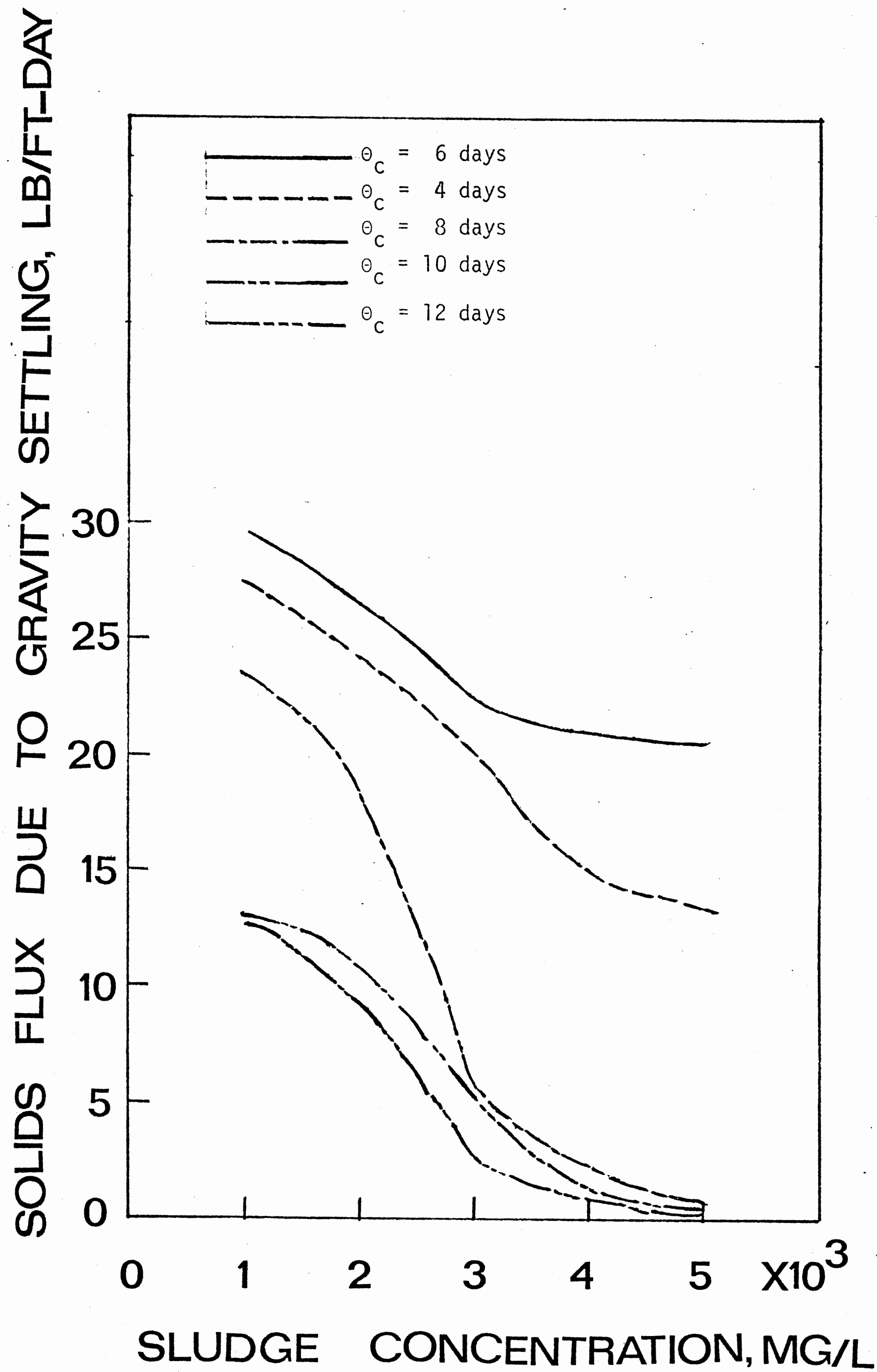

SOLIDS FLUX DUE TO GRAVITY SETTLING, LB/FT.DAY
30
25
20
15
10
5
0
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

Figure 26. Solids Flux vs. Sludge Concentration at Sludge Age of 12 Days



SOLIDS FLUX DUE TO GRAVITY SETTLING, LB/FT-DAY
30
25
20
15
10
5
0
0
1
2
3
4
5
X10 3
SLUDGE CONCENTRATION, MG/L

Figure 27. Solids Flux vs. Sludge Concentration at All Tested Sludge Ages



Θ_c = 6 days
Θ_c = 4 days
Θ_c = 8 days
Θ_c = 10 days
Θ_c = 12 days
SOLIDS FLUX DUE TO GRAVITY SETTLING, LB/FT-DAY
0
5
10
15
20
25
30
0
1
2
3
4
5
X10^3
SLUDGE CONCENTRATION, MG/L

only to initial solids concentrations.

To develop a model in which sludge age is considered, the data from Figure 13 were used. This figure shows the relation between zone settling velocity and initial solids concentration at different sludge ages. Since each curve in this figure is broken into two straight lines, it was a problem to develop one model. To eliminate this defect it was decided to develop one model for the first part of straight lines and another model for broken lines. The first model can handle the solids concentration up to 3000 mg/l, and the second model will be for 3000 to 5000 mg/l of initial suspended solids.

For the first part of the straight line from Figure 13 it can be concluded that

$$V = V_0 - nX \tag{4.1}$$

where

V = zone settling velocity, cm/min

V_0 = initial velocity, cm/min

n = slope of each straight line, cm·l/mg·min

X = initial solids concentration, mg/l

To relate the slope of each straight line and their intercept with the vertical axis (initial velocity) with sludge age, the amount of V_0 and n for different sludge ages was plotted versus sludge age. From these two new plots (Figures 28 and 29) it was concluded that

$$V_0 = - K\Theta_c + b \tag{4.2}$$

where

Figure 28. Initial Velocity (from Figure 13) vs. Sludge Age

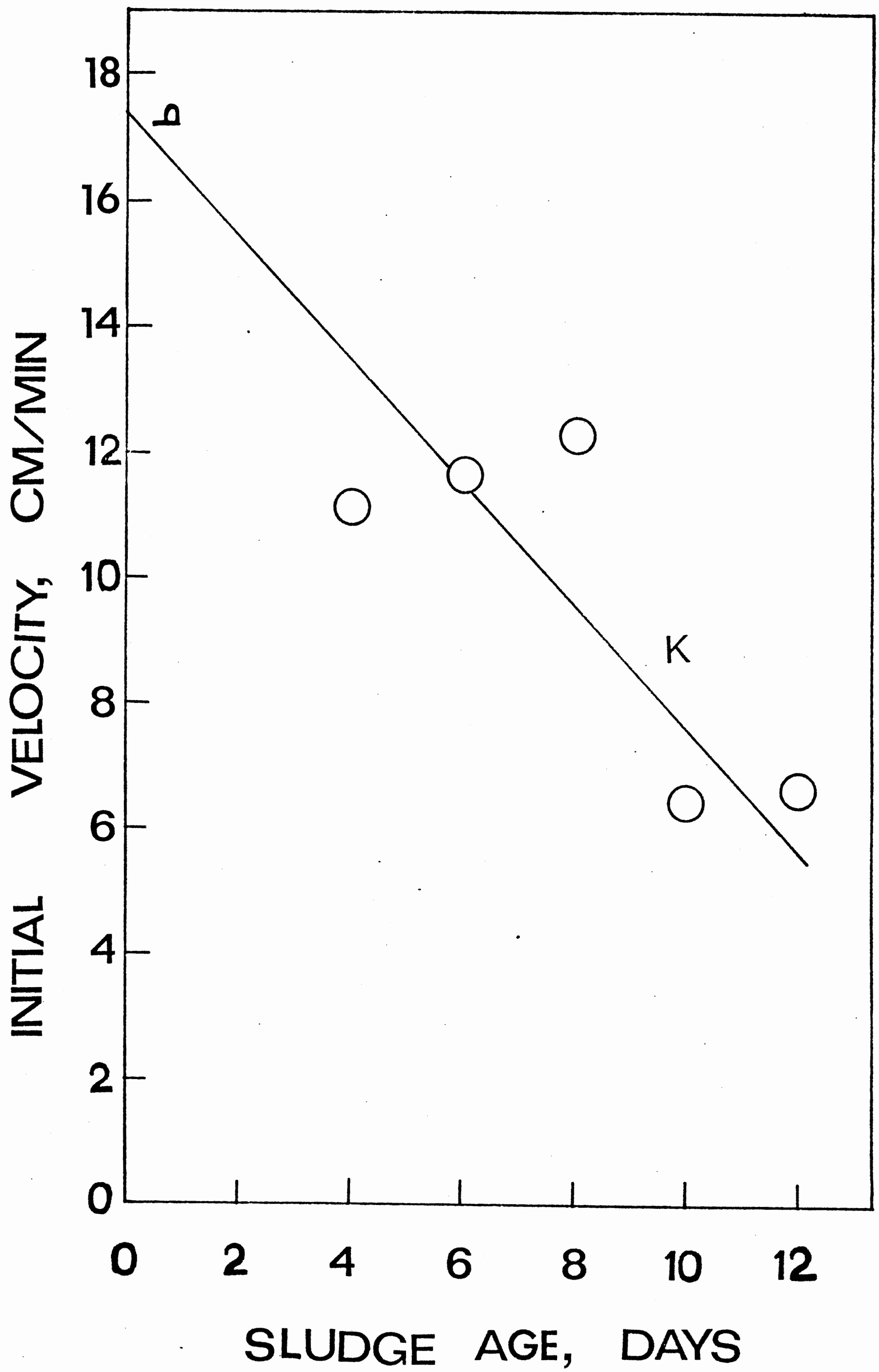
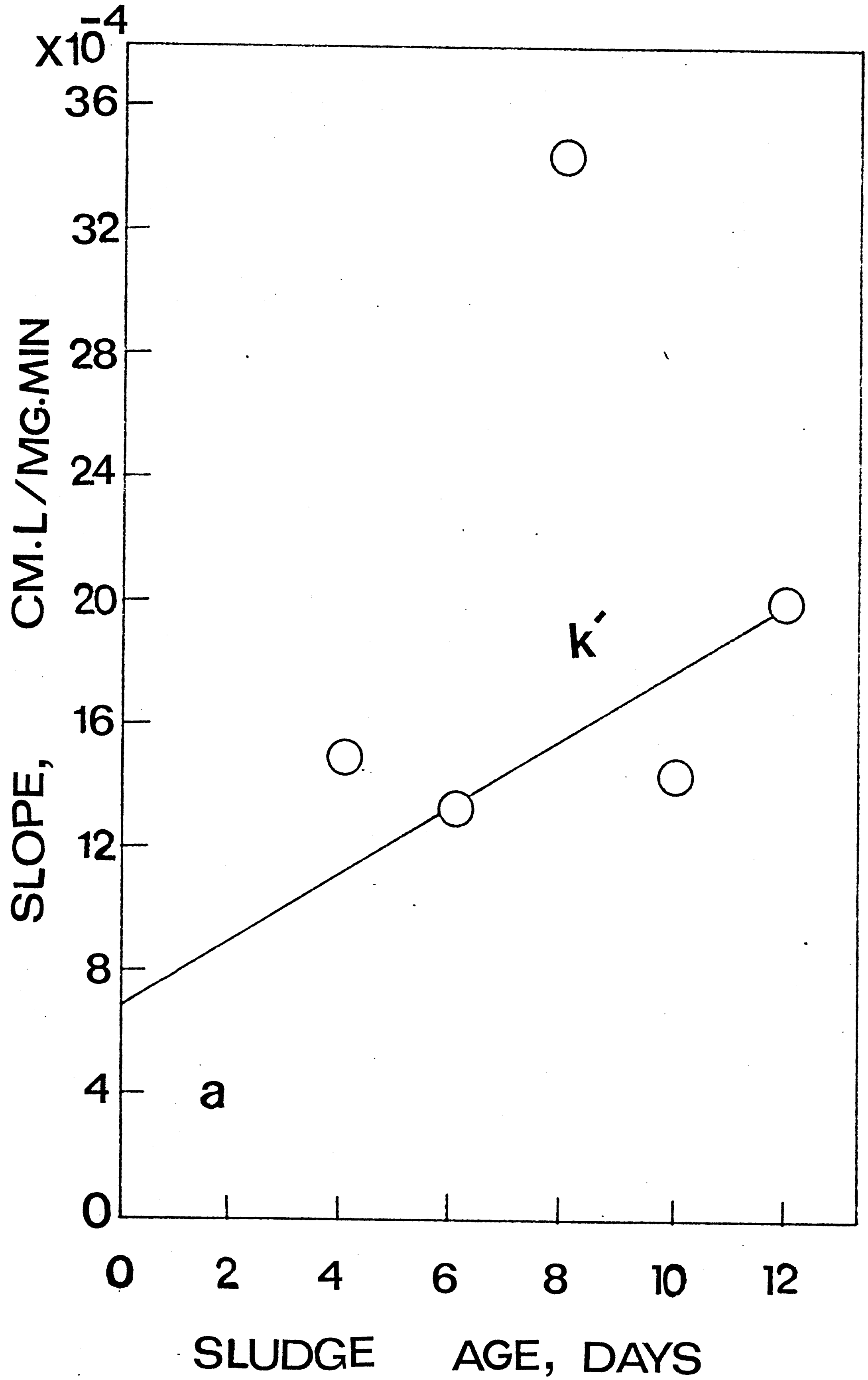

18
16
14
12
10
8
6
4
2
0
INITIAL VELOCITY, CM/MIN
b
K
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 29. Slope (from Figure 13) vs. Sludge Age


x10^-4
36
32
28
24
20
16
12
8
4
0
SLOPE, CM.L/MG.MIN
k'
a
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

K = slope of the straight line when V_0 is plotted versus Θ_c

b = the intercept of the above line with vertical axis

Θ_c = sludge age, day

and

$$n = K'\Theta_c + a \qquad (4.3)$$

where

K' = slope of the line drawn when n is plotted versus Θ_c

a = intercept of this line with vertical axis

If the expressions for V_0 and n are substituted in Equation (1), the following relation between zone settling velocity, initial solids concentration, and sludge age results.

$$V = (-K\Theta_c + b) - (K'\Theta_c + a)X \qquad (4.4)$$

when $6 \leq \Theta_c \leq 12$ days

The constants used in this equation are measured from each plot.

$K = 1 \dfrac{\text{cm}}{\text{min - day}}$

$K' = 1.08 \times 10^{-4} \dfrac{\text{cm}\cdot\text{l}}{\text{min}\cdot\text{day}\cdot\text{mg}}$

$b = 17.4 \dfrac{\text{cm}}{\text{min}}$

$a = 7 \times 10^{-4} \dfrac{\text{cm}\cdot\text{l}}{\text{mg}\cdot\text{l}\cdot\text{min}}$

$X \leq 3000$ mg/l

This equation works only when the concentration of initial solids does not exceed 3000 mg/l. When this limit is exceeded, another equation can be developed, in which the procedure is the same but constants are different. This equation will be for the broken part of Figure 13.

$$V' = (-K_1\Theta_c + b_1) - (K_1'\Theta_c + a_1)X' \qquad (4.5)$$

when $6 \le \Theta_c \le 12$

From Figures 30 and 31:

$K_1 = 0.82 \frac{cm}{min \cdot day}$, which is the slope of the straight line when V_0' is plotted versux Θ_c

$K_1' = 8.3 \times 10^{-6} \frac{cm \cdot l}{min.day.mg}$, which is the slope of the line drawn when n_1 is plotted versus Θ_c

$b_1 = 11.25$ cm/min, which is the intercept of this line with vertical axis

$a_1 = 2.6 \times 10^{-4} \frac{cm \cdot l}{mg \cdot min}$ which is the intercept of this line with vertical axis

$X_1 \ge 3000$ mg/l

Equation 5 can be used only when the concentration of initial solids is equal or exceeding 3000 mg/l. This model can be used when

$6 \le \Theta_c \le 12$ days

Figure 30. Initial Velocity (from Figure 13) vs. Sludge Age

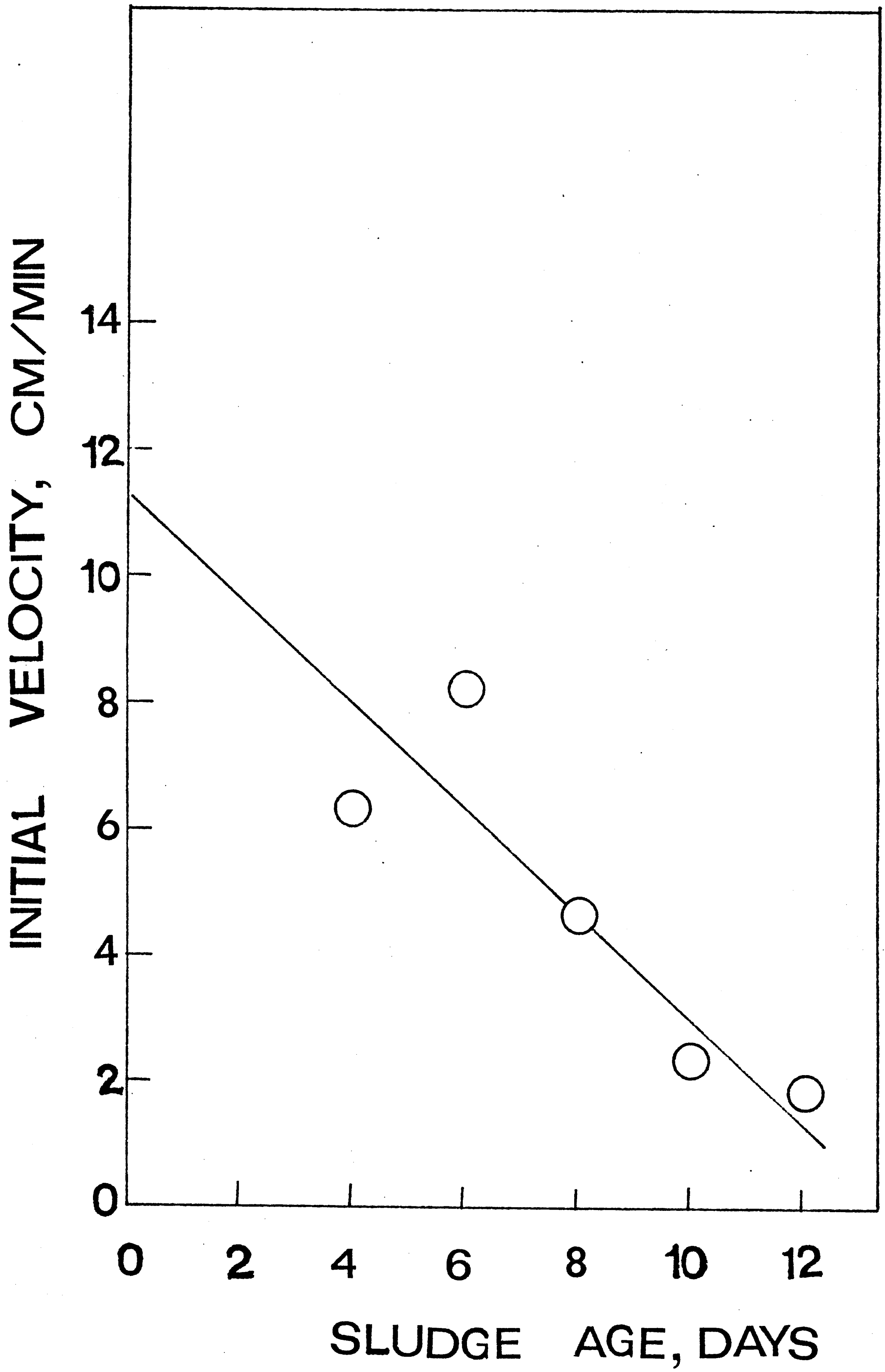
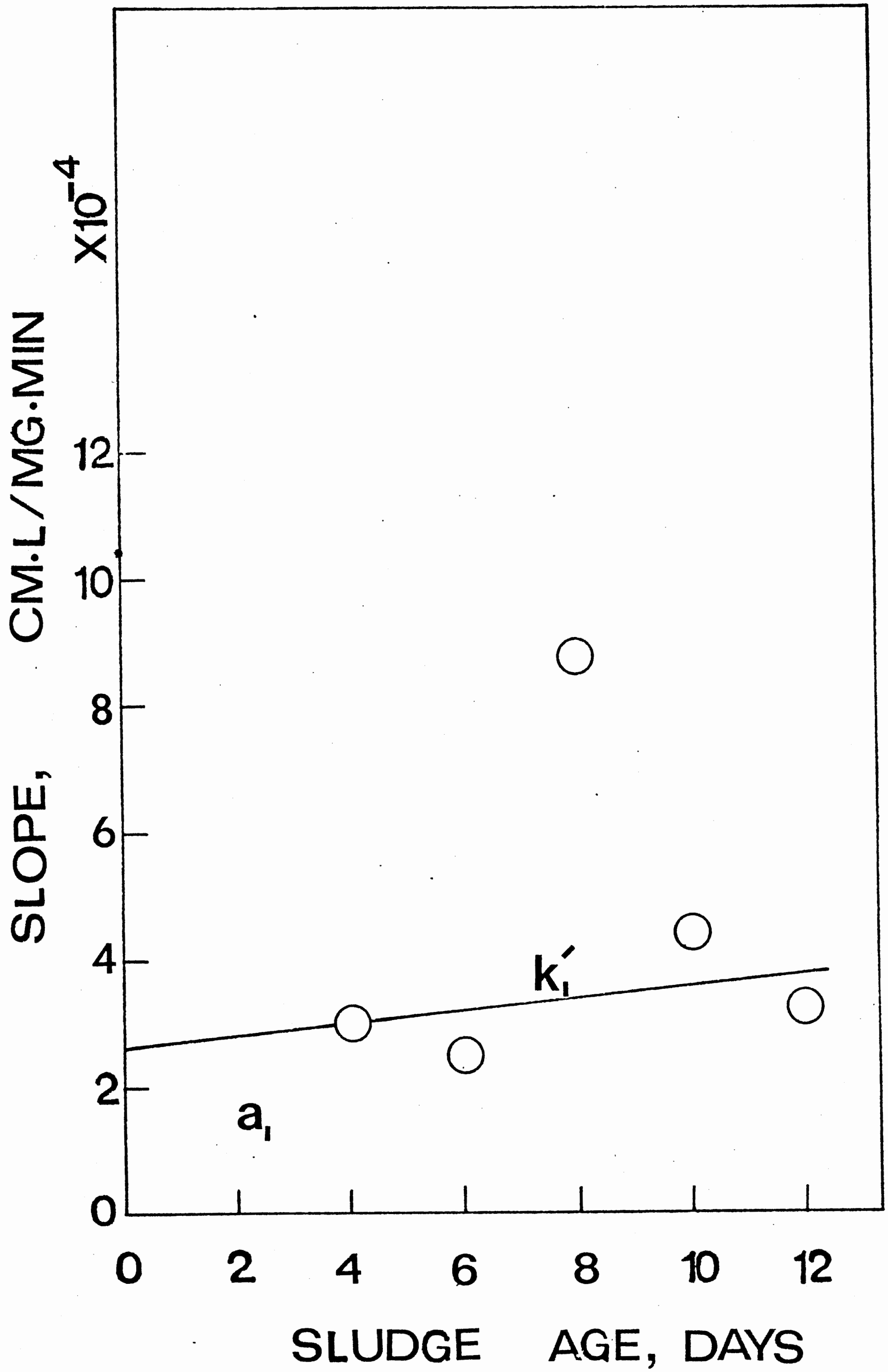

INITIAL VELOCITY, CM/MIN
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

Figure 31. Slope (from Figure 13) vs. Sludge Age


SLOPE, CM·L/MG·MIN X10⁻⁴
0
2
4
6
8
10
12
a₁
k₁′
0
2
4
6
8
10
12
SLUDGE AGE, DAYS

CHAPTER V

DISCUSSION

Operating Data

Sludge age has a direct effect on the clarification quality of an activated sludge treatment plant. If a usable sludge age is not employed in running a wastewater treatment plant, it will not only deteriorate the quality of effluent, but will also affect the efficiency of the plant operation. The reason is in various sludge ages the characteristics of the sludge and also sludge settling will change and with a given sludge age, a type of microorganism which has a low settleability may become predominant and a direct deterioration in the treatment plant effluent quality will occur; the plant will maintain a 30-30 standard for effluent. Loss of suspended solids in the effluent also has an effect on effluent BOD. As McCarty and Broderson (28) showed, losing of each milligram of suspended solids in plant effluent commonly increases the effluent BOD by about 0.5 mg. Also, as is seen in Figures 2, 3, 4, and 5, the sludge ages have a direct effect on the removal and its efficiency in BOD and TOC. It can be seen that the removal and removal efficiency in both BOD and TOC increased with increasing sludge age. As shown in Figure 6, the amount of suspended solids in the effluent is high at 4-day sludge age and has a maximum of 32.5 mg/l at 6-day sludge age. The reason for this can be because of suddenly changing the sludge age from 10 days to 6 days. This probably caused some kind of shock for the predominant type of microorganisms. The effluent in this period of time when the reactor was running under 6-day sludge age was quite turbid. This turbidity decreased somewhat in 4-day sludge age. The lowest amount of suspended solids occurred in 10-day sludge age with the amount of 7 mg/l.

Discussion on Settling Data

The main point of this investigation was to develop a mathematical model between zone settling velocity, initial solids concentration and sludge age. As pointed out in the literature review, there is a relationship between zone settling velocity and initial solids concentration. Several models were developed by some researchers. One of these models expressing this relationship was developed by Dick (26). This model is described as

$$V = aX^{-n} \tag{5.1}$$

where

V = zone settling velocity, ft/min

a = initial velocity (intercept), ft/min

n = slope of the line, when V is plotted versus X in a log paper, $\frac{\text{ft.l}}{\text{mg.min}}$

X = initial solids concentration,

In this equation, a and n are both variables which should be determined experimentally. The important element in Dick's equation (26) is that he did not consider sludge age as a function which affects the zone settling velocity.

The other model is an equation by Vesilind (20), which is described as

$$V = V_0 e^{-B_0 C_i} \tag{5.2}$$

where

V = initial settling rate, ft/min

C_i = sludge concentration, mg/l

B_0 = sludge constant = 4.5×10^{-4} l/mg

V_0 = settling velocity of individual sludge particles, ft/min

Bisogni and Lawrence (6) reported that V_0 is dependent on sludge age:

$$V_0 = 0.0836\ \Theta_c - 0.24 \text{ ft/min}$$

This model can be used only when

$$3 \leq \Theta_c \leq 12 \text{ days}$$

Equation (5.2) can be obtained when a series of settling velocity data on a semilog paper is plotted versus initial solids concentration.

Another equation which can be described as

$$V_u = V_0(1 - \phi)^{4.65} \tag{5.3}$$

was originated by Richardson and Zaki (29). As a modification of this equation, Krone (30) suggested the following form:

$$V = V_0(1 - KC)^{4.65} \tag{5.4}$$

where

V = group settling velocity

V_0 = settling velocity of individual aggregates

C = initial concentration of suspended solids

K = volume of aggregate/gram of solids

Φ = aggregate volume fraction, $\Phi = KC$

Plotting of $V^{1/5}$ versus C should give a straight line, and V_0 and Φ should be obtained from its intercept and slope. Φ is related to the floc and primary particle specific gravities (P_F and P_S, respectively) by the equation

$$\Phi(P_F - 1) = (P_S - 1)$$

This index 4.65 is valid only for rigid spheres. For cubical and disc-shaped particles, values of 5.85 and 4.15, respectively, can be used. This model is originally proposed for the settling of mud and chemical slurries and probably cannot be used for biological solids, or at least Θ_c cannot be a functioning parameter in this equation.

Taking the Vesilind model (20) and using the constants offered by Bisogni and Lawrence (6) and giving different numbers for sludge age and initial solids concentration, solving for zone settling velocity will show that as the sludge age increases, the zone settling velocity of sludge will increase also. However, utilizing the two equations offered in this study will yield different results. In this case it can be seen that as the sludge age increases, the settling velocity will decrease.

Comparing these three equations with the equation offered in this study will show that in all of these equations the relation between zone settling velocity and initial solids concentration is the same. As the initial solids concentrations increase, the zone settling velocity of sludge will decrease. In only one of these three equations is sludge age considered to be a factor affecting the settling characteristics of sludge.

The results obtained in this investigation are completely different from that of Bisogni and Lawrence (6). As they pointed out, when the sludge age increases, the zone settling velocity of the sludge will increase also. Bisogni and Lawrence have made their studies for only one solids concentration of 2000 mg/l.

As can be seen in Figure 14, the zone settling velocity from 4-day sludge age is going to increase to a maximum at 6-day sludge age; from this maximum it will decrease with increasing of sludge age.

In the Bisogni and Lawrence studies, they found that the sludge volume index would decrease with increasing sludge age. In their studies they reported that the sludge volume index first increased until 3.5 day of sludge age, and then decreased.

In the present study, in Figure 21 it was seen that the sludge volume index will increase with increasing sludge age.

Another aspect which should be considered is the solids flux curve due to gravity. As is shown in Figure 27, except for 4-day sludge age, the solids flux decreased with increasing sludge age.

The differences between the Bisogni and Lawrence results and the results obtained in the present study are probably due to several reasons. One of these reasons can be because of the changes in the bacterial or zoogloeal population's physical or biochemical character. This change in bacteria character can be due to the type of feed used. In this study, a base mixed solution which differs from that in the

Biosogni and Lawrence studies was used. Also, the conditions provided for the activated sludge unit under study or even the condition for running the settleability tests may have brought up these changes in the results. Also, it may be because of the extreme population shifts from a normal bacterial or zoogloeal type to a filamentous type. This shift was seen many times during the unit's run, especially in high sludge ages. This shift may be because of many parameters which are involved in the running of the unit. Such a parameter can be pH changes or oxygen deficiencies, etc.

Probably developing a mathematical model for a certain type of sludge and conditions which relate zone settling velocity, initial solids concentration, and sludge age may result in serious error when used for sludges other than those for which it was developed.

CHAPTER VI

CONCLUSIONS

The following conclusions resulting from this investigation are valid only in the range of solids concentrations and sludge ages studied in this investigation.

1. A mathematical model can be developed to relate zone settling velocity, initial solids concentration, and sludge age. This model can be in the following form for two different ranges of initial solids concentration up to 3000 mg/l and 3000 to 5000 mg/l.

$$V = (-K\Theta_c + b) - (K'\Theta_c + a)X$$

$$6 \leq \Theta_c \leq 12 \text{ days}$$

$$\text{when } X \leq 3000 \text{ mg/l}$$

and

$$V' = (-K_1\Theta_c + b_1) - (K_1'\Theta_c + a_1)X'$$

$$6 \leq \Theta_c \leq 12 \text{ days}$$

$$\text{when } X \geq 3000 \text{ mg/l}$$

Further explanation for each term is given in Chapter IV.

2. According to this investigation, it was recognized that except for 4-day sludge age, zone settling velocity will decrease both with

increasing of initial solids concentration and increasing of sludge age.

3. Sludge volume index, except for 4- and 6-day sludge ages which are almost constant over the range initial solids concentrations, will increase with an increase in both sludge age and solids concentration.

4. In this study, it was seen that except for 4-day sludge age, solids flux decreased with an increase in both solids concentration and sludge age.

5. Removal efficiency of soluble effluent BOD and effluent TOC increased as the sludge age increased.

6. Effluent suspended solids concentration varies over the range of sludge age.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

1. Study the effect of sludge age and initial solids concentration at the zone settling velocity in a system with a slow mixing device (using stirrer in the settling test).

2. Run a series of activated sludge units with different types of feed, and investigate whether Vesilind (20) and Bisogni-Lawrence (6) models can work for different types of feeds.

3. Study the effect of sludge age on the zone settling velocity for initial solids concentrations less than 1000 mg/l.

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