# EVALUATION OF BIOLOGICAL SLUDGE PROPERTIES INFLUENCING VOLUME REDUCTION

By

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# PROPERTIES INFLUENCING
# VOLUME REDUCTION

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## TABLE OF CONTENTS

# LIST OF TABLES

## LIST OF FIGURES

Figure Page

# CHAPTER I

# INTRODUCTION

A major cost in the operation of an activated sludge wastewater treatment plant is that incurred by the treatment and disposal of the biological solids produced by the process. In a recent book by Vesilind (1979), it is stated that 30 to 40 percent of the capital cost and approximately 50 percent of the operating cost of a treatment plant are typically associated with sludge handling. Further, it is predicted that between the years 1972 and 1990 the volume of sludge produced in the United States will double due to federally mandated improvements in existing treatment plants as well as the added construction of new facilities. Large cities, in particular, will be adversely affected by these mandates due to both the shortage and high costs of those sites available for land disposal. The development of improved volume reduction techniques as well as a better understanding of the mechanisms involved in sludge volume reduction are goals worth pursuing during this period.

One of the major objectives of sludge treatment is the removal of a substantial amount of water so that handling and disposal are facilitated. In its natural state, waste activated sludge typically contains only 0.5 to 1.5 percent solids and is usually concentrated to at least 15 percent solids before final disposal is made (Vesilind, 1979). As would be expected, the time and energy required to attain this final state is, in many ways, dependent on the nature of the sludge itself.

Much research has focused on those sludge properties believed to be most responsible for difficulties encountered in thickening and dewatering. However, knowledge is still insufficient to allow accurate predictions to be made of the resultant thickening or dewatering performance of any given sludge. Part of the reason for these shortcomings is due to the manner in which most of the research is conducted. Frequently, the studies are performed with sludges maintained in a controlled laboratory environment where chemical and biological properties can be easily altered by simple changes in the growth conditions. In this way, the researcher is able to carefully examine the effects that changes in one isolated property may have on a target parameter (i.e., thickening or dewatering). Since activated sludge may be produced under a practically limitless variety of environmental conditions, it is to be expected that this form of research has resulted in a plethora of implicated sludge properties.

Admittedly, research of a fundamental nature is necessary to establish a base of information. However, by examining only a few isolated parameters at a time, it has not been possible to establish the relative importance of each property. Though several properties may be well correlated to volume reduction difficulties in laboratory studies, it is believed that, under field conditions, only a few may be found to have a significant impact on thickening and/or dewatering.

It is the purpose of this study to bring together several of the more prevalent thickening and dewatering hypotheses and concurrently test them on both laboratory and field sludges. By doing this, it is believed that a clearer picture may be attained regarding which properties are most responsible for volume reduction problems and which ones are merely secondary in importance.

# CHAPTER II

## LITERATURE REVIEW

In 1978, a meeting was held between Water Pollution Control Federation representatives and officials of the U.S. Environmental Protection Agency in which priority areas of wastewater research were discussed ("New WPCF Reports . . .", 1982). As a result of the meeting, the management of municipal sludge was identified as one of two areas which warranted increased research emphasis. A subcommittee was formed to examine the needs in sludge management research and a detailed report (An Analysis of Research Needs . . . , 1982) was produced which spells out the specific areas needing greater efforts. Among the findings were a need for fundamental studies concerning sludge properties and for the development of improved methods for predicting thickening and dewatering performance based on those properties.

### Thickening and Dewatering Techniques

Thickening has been defined as the concentration of sludge to less than 15 percent solids with dewatering being described as the concentration of solids to greater than 15 percent (Vesilind, 1979). These are general definitions but may be used to differentiate the unit processes involved in volume reduction.

Gravitational settling, flotation, and centrifugation are the methods generally used for thickening of wastewater sludges (Metcalf and Eddy, Inc., 1979). Of these, gravitational settling is the method most frequently associated with the generic term "thickening." Vesilind (1979) states that the most widely used batch generic term "thickening." Vesilind (1979) states that the most widely used batch thickening test is probably the sludge volume index (SVI), which itself is a form of gravitational settling.

For dewatering of wastewater sludges, a larger variety of processes are available. They include vacuum filters, centrifuges, filter presses, horizontal belt filters, drying beds, and lagoons (Metcalf and Eddy, Inc., 1979). Vacuum filtration has been in use for over 50 years and is generally the method against which all other mechanical methods are compared (Vesilind, 1979).

## Properties Affecting Thickening

A sludge which is difficult to thicken, or settle, by gravity is commonly referred to as a bulking sludge and has been defined by Pipes (1978) in terms of SVI. He states that a sludge can be considered normal when its SVI is less than 100 ml/gm, moderately bulking when the SVI is between 100 and 200 ml/gm, and severely bulking when its SVI is greater than 200 ml/gm. Further, Pipes notes that the definition of bulking is not dependent on the zone settling velocity (ZSV) nor the concentration of effluent suspended solids. In light of this, the great majority of literature on thickening uses SVI as the parameter to indicate difficulties.

Wesley and Pipes (1978) have extensively researched the causes of sludge bulking and come to the conclusion that, in most cases, bulking is due to the abundant growth of filamentous microorganisms. Under such circumstances, the bulking effect is a mechanical one in that the filaments extend from the particle surfaces and hold them apart, interfering with the compaction required for a well-settled sludge. Finstein and Heukelekian (1967) were among the first researchers to quantify the effect which filamentous microorganisms have on the settleability of activated sludge. By actually measuring filaments with the aid of a micro-projector, they were able to establish, for the first time, a fairly direct correlation between total filament length and SVI.

Since the time of Finstein and Heukelekian's pioneering work, further research has been conducted to better define the effects which filaments have on SVI and associated parameters. In 1978, Sezgin et al. authored a unified theory of filamentous bulking which stated, in part, that increases in SVI, reflocculation time, and the 60 minute compact volume were all directly related to any increases in filament length above 10 µ/ml of activated sludge. These same parameters appeared to be independent of filament lengths less than 10 µ/ml. In no case was zoogleal bulking found nor were floc particles ever totally void of filaments.

Another sludge characteristic which has been associated with settleability is the size of the floc particle itself. Sezgin (1982) found that, when filament length concentrations were less than 10 µ/mg suspended solids, increases in mean floc size were principally responsible for increases in the SVI and that, when filament lengths were greater than the specified concentration, the effect of floc size on SVI was insignificant.

Next to filament length, the sludge surface charge is probably the most often cited factor affecting settleability. A linear relationship between SVI and the surface charge of sludge particles was established by Forster (1968) using non-filamentous activated sludge from a pilot-scale plant and later confirmed for sludges from three other treatment operations (Steiner et al., 1976).

In one of the earliest articles on activated sludge bulking (Heukelekian and Weisberg, 1956), a high bound water content was identified as being characteristic of zoogleal (non-filamentous) sludges with high SVI's. It was believed that this water, which is chemically bound to the individual particles, caused the sludge to become highly hydrated and, thus, experience poor settleability. In the same study, it was found that the correlation between bound water and SVI did not hold true for filamentous forms of bulking.

Besides the more predominant causes and correlations cited above, there have been numerous other factors put forth as being possible reasons for sludge bulking. The chemical make-up of the sludge is often proposed as having an influence on that sludge's ability to flocculate and/or settle. Forster found that the SVI of non-filamentous sludges was inversely proportional to the ammonia-nitrogen to soluble phosphate ratio in the mixed liquor (1968) and directly related to the total carbohydrate content of the sludge (1971). Magara et al. (1976) creported that increases in the concentration of exocellular polymer and poly-beta-hydroxybutyric acid in activated sludge correspond directly to increases in the SVI. Claims that the magnesium content of a sludge is inversely proportional to the SVI as well as that the percent bound water is directly related to the surface charge have also been made by Forster and Dallas-Newton (1980).

A few of the non-chemically related factors proposed as having an effect on SVI include the density and strength of floc particles (Magara et al. 1976), the biological solids retention time (SRT) (Bisogni and Lawrence, 1971), and the sludge concentration in the mixed liquor (Somers, 1968).

## Properties Affecting Dewatering

Sludge characteristics which have been reported to influence dewatering are probably even more numerous than those associated with thickening. A recent design manual published by the U.S. Environmental Protection Agency (1982) lists seven sludge characteristics which the agency believes have the greatest effect on dewatering. A more extensive list has been put together by Karr and Keinath (1978), though not all factors are entirely exclusive of each other.

One factor, particle size, was singled out from both lists as having the greatest influence on dewaterability. It was found by Karr and Keinath that the supracolloidal solids (1 to 100 µm in diameter) had more impact than any other size category. It was suggested that particles of that size blinded the filter medium by becoming lodged in the filter pores, thus resulting in a high resistance to filtration.

In 1970, Tenney et al. examined the effect several factors had on the filterability of biological sludges. They found that, as the degree of solids dispersion decreased, the filterability increased. In other words, it was determined that a well-flocculated sludge dewaters better than one with dispersed growth. It was also found that pH, solids concentration, and sludge holding time affected filtration rates.

In examining the influence of polyelectrolyte dosage on dewatering, Roberts and Olsson (1974) found that optimal dewatering was achieved when the dosage was such that a zero surface charge was obtained on the anionic colloidal particles in the sludge. It was also shown that dewaterability was independent of the concentration of macroscopic particles (larger than 10 μm) and directly related to colloidal particle (smaller than 10 μm) content.

A study of the drainability of waste activated sludge on sand drying beds (Randall et al., 1971) produced several conclusions as to influential factors. It was found that increases in retained water were directly proportional to the total carbohydrate content yet inversely proportional to cellular protein. No correlation could be found between sludge drainability and factors such as volatile solids, sludge volume index, and pH. Of all factors considered, solids concentration was determined to be dominant.

Wu et al. (1982) examined the effect that growth conditions have on the filterability of activated sludge. It was concluded that the excessive growth of filaments, occurrence of dispersed growth, and overproduction of extracellular polymers result in poor filtration. In contrast, large, strong flocs and sludges with short filaments were found to dewater quite well. Correlations were also established between filterability and sludge age, carbohydrate and protein content of the sludge, food to microorganism ratio, cell surface charge, and the concentration of nitrogen in the feed.

## Properties Affecting Both Thickening and Dewatering

Stating that the degree of dispersion is a factor which affects both drainability and settleability, Randall et al. (1971) held that a correlation between the two should be possible, though produced no results substantiating the claim.

Most articles previously cited in this review dealt with either thickening or dewatering problems, but not both. However, many of the factors mentioned in the individual articles were common to both operations. These common factors included sludge retention time, carbohydrate concentration, presence of lengthy filaments, sludge surface charge, strength of the floc particles, and solids concentration.

One such factor, the concentration of extracellular polymer, was independently studied by two research teams to determine its role in the thickening and dewatering of activated sludge. Ironically, these two groups came up with opposing conclusions. Novak et al. (1977) found that an increase in the polymer level resulted in a decrease in both the filtration rate and the thickening velocity of the sludge. One the other hand, Gulas et al. (1979) reported enhanced thickening and dewatering rates when polymer concentrations increased. Different testing methods (gravity settling by Novak et al. and dissolved air flotation by Gulas et al.) may have been responsible for the opposing thickening results.

# CHAPTER III

# MATERIALS AND METHODS

## Sample Collection

To achieve the stated purpose of this study, twenty-eight biological sludge samples were collected and analyzed. Of these, twenty-three were from full-scale municipal facilities and five were from bench-scale units.

The full-scale wastewater treatment plants involved in the study were all located within a seventy-five mile radius of Stillwater, Oklahoma. These included the Ponca City, Pawnee, Enid, and Perry municipal facilities as well as three located in the Oklahoma City area (North Canadian, Chisolm Creek, and Deer Creek) and four in the Tulsa area (Southside, Northside, Flatrock, and Haikey Creek). Multiple visits were paid to some facilities.

The bench-scale units from which samples were collected were operated by graduate students in the Bioenvironmental Engineering laboratories at Oklahoma State University. These units were fed a synthetic waste consisting of Sego, mineral salts, and tap water. In addition, the feed solutions for four of the five units included various heavy metals.

## Sample Analysis

In order to reduce the possibility of alterations in the composition and nature of any given sludge sample, storage time was held to a minimum. With the exception of protein and carbohydrate, all analyses were completed within four hours of sample delivery to the laboratory. For determination of the carbohydrate and protein contents, samples were stored at $4^{o}C$ until a sufficient number had been collected to warrant their analysis.

In addition to carbohydrate and protein determinations, analyses of the sludge samples included sludge volume index, zone settling velocity, suspended solids, volatile suspended solids, bound water content, electrophoretic mobility, specific resistance to filtration, filament length and quantity, and floc particle size and quantity. To optimize the total time required for completion of all analyses, the following itinerary was established and employed throughout the course of this study.

## Analytical Itinerary

Upon delivery of the sample to the Bioenvironmental Engineering laboratories, a 60 ml aliquot was collected from the well-mixed sample and stored at $4^{o}C$. Next, two liters of the mixed sample was centrifuged at 1725 X G for 10 minutes to obtain a clarified supernatant, for use in settling test dilutions, and a thickened pellet, which would be used in subsequent specific resistance and bound water analyses. Settling tests were then performed using three separate suspended solids concentrations, which allowed for development of a correlation between settling characteristics and concentration. While the samples were allowed to settle, another aliquot was taken and the test for electrophoretic mobility performed. Upon completion of the settling and electrophoretic mobility tests, an undiluted sample was taken and the solids analyses performed. While samples were drying in the oven, a portion of the sludge thickened by centrifugation was taken and tested for specific resistance to filtration. Afterward, the remainder of the thickened sludge was centrifuged at 20,000 X G for 15 minutes and the resultant pellet used in determination of the bound water content. Finally, a small aliquot of the original sample was examined under the microscope for floc and filament quantification. As mentioned previously, carbohydrate and protein analyses were performed at a later date, though storage time was kept to less than two months.

## General Analytical Methods

Suspended and volatile suspended solids (SS and VSS, respectively) were determined by glass fiber filtration in accordance with Standard Methods (1976). Sludge volume index (SVI) and zone settling velocity (ZSV) tests were performed in a 1-liter graduated cylinder using three different SS concentrations, as recommended by Sezgin (1980). The sludge-liquid interface was recorded at 1-minute intervals for ten minutes and the 30-minute settled sludge volume noted, as specified in Standard Methods (1976). All reported SVI and ZSV values are for interpolated SS concentrations of 1000 mg/l. The analytical procedures for determination of protein and carbohydrate content, expressed as percent dry weight of sludge, were taken from the Ramanathan et al. M-2 manual (1968).

The electrophoretic mobility for each sludge sample (diluted with its own supernatant) was calculated following the procedures outlined in the Zeta-Meter Manual (1975). All measurements were completed within one minute of initiation to minimize thermal turnover. All final results were corrected to 25°C.

For determination of specific resistance, the method described by Coackley and Jones (1956) was followed. Using a Buchner funnel apparatus and a thickened sludge, specific resistance, r, was calculated as:

$$r = 2PA\,b/\mu v$$

where $P$ = pressure (vacuum), $N/m^2$
$A$ = area of filter, $m^2$
$b$ = slope of straight line drawn through a plot of (time of filtration/volume of filtrate) vs. volume of filtrate, $sec/m^6$
$\mu$ = viscosity, $N * sec/m^2$
$C$ = dry cake solids per liquid volume in sludge before filtration, $Kg/m^3$.

The units for specific resistance were expressed as terameters per kilogram (Tm/kg), as recommended by Christensen (1983).

## Bound Water Procedure

The dilatometric method for the determination of bound water, as described by Heukelekian and Weisberg (1956), was used in this research. This method is based on the principle that water which is chemically bound to individual particles will not freeze at temperatures below the freezing point of free water. The bound water method, originally developed for soil studies, was adapted by Heukelekian and Weisberg for use with activated sludge.

To begin the procedure, a sample of thickened sludge (approximately 10 per cent solids) is introduced into a tared dilatometer, fitted with a calibrated stem (Figure 1). The dilatometer plus sludge is weighed, then filled to the top calibration with kerosene, noting the volume required. Similar quantities of sludge and kerosene are placed into another dilatometer which has a thermometer substituted for the calibrated stem and is used for monitoring temperature changes. The two dilatometers are then placed in a freezer for two hours, after which time the temperature and resultant volume of the kerosene is recorded.

To determine the amount of expansion free water experiences when freezing, a standard kerosene curve and a standard kerosene plus water curve (Figure 2) are developed. This is done by placing a known amount of kerosene, or kerosene plus water, into a calibrated dilatometer and, as the temperature is reduced, recording several different volumes of reduction. From these two curves, the amount free water expands upon freezing can be determined (ml expansion/ml water).

By noting the predicted contraction of kerosene alone from the standard curve, the expansion due to water in the sludge plus kerosene system can be

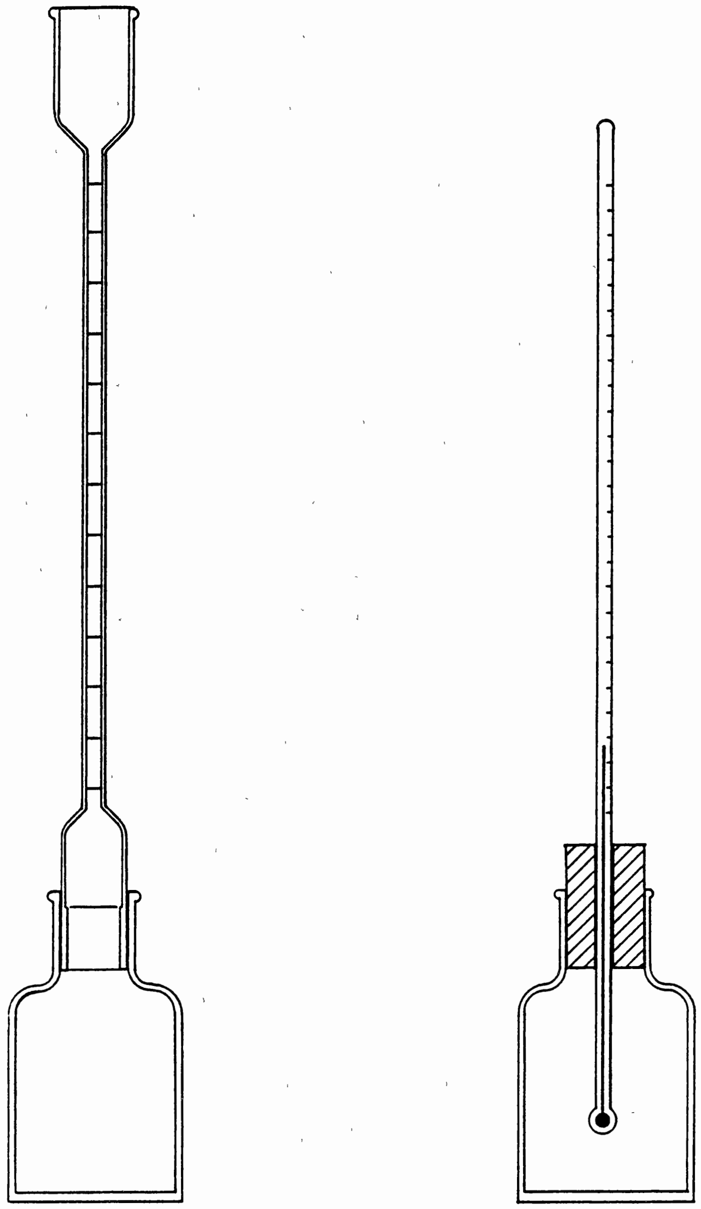

Figure 1. Dilatometer and dilatometer base fitted with thermometer

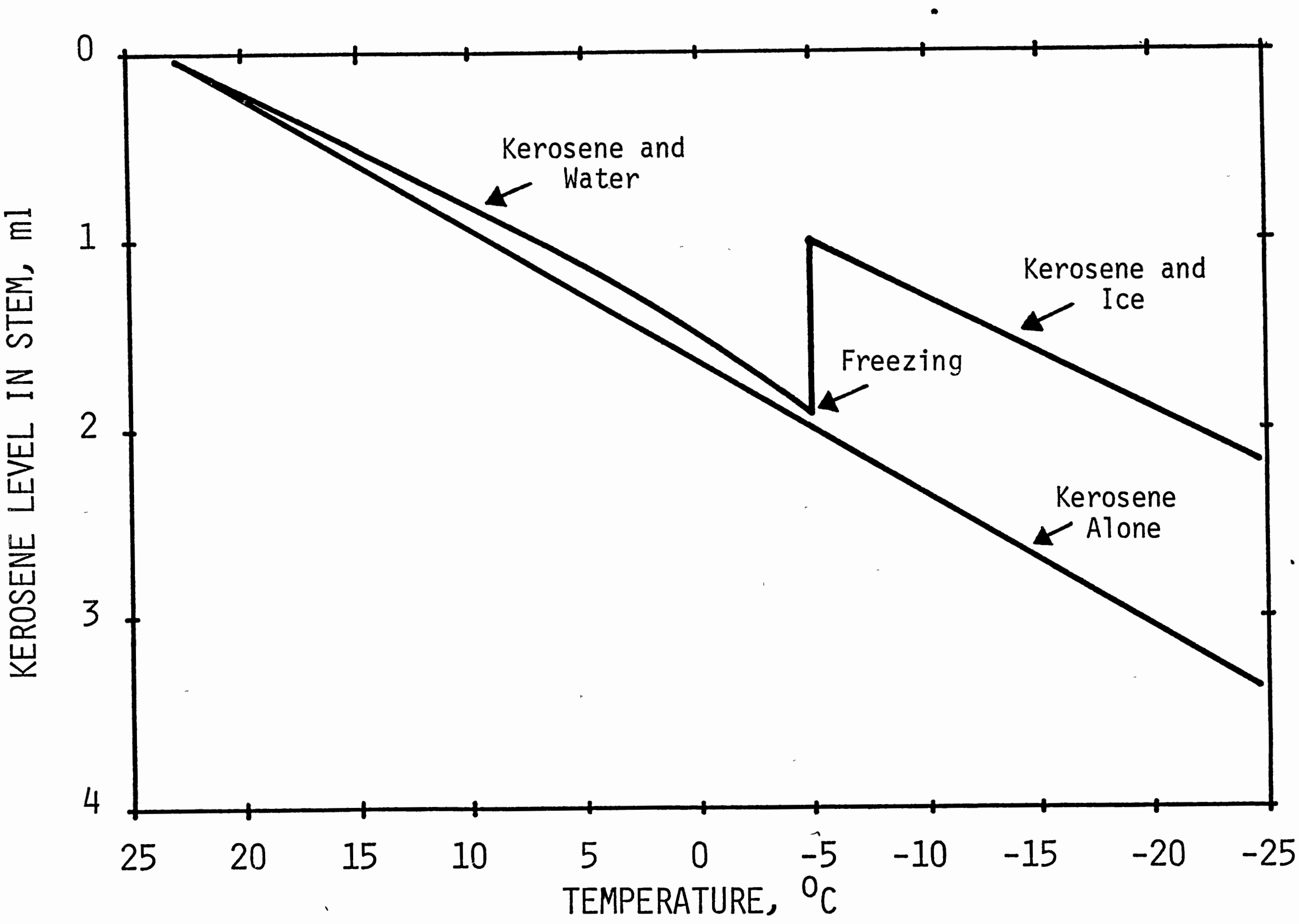

Figure 2. Standard curves for dilatometer studies

determined. With this information, the amount of water responsible for expansion is calculated. This amount represents the free water and, knowing the amount of total water from oven drying the sludge, the bound water content can be determined.

An example calculation helps to better explain the procedure. 160 gm of sludge at 10% solids is placed in the dilatometer. This represents 1.6 gm of solids and 14.4 gm of total water. 74 ml of kerosene is then titrated into the dilatometer. The system, with an initial temperature of 23.0°C, is placed in a freezer and removed two hours later, with a resultant temperature of -13.0°C and a contraction of 1.20 ml. From the standard kerosene curve, it is determined that 88.8 ml of kerosene contracts 2.50 ml at -13.0°C. Since the contraction of kerosene is linear, the 74 ml of kerosene should have contracted 74/88.8 X 2.50 = 2.08 ml. Therefore, 2.08 - 1.20 = 0.88 ml is due to free water expansion.

From the kerosene plus water curve, it is seen that 10 ml of water expands 1.0 ml at -13.0°C. Therefore, 0.88 ml expansion represents 8.8 ml, or 8.8 gm, of free water. Since it was previously determined that 14.4 gm of total water existed, 14.4 - 8.8 = 5.6 gm of bound water is present. To determine the percent bound water, the amount of bound water is divided by the amount of solids, or 5.6 gm bound water/1.6 gm solids X 100% = 350 percent bound water.

## Floc and Filament Quantification Procedure

An adapted version of the method developed by Sezgin et al. (1978) was used to determine floc and filament sizes and numbers. First, a mixed liquor sample was taken with a wide-tip pipette (6 mm diameter opening) and diluted with distilled water to a concentration of 2 to 3 mg/l. After gently stirring the dilution, a sample of diluted sludge was transferred to a 1-ml Sedgewick-Rafter counting chamber, using the same wide tip pipette. With the aid of a binocular microscope at 125 X and an ocular micrometer scale, all flocs and filaments within a known portion of the chamber were counted and sized. Flocs were measured by their maximum diameter and assigned to the following ranges: 15 to 37.5 μ, 37.5 to 75 μ, 75 to 112.5 μ, 112.5 to 150 μ, 150 to 300 μ, 300 to 450 μ, 450 to 750 μ, and greater than 750 μ. All floc particles greater than 750 μ in diameter were sized individually. Filaments were counted and assigned to the same maximum dimensions as were the flocs. Filaments greater than 750 μ in length were also sized individually. Generally, one hour was required for the microscopic analysis of flocs and filaments.

# CHAPTER IV

# RESULTS

With the exception of two sites, Haikey Creek and Deer Creek, all field samples were collected from the aeration basins of conventional activated sludge wastewater treatment facilities. The Haikey Creek sample was from an activated sludge plant which uses purified oxygen ("Purox") for aeration purposes. The Deer Creek sample was taken from the nitrification basin of a plant which employs rotating biological contactors.

The sludge retention time was not known for each facility but, by way of conversation with plant employees, a relative sludge age could be approximated. The Perry, Pawnee, and Flatrock facilities did not waste sludge on a frequent basis and would be considered to operate with a long sludge retention time. The Deer Creek nitrification basin, by necessity, also had a long sludge retention time. The Ponca City and Enid plants operated at intermediate times and the remainder of the plants (Tulsa Southside, Tulsa Northside, North Canadian, Haikey Creek, and Chisolm Creek) wasted sludge regularly and maintained relatively shorter sludge retention times.

As mentioned previously, the bench-scale data was obtained from units fed a synthetic waste consisting of Sego, mineral salts, and tap water. In addition, silver was added to the base mix of two units, one of which was maintained at a sludge age of 6 days and the other at 18 days. Zinc and lead, respectively, were added to the base mix of two other reactors, each held at a 12 day sludge retention time, while the fifth reactor, also maintained at 12 days, received the base mix alone.

A summary of the collected data is presented in Table I. It consists of the values obtained through the several analytical observations made on each of the samples. Protein data is missing for 10 of the 28 samples due to failure of the original analytical procedure and the subsequent loss of representative samples. The term, supracolloidal particle, refers to those floc particles which are less than 100 µ in diameter, as determined through the microscopic examinations of the sludge samples. Also, the filament length data represents the total combined measurement of both attached and free-floating filaments. Otherwise, all data presented in Table 1 are as described in the Materials and Methods section.

Comparison plots were drawn for those parameters which have been cited in the literature as having some effect on either thickening or dewatering (Figures 3-18). For the sludge volume index, plots were constructed versus filament length, mean floc diameter, protein content, carbohydrate content, volatile suspended solids, bound water, and electrophoretic mobility. Since the sludge volume index and zone settling velocity are simply alternate methods for measuring thickening properties and, generally, are closely associated with one another, only an illustrative plot of the latter versus filament length was drawn. For the specific resistance, plots against bound water, protein content, carbohydrate content, supracolloidal particles, electrophoretic mobility, filament length, and zone settling velocity were constructed. Upon recognition of the strong and similar relationships between the sludge volume index and both the filament length and protein content, an additional plot was drawn relating protein content to filament length.

The initial statistical analysis of the data entailed calculating the correlation coefficient (r) and the standard error of estimate (S) for each set of paired variables. A visual analysis of the plots suggested a curvilinear relationship in several cases and, in an effort to increase the correlation coefficients and

## TABLE I

## DATA SUMMARY

| SAMPLE SOURCE | SLUDGE VOLUME INDEX ml/g | ZONE SETTLING VELOCITY cm/hr | VOLATILE SUSPENDED SOLIDS % | PROTEIN % | CARBO-HYDRATE % | ELECTRO-PHORETIC MOBILITY u·cm/s·v | BOUND WATER % | SPECIFIC RESISTANCE Tm/kg | TOTAL FILAMENT LENGTH $10^6$u/mg | MEAN FLOC DIAMETER u | SUPRA-COLLOIDAL PARTICLES % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PERRY | 218 | 422 | 65.8 | - | 5.3 | -1.30 | 340 | 20.6 | 21.5 | 54.4 | 56.5 |
| CHISOLM CREEK | 184 | 401 | 80.3 | - | 10.1 | -1.43 | 260 | 40.7 | 14.5 | 95.2 | 64.6 |
| PONCA CITY | 116 | 554 | 76.3 | - | 6.2 | -1.17 | 282 | 45.2 | 15.1 | 71.4 | 78.5 |
| SOUTHSIDE | 263 | 146 | 84.6 | - | 8.3 | -2.25 | 501 | 245.1 | 30.6 | 57.7 | 89.6 |
| NORTH CANADIAN | 133 | 541 | 79.3 | - | 7.1 | -1.91 | 334 | 179.7 | 7.0 | 47.0 | 94.7 |
| SOUTHSIDE | 226 | 192 | 84.7 | - | 8.4 | -2.07 | 323 | 177.2 | 33.2 | 56.8 | 89.7 |
| FLATROCK | 48 | 1669 | 74.2 | - | 6.4 | -3.47 | 235 | 426.6 | 1.5 | 49L9 | 96.8 |
| PERRY | 69 | 1960 | 57.6 | - | 4.8 | -1.85 | 268 | 66.8 | 11.1 | 45.6 | 95.2 |
| SOUTHSIDE | 110 | 1240 | 79.5 | - | 7.3 | -2.01 | 348 | 191.7 | 16.5 | 48.6 | 94.8 |
| HAIKEY CREEK | 49 | 1995 | 73.9 | 40.1 | 14.2 | -2.44 | 206 | 63.2 | 0.5 | 65.3 | 81.9 |
| PAWNEE | 57 | 693 | 58.6 | 20.5 | 8.7 | -3.25 | 247 | 28.5 | 5.2 | 63.1 | 85.7 |
| DEER CREEK | 59 | 1178 | 54.3 | 23.0 | 13.2 | -1.93 | 359 | 41.9 | 11.4 | 48..7 | 94.9 |
| CHISOLM CREEK | 97 | 681 | 68.6 | 37.9 | 7.9 | -2.08 | 346 | 29.0 | 11.2 | 53.9 | 90.5 |
| ENID | 56 | 1644 | 66.2 | 41.3 | 11.2 | -1.88 | 289 | 10.4 | 6.1 | 51.8 | 93.3 |
| CHISOLM CREEK | 142 | 536 | 72.6 | 39.9 | 7.6 | -1.40 | 392 | 53.4 | 14.7 | 62.5 | 85.6 |
| NORTH CANADIAN | 98 | 1225 | 76.0 | 42.1 | 7.5 | -1.86 | 276 | 299.0 | 14.6 | 44.8 | 96.8 |
| SOUTHSIDE | 209 | 374 | 81.2 | 44.3 | 9.4 | -1.97 | 511 | 62.4 | 29.1 | 72.0 | 80.2 |
| HAIKEY CREEK | 45 | 1428 | 75.5 | 33.8 | 15.6 | -1.80 | 293 | 175.0 | 4.5 | 45.1 | 97.3 |
| NORTHSIDE | 453 | 116 | 80.2 | 48.0 | 11.5 | -1.95 | 378 | 23.5 | 116.0 | 75.7 | 74.7 |
| FLATROCK | 47 | 693 | 67.8 | 30.6 | 12.8 | -2.10 | 194 | 165.0 | 4.8 | 45.3 | 97.7 |
| SOUTHSIDE | 347 | 143 | 78.7 | 45.8 | 7.2 | -2.21 | 456 | 180.4 | 61.2 | 58.5 | 88.5 |
| NORTHSIDE | 417 | 156 | 80.1 | 46.1 | 12.2 | -1.98 | 334 | 29.9 | 90.9 | 78.9 | 71.6 |
| SOUTHSIDE | 473 | 116 | 81.0 | 47.4 | 10.7 | -1.81 | 414 | 182.5 | 144.8 | 49.5 | 91.3 |
| LABORATORY | | | | | | | | | | | |
| BASE MIX (BM) | 289 | 286 | 77.8 | 26.0 | 10.2 | -2.53 | 442 | 47.0 | 6.4 | 63.7 | 82.5 |
| BM + ZINC | 118 | 387 | 69.1 | 23.1 | 12.7 | -3.43 | 374 | 1.5 | 2.7 | 126.9 | 63.4 |
| BM + LEAD | 200 | 345 | 56.1 | - | 11.7 | -2.69 | 479 | 287.2 | 2.0 | 56.6 | 90.2 |
| BM + SILVER (6 DAY SRT) | 50 | 1465 | 88.3 | 27.5 | 9.2 | -1.19 | 465 | 115.8 | 0.0 | 71.4 | 81.1 |
| BM + SILVER (18 DAY SRT) | 49 | 1941 | 89.5 | 41.7 | 9.1 | -1.69 | 504 | 13.1 | 5.1 | 103.1 | 56.1 |

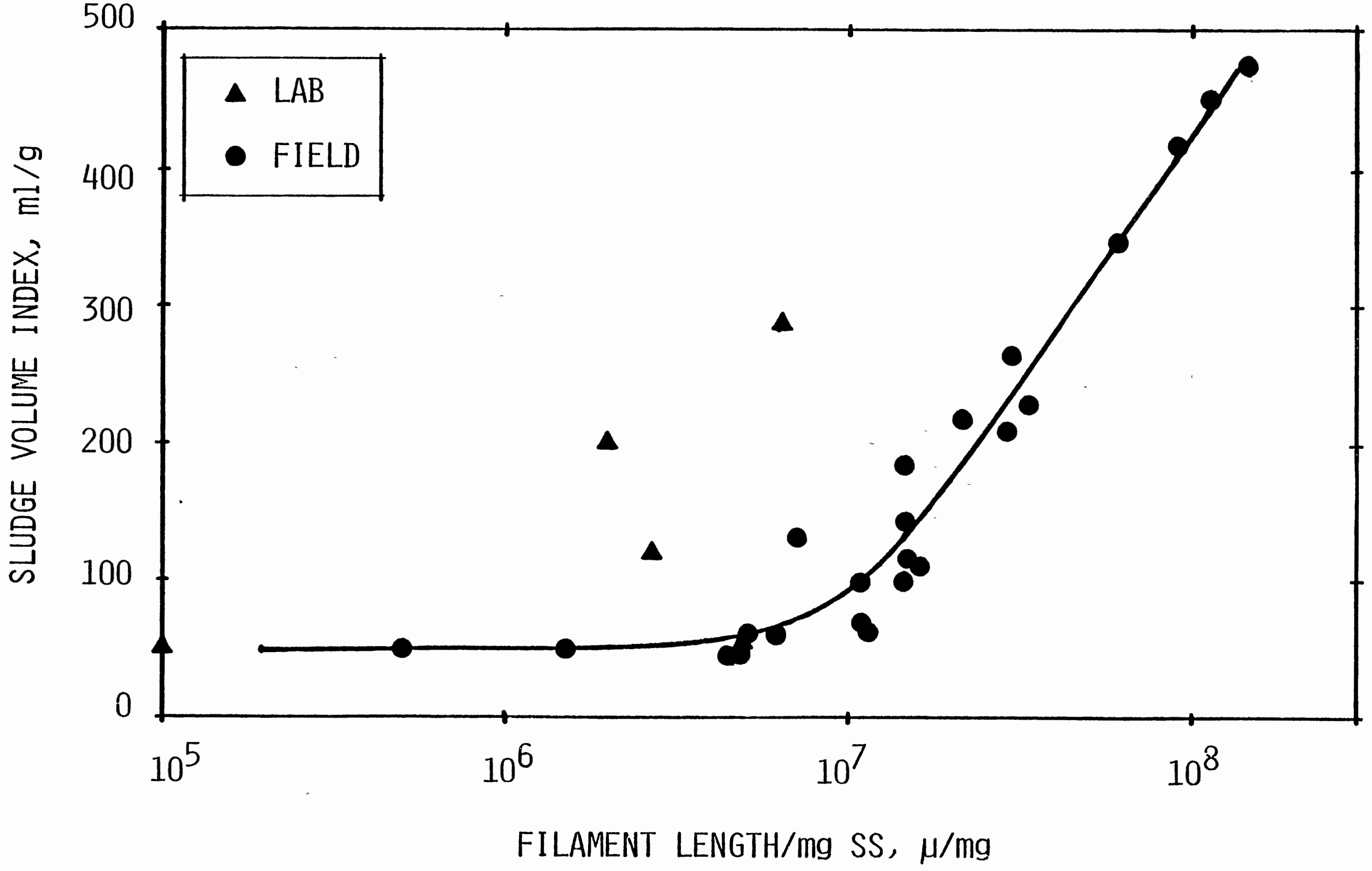

Figure 3. Sludge volume index versus filament length

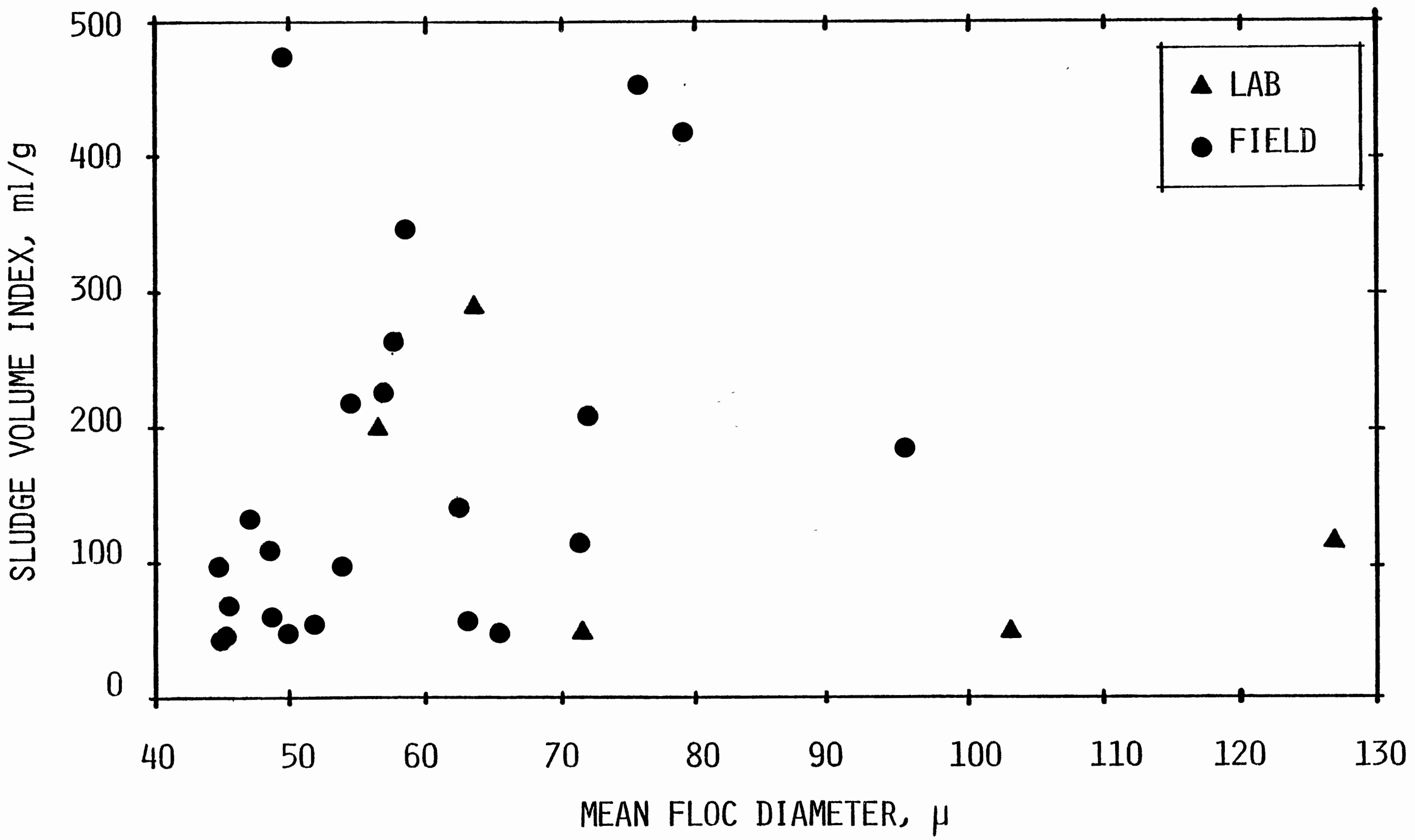

Figure 4. Sludge volume index versus mean floc diameter

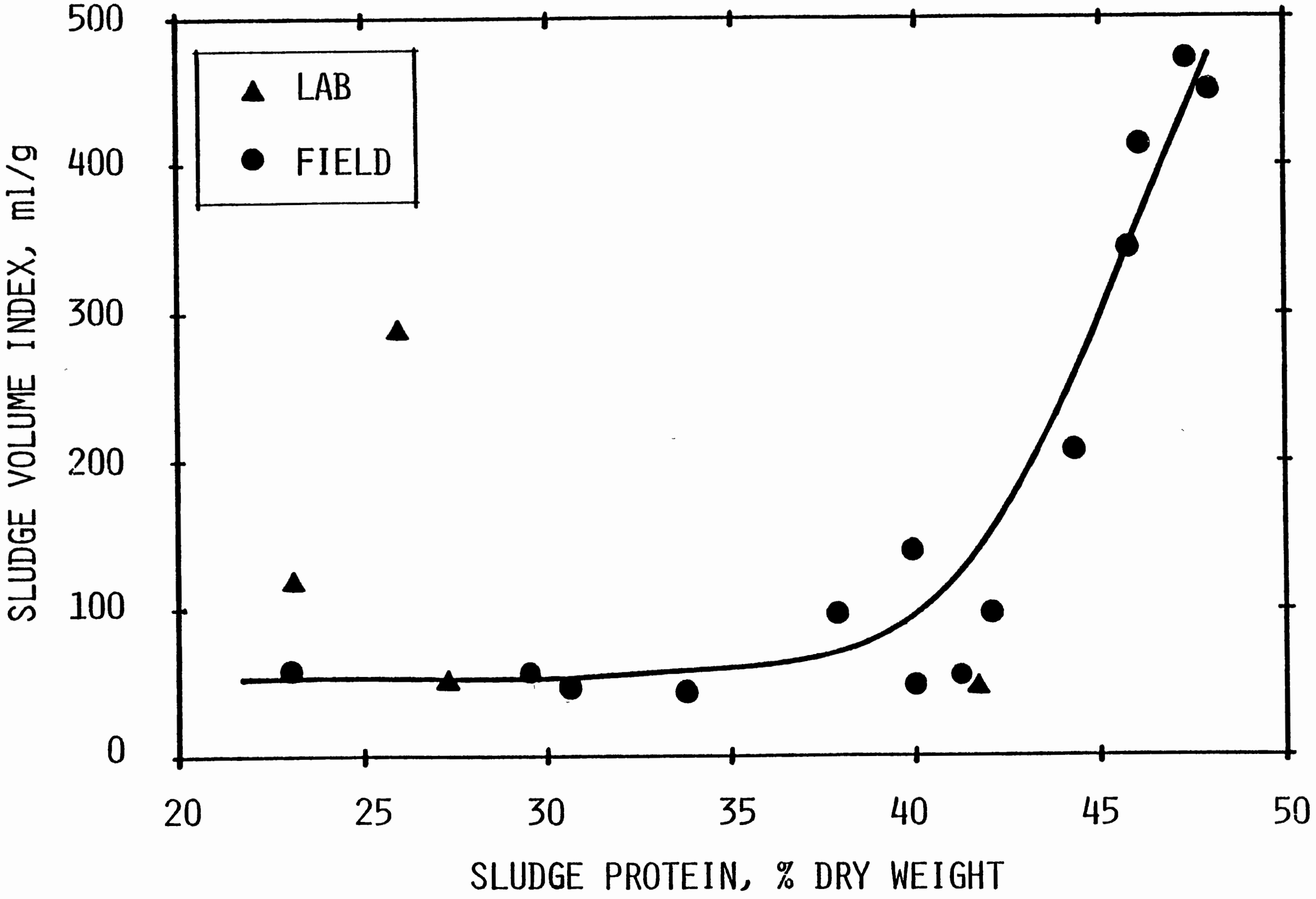

Figure 5. Sludge volume index versus percent sludge protein

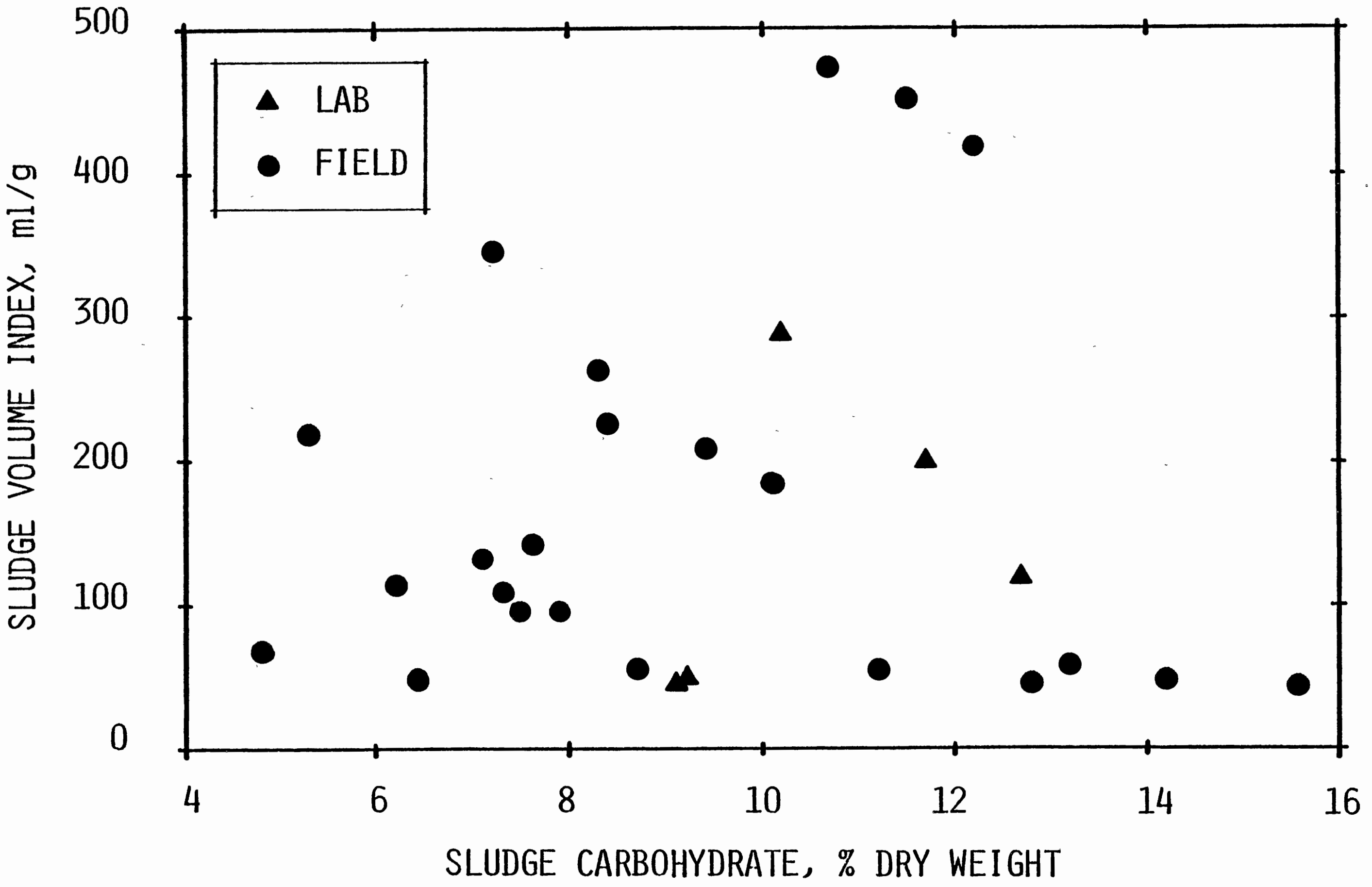

Figure 6. Sludge volume index versus percent sludge carbohydrate

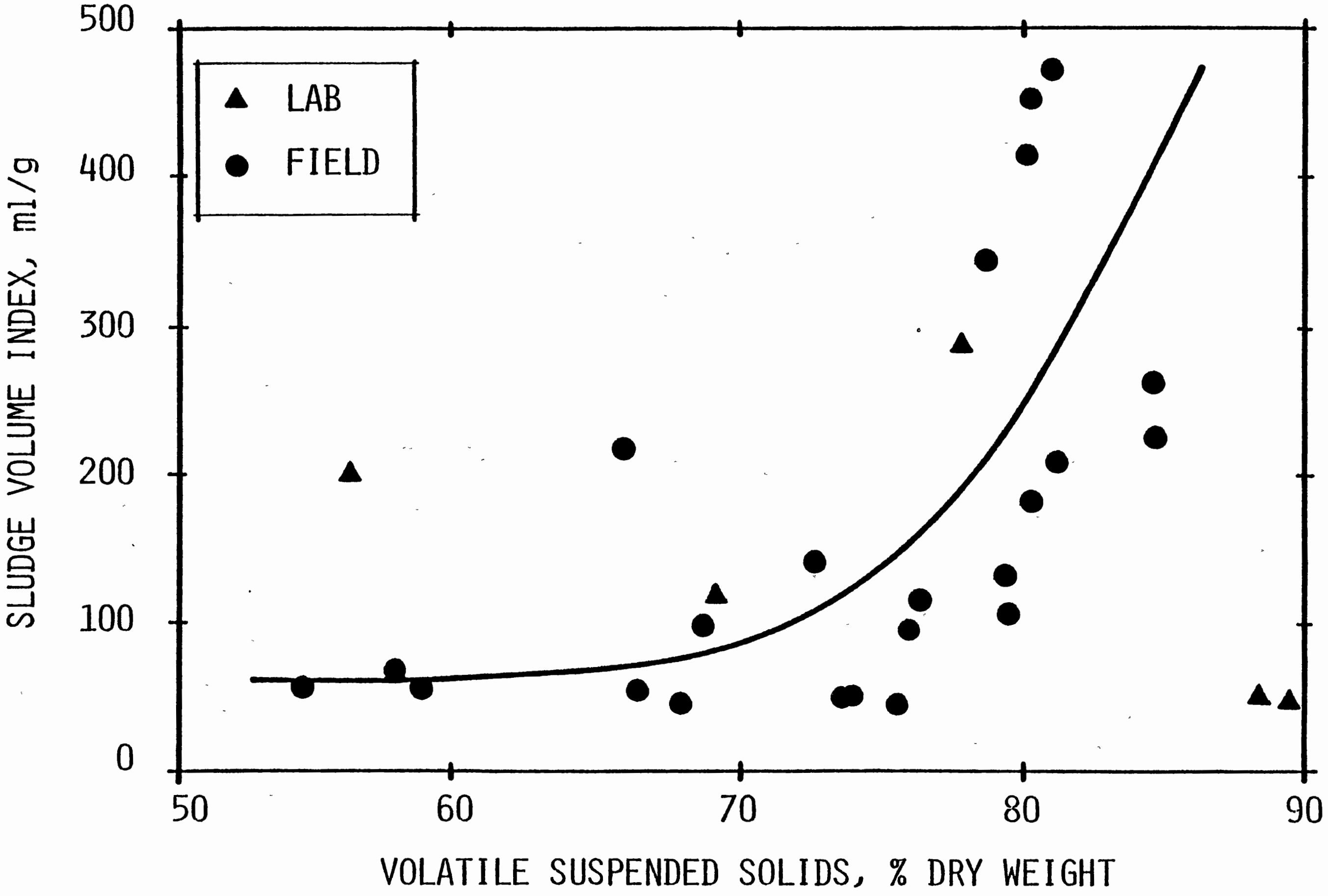

Figure 7. Sludge volume index versus percent volatile suspended solids

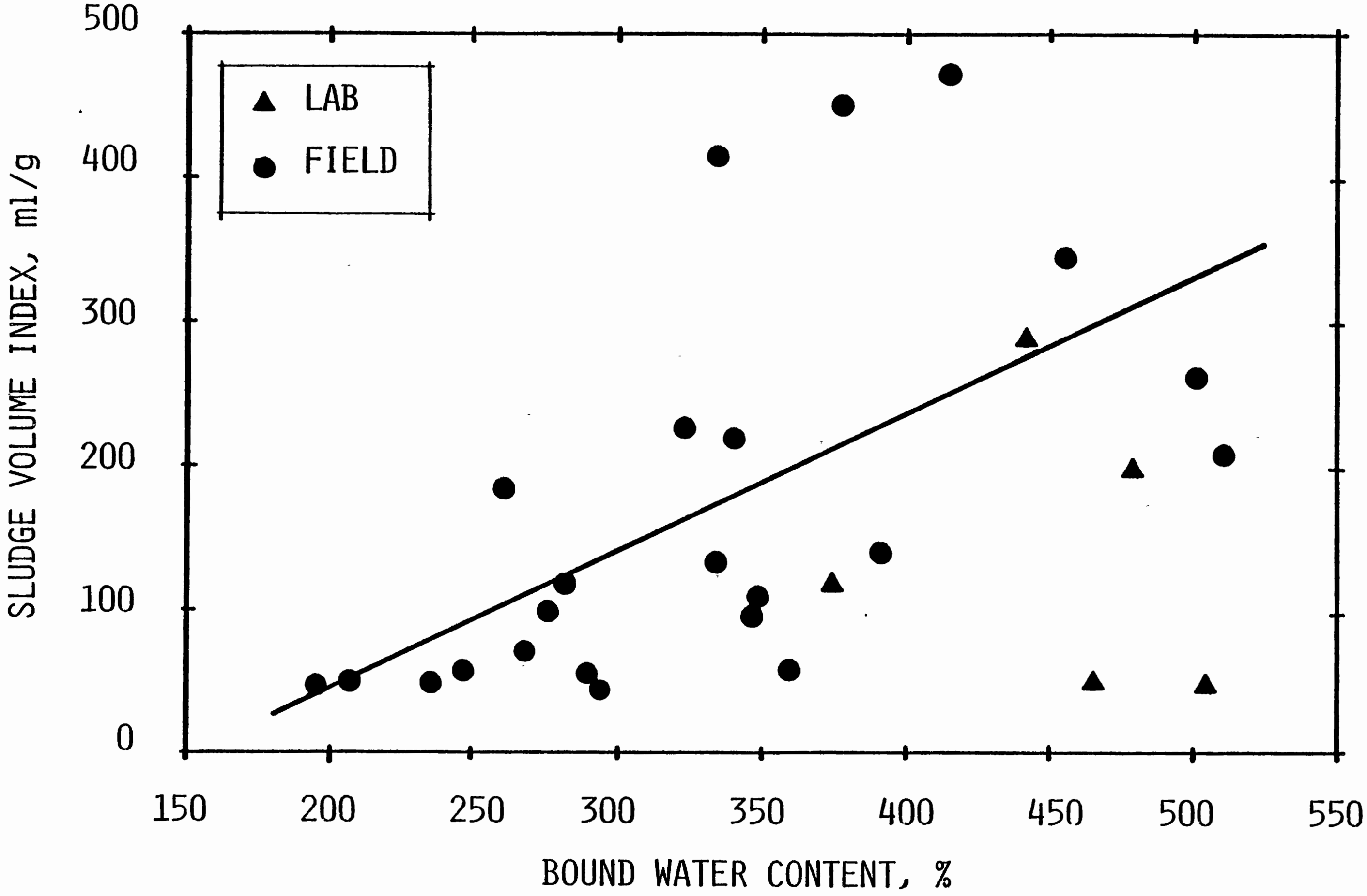

Figure 8. Sludge volume index versus percent bound water

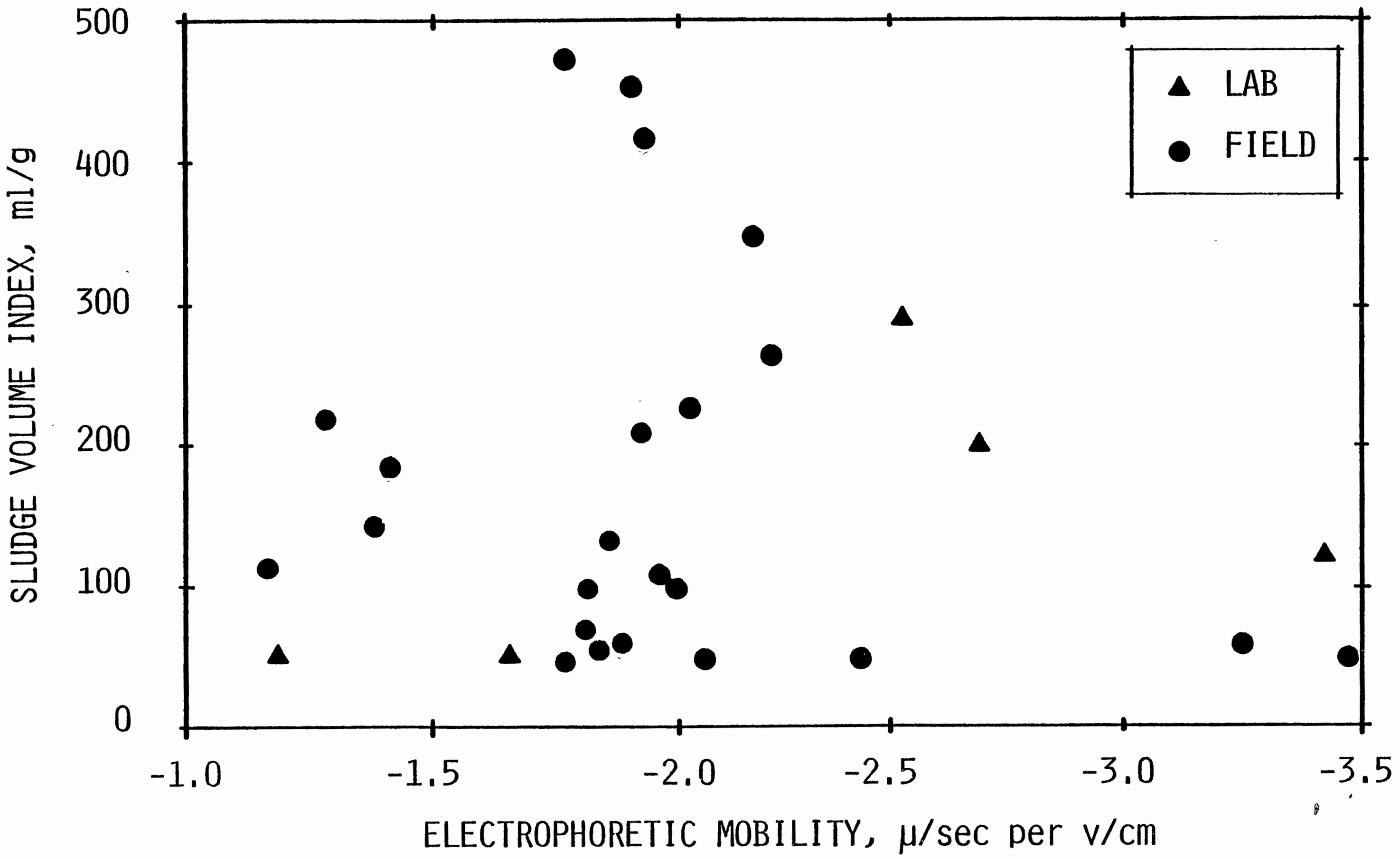

Figure 9. Sludge volume index versus electrophoretic mobility

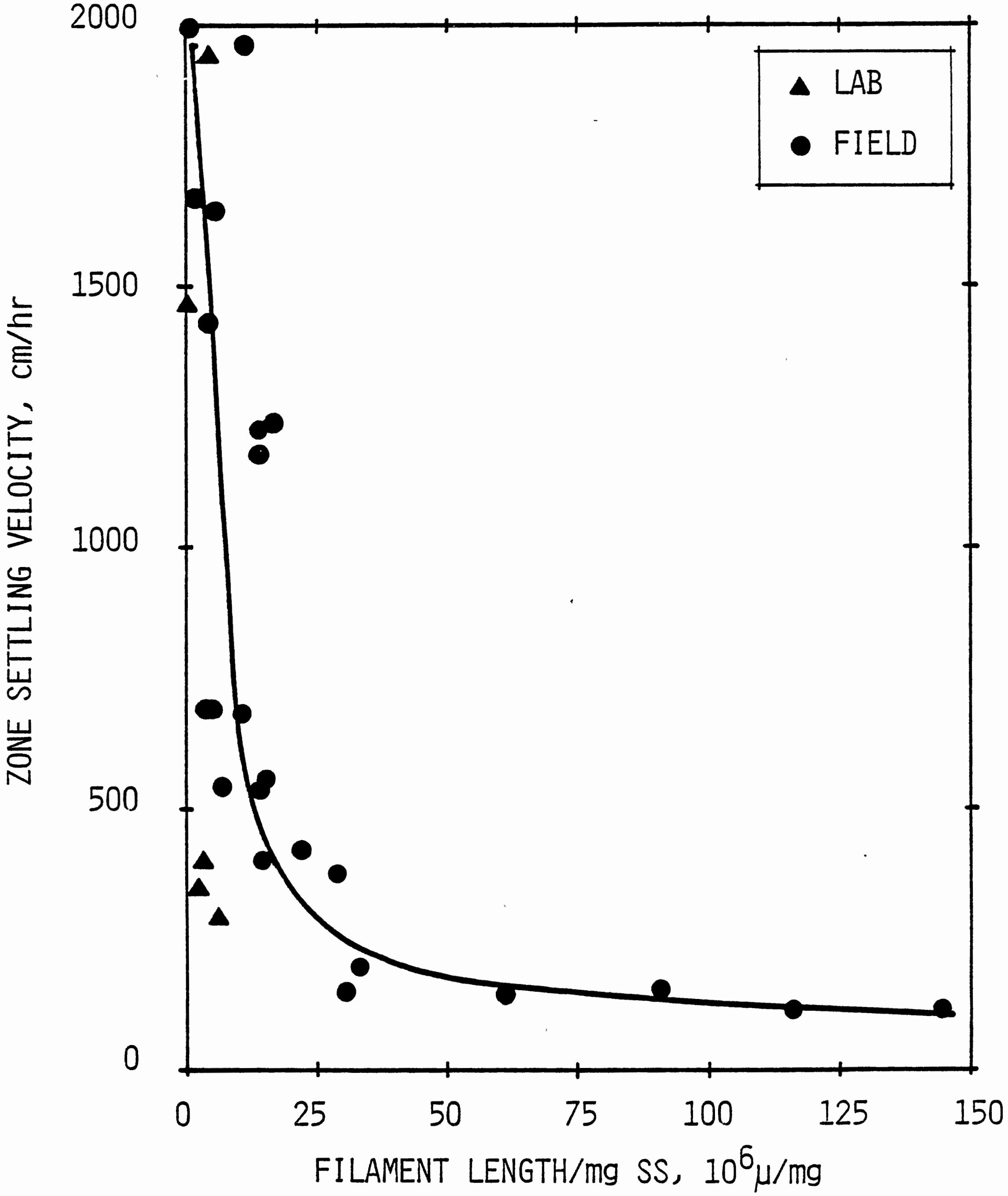

Figure 10. Zone settling velocity versus filament length

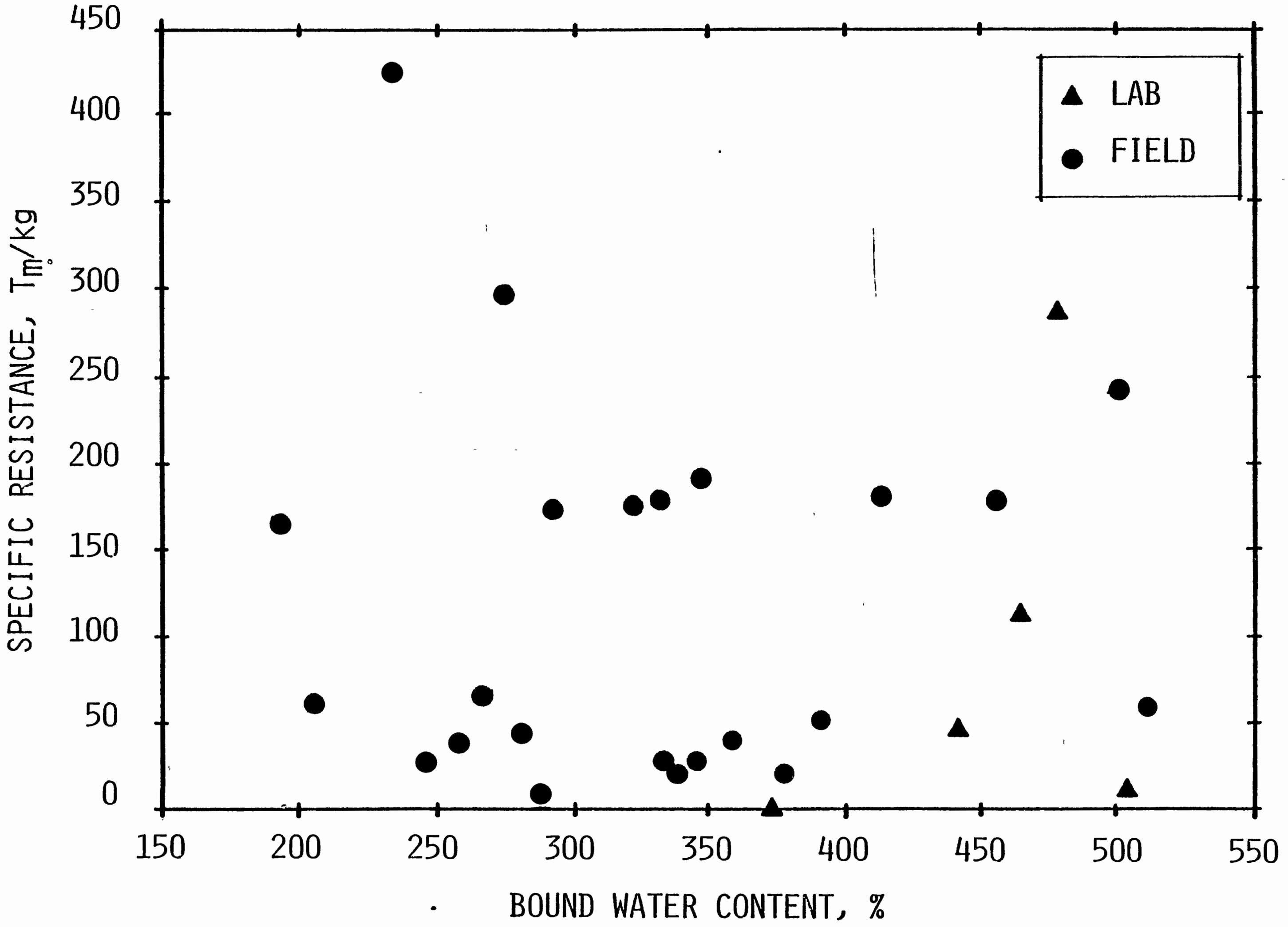

Figure 11. Specific resistance versus percent bound water

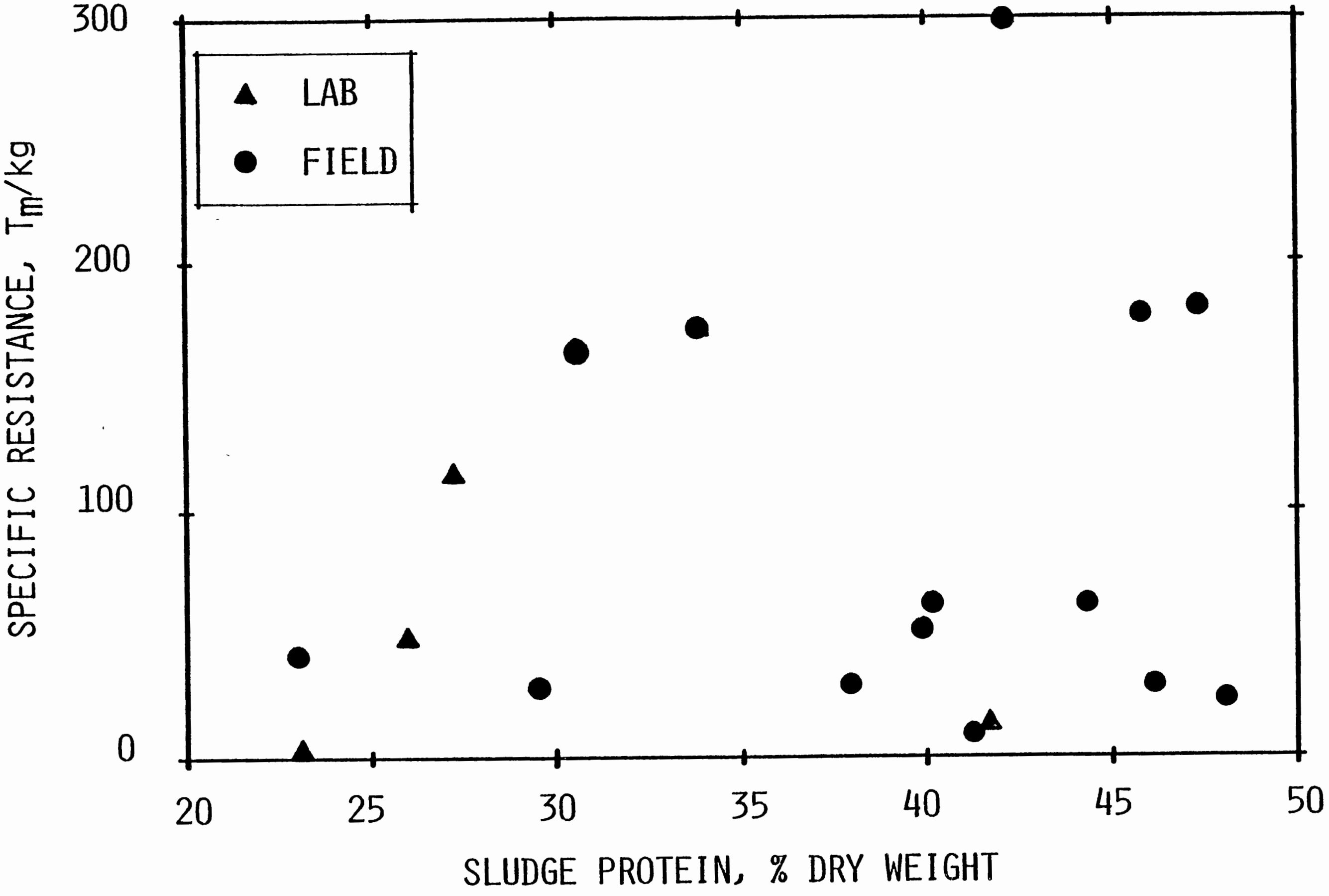

Figure 12. Specific resistance versus percent sludge protein

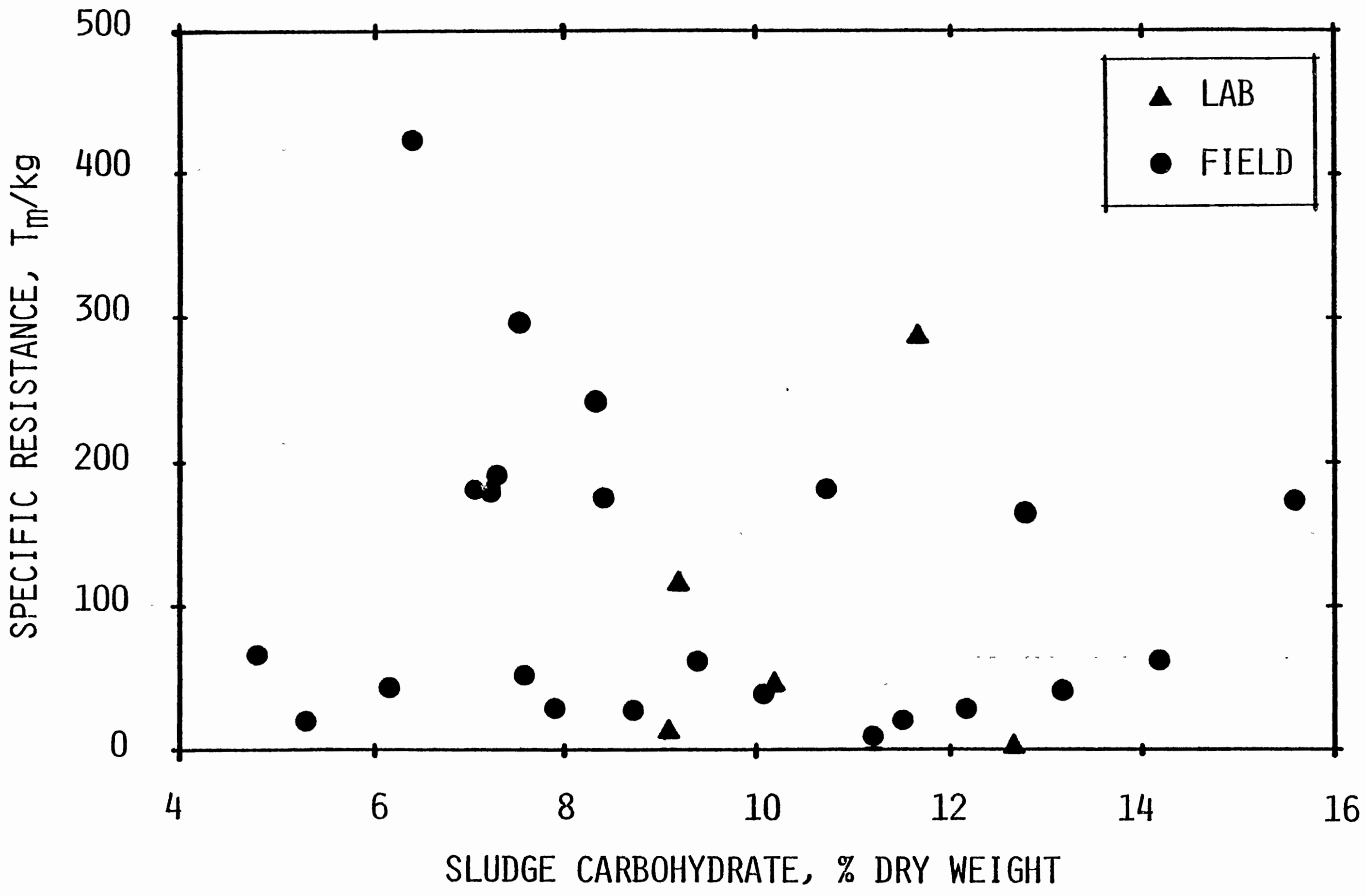

Figure 13. Specific resistance versus percent sludge carbohydrate

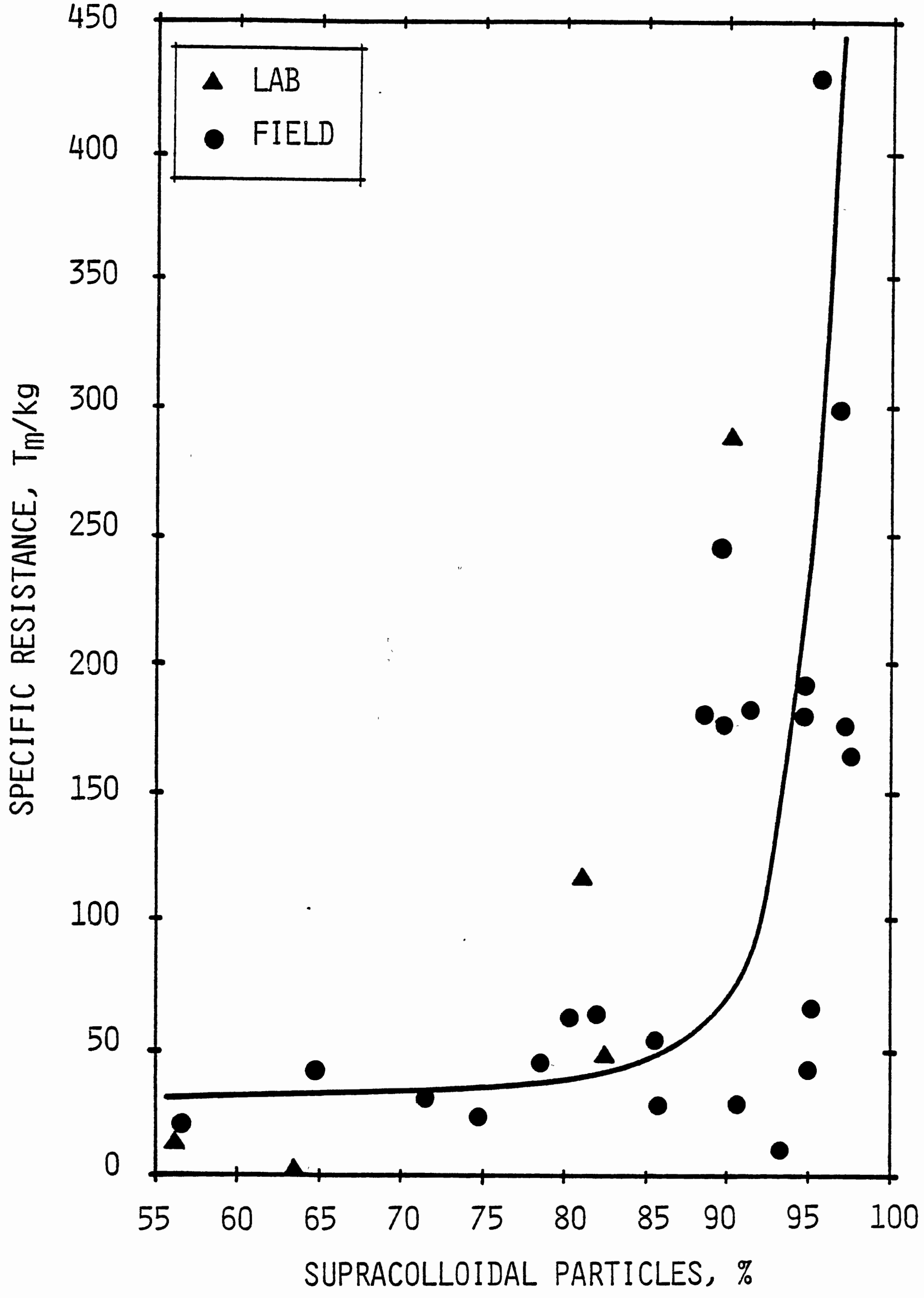

Figure 14. Specific resistance versus percent supracolloidal particles

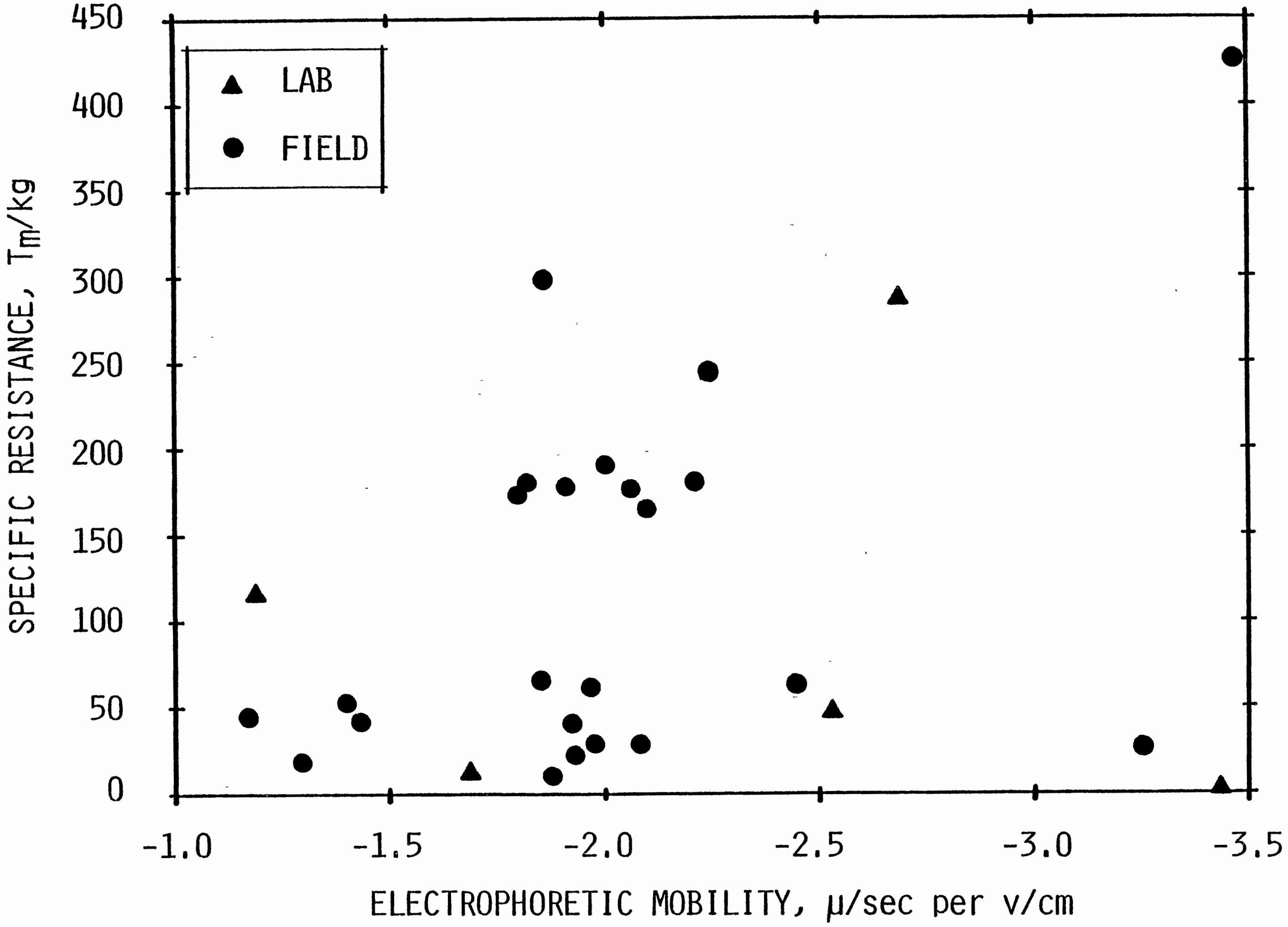

Figure 15. Specific resistance versus electrophoretic mobility

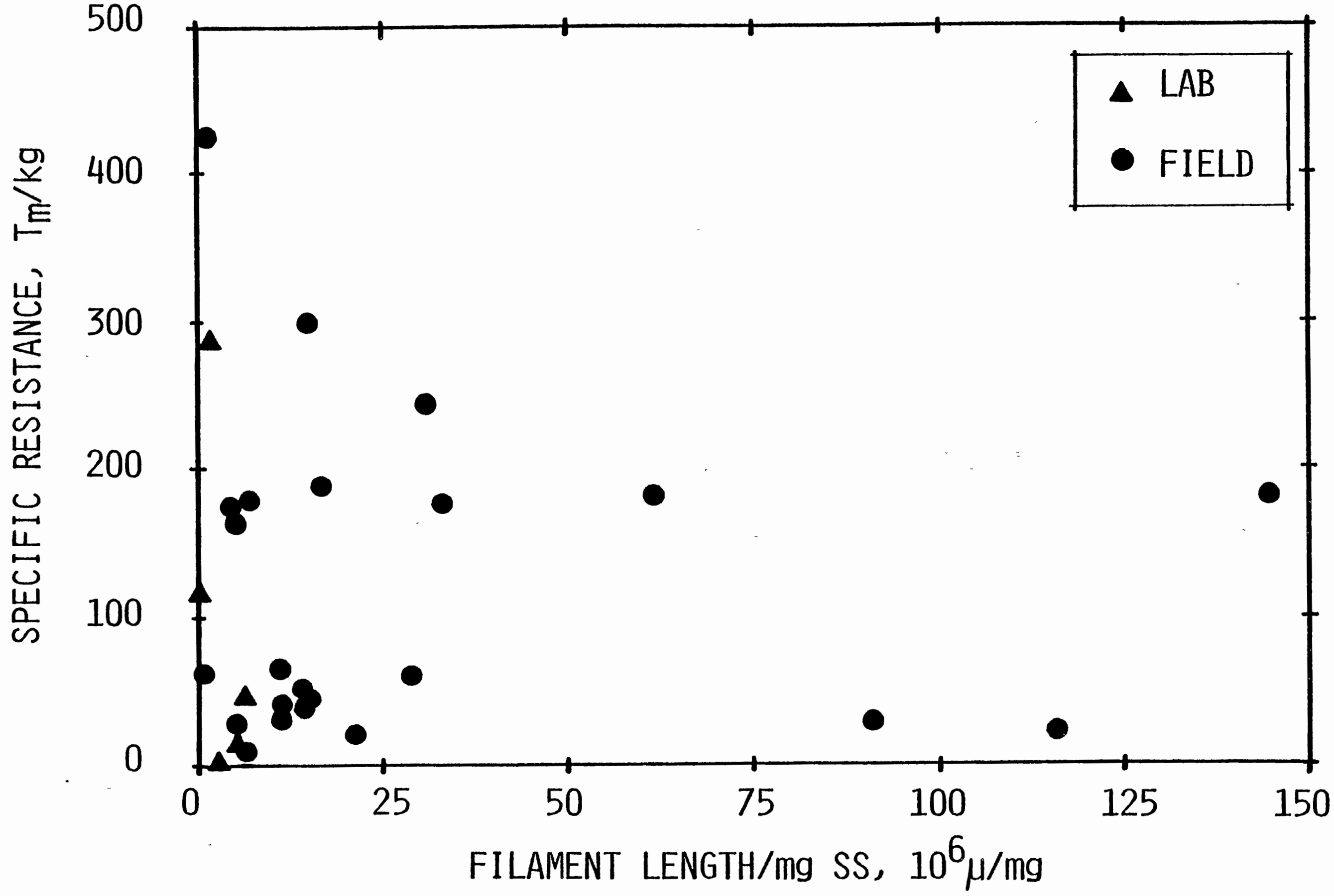

Figure 16. Specific resistance versus filament length

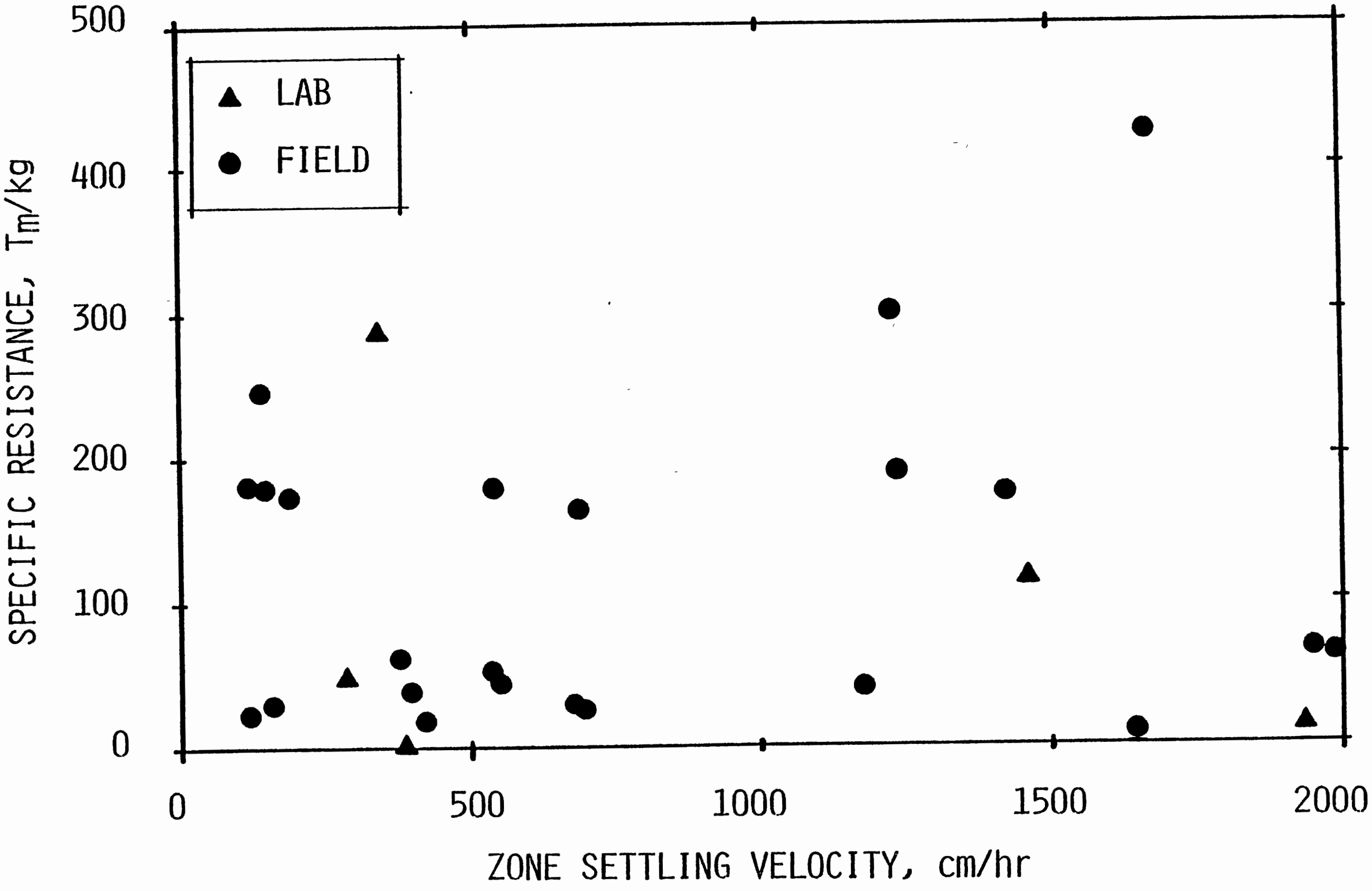

Figure 17. Specific resistance versus zone settling velocity

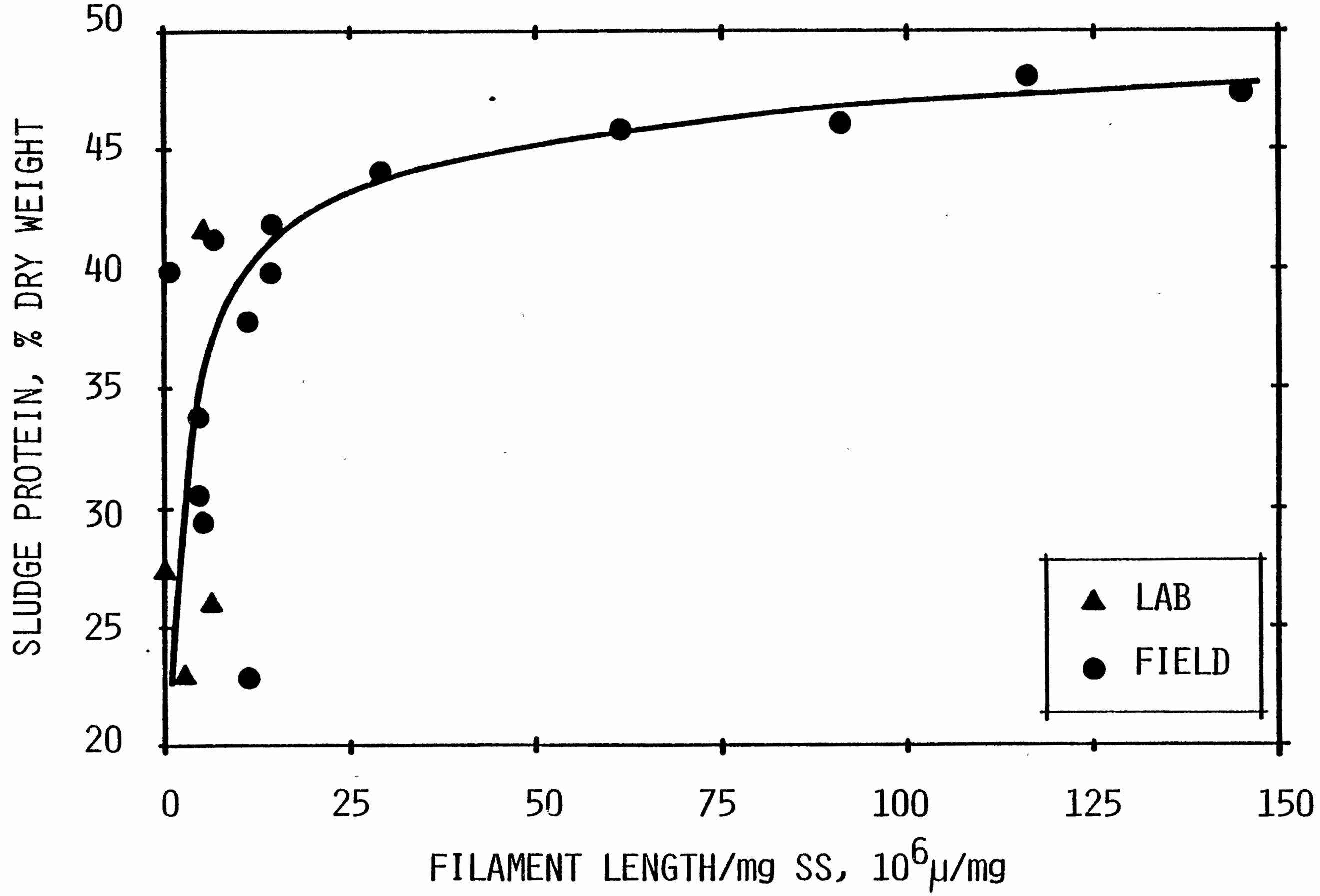

Figure 18. Percent sludge protein versus filament length

decrease the standard errors of estimate, an attempt was made to linearize the data for these plots through the use of logarithmic, reciprocal, and polynomial transformations. Since none of these manipulations resulted in any marked improvements in linearity, freehand curves were fitted by a graphic method and both the indices of correlation (i) and the standard errors of estimate ($\bar{S}$) determined in accordance with Ezekiel and Fox (1959). In addition, all coefficients and indices of correlation were adjusted for sample size. Curves were fitted to the field data alone since it was noted that the data obtained from the bench-scale units usually failed to follow any apparent plotting trends.

Recognizing that the value for a perfect correlation is 1.0 and for a total absence of correlation is 0.0, it was decided that the line or curve of best fit would be drawn on the graph only if either the adjusted coefficient or adjusted index of correlation (r and i, respectively) was greater than 0.50. If the adjusted correlation was less than 0.50, the relationship was not considered strong enough to be represented by a line. The decision as to whether the relationship should be represented by a curve or a straight line was based on the standard error of estimate value, with the function having the lowest value being considered the most representative.

Table II is a summary of the statistical data calculated for each pair of variables.

## TABLE II

## STATISTICAL ANALYSIS OF DATA

| FIGURE | PAIRED VARIABLES | ALL DATA |  |  |  | FIELD DATA ONLY |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | n | d | r | S | n | d | r | S | $\bar{d}$ | I | $\bar{S}$ |
| 3 | SVI VS FILAMENT LENGTH | 28 | 0.769 | 0.877 | 62.3 | 23 | 0.874 | 0.935 | 48.3 | 0.959 | 0.979 | 27.6 |
| 4 | SVI VS MEAN FLOC DIAMETER | 28 | 0 | 0 | 131.6 | 23 | 0.117 | 0.343 | 127.9 | - | - | - |
| 5 | SVI VS SLUDGE PROTEIN | 18 | 0.271 | 0.520 | 132.0 | 14 | 0.524 | 0.724 | 114.5 | 0.940 | 0.970 | 40.6 |
| 6 | SVI VS SLUDGE CARBOHYDRATE | 28 | 0 | 0 | 132.1 | 23 | 0 | 0 | 139.3 | - | - | - |
| 7 | SVI VS VOLATILE SUSPENDED SOLIDS | 28 | 0.077 | 0.277 | 124.6 | 23 | 0.282 | 0.531 | 115.4 | 0.307 | 0.554 | 113.3 |
| 8 | SVI VS BOUND WATER | 28 | 0.137 | 0.371 | 120.5 | 23 | 0.323 | 0.569 | 112.0 | 0.104 | 0.322 | 125.6 |
| 9 | SVI VS ELECTROPHORETIC MOBILITY | 28 | 0 | 0 | 131.7 | 23 | 0 | 0 | 136.6 | - | - | - |
| 10 | ZSV VS FILAMENT LENGTH | 28 | 0.238 | 0.488 | 552.9 | 23 | 0.315 | 0.561 | 513.0 | 0.561 | 0.749 | 411.0 |
| 11 | SPECIFIC RESISTANCE VS BOUND WATER | 28 | 0 | 0 | 109.5 | 23 | 0 | 0 | 110.0 | - | - | - |
| 12 | SPECIFIC RESISTANCE VS SLUDGE PROTEIN | 18 | 0 | 0 | 83.6 | 14 | 0 | 0 | 90.6 | - | - | - |
| 13 | SPECIFIC RESISTANCE VS SLUDGE CARBOHYDRATE | 28 | 0 | 0 | 107.9 | 23 | 0 | 0 | 107.8 | - | - | - |
| 14 | SPECIFIC RESISTANCE VS SUPRACOLLOIDAL PARTICLES | 28 | 0.322 | 0.567 | 88.5 | 23 | 0.273 | 0.522 | 91.6 | 0.331 | 0.575 | 90.0 |
| 15 | SPECIFIC RESISTANCE VS ELECTROPHORETIC MOBILITY | 28 | 0.052 | 0.228 | 104L7 | 23 | 0.163 | 0.403 | 98.3 | - | - | - |
| 16 | SPECIFIC RESISTANCE VS FILAMENT LENGTH | 28 | 0 | 0 | 109.5 | 23 | 0 | 0 | 109.8 | - | - | - |
| 17 | SPECIFIC RESISTANCE VS ZSV | 28 | 0 | 0 | 109.4 | 23 | 0 | 0 | 108.8 | - | - | - |
| 18 | SLUDGE PROTEIN VS FILAMENT LENGTH | 18 | 0.386 | 0.622 | 6.7 | 14 | 0.492 | 0.634 | 5.8 | 0.461 | 0.679 | 5.5 |

n = number of observations
d = coefficient of determination for linear relation
r = coefficient of correlation for linear relation
S = standard error of estimate for linear relation
$\bar{d}$ = index of determination for curvilinear relation
I = index of correlation for curvilinear relation
$\bar{S}$ = standard error of estimate for curvilinear relation

# CHAPTER V

# DISCUSSION

## Analysis of Individual Correlations

### Filament Length and the Sludge Volume Index

For the field data, a very strong correlation was observed between the SVI and total filament length ($r = 0.935$, $i = 0.979$), with 95.9% of the variance in SVI being accounted for by differences in the filament length (based on the curvilinear relationship). Inclusion of the bench-scale data resulted in a slightly reduced correlation ($r = 0.877$).

The unified filamentous bulking theory formulated by Sezgin et al. (1978) holds that an overgrowth of extended filaments from the floc surface results in a bridging effect which hinders settling and compaction. In addition, it proposes that filaments serve as the backbone to strong floc particles and that the complete absence of filaments would produce a poor settling, pin-point floc.

For the most part, the findings of this research complimented the filamentous bulking theory. Sludges exhibited poorer settling characteristics as filament lengths extended beyond $10^7\mu$/mg TSS. This was in agreement with Sezgin et al. (1980) who found that the total filament length of $10^7\mu$/mg TSS was a good dividing point between bulking and non-bulking sludges. In addition, most sludges with short filament lengths ($5 \times 10^6\mu$/mg TSS) possessed visually turbid supernatants upon settling. However, an exception to this was found with the bench-scale sludges fed the heavy metal additives. Despite short filament lengths (and the complete absence of such in one sample), they produced large, compact flocs and clear supernatants.

In light of this, it appears that the proposed bulking theory is quite applicable to municipal sludges from full-scale facilities but may not be comprehensive enough to be termed "unified." It is possible that when a sludge is totally void of filaments, other factors (perhaps extracellular polymers) may come into play to enhance its cohesiveness. If so, this would account for the findings regarding the laboratory sludges.

On the other hand, the microscopic measurement of filament length allows only for the detection of those filaments extending from the floc surfaces. If filaments serve as a backbone to the floc but do not extend from it, they are unaccounted for. For this reason, perhaps an alternative method needs to be developed which is capable of accurately measuring filament quantity, regardless of length or location.

## Mean Floc Diameter and the Sludge Volume Index

For the samples collected from the municipal treatment plant, only a weak correlation was observed between the SVI and mean floc diameter ($r = 0.343$), with inclusion of the bench-scale data bringing the correlation to zero.

Increases in floc size have not been implicated as the cause of sludge bulking though an association with increases in non-bulking SVI's has been noted by Sezgin (1982). He found that SVI varied with floc size at filament lengths less than $10^7 \mu$/mg TSS but, when filaments extended beyond this point, no effect of floc size was evident.

A similar relationship could not be seen with the samples used in this research. For sludges with total filament lengths less than $10^7 \mu$/mg TSS, the range in SVI was only from 45 to 56. These low SVI's would not be of general concern and any correlation to floc size would be merely coincidental.

The fact that any correlation could be found between SVI and floc size is probably due to the effect filaments have on the flocs. As filament lengths increase, the flocs tend to become more loosely agglomerated, thereby increasing in apparent size. Since filament lengths are strongly associated with SVI, it follows that the changes in floc size also exhibit some correlation.

It is worth noting that the mean floc diameters of the bench-scale sludges were among the largest of all samples tested, yet their corresponding SVI's were below the average. Microscopic observation of these samples typically showed large, compact flocs with short to no filaments. This would indicate that the density rather than the size is more important with regard to good settling characteristics.

## Sludge Protein and the Sludge Volume Index

For the field samples, a high degree of curvilinear correlation was found between the SVI and sludge protein content (i = 0.970), with 94% of the changes in SVI being due to corresponding changes in the protein content. A somewhat lower linear correlation was found (r = 0.724), with addition of the bench-scale data reducing it even further (r = 0.520).

These results are surprising in that previous citings of this strong relationship have not been common and no hypothesis exists with respect to the cause. Recognizing the moderately strong correlation between protein content and filament length (i = 0.679), it may be that increases in sludge protein are actually indirectly linked with higher SVI's by way of the filaments. In other words, a high protein content may be typical of filamentous bacteria which, in turn, are typical of a bulking sludge. If this is the case, it warrants further investigation in that it may lead to a surrogate means of filament quantification.

Caution should be taken, however, in lending too much weight to these results. Since only fourteen samples are included in the statistical analysis of the field sludges, the results may be atypical. More extensive field studies are needed before definitive conclusions can be drawn.

### Sludge Carbohydrate and the Sludge Volume Index

For the sludges analyzed in the course of this study, no correlation was found between the SVI and the carbohydrate content.

The carbohydrate content has never been considered to be a major factor in sludge bulking, though Forster (1971) has been able to show corresponding increases in SVI and sludge carbohydrate for samples from a pilot-scale treatment facility. However, of the ten samples used to establish the correlation, three had carbohydrate concentrations greater than 37%. Such high concentrations would be considered quite atypical in a full-scale facility and, for all practical reasons, would only be experienced in experimental pilot- or bench-scale systems. Of the other seven samples in Forster's study, the highest SVI recorded was 127, which was for a sludge with a carbohydrate content of 12.7%. This would barely constitute a bulking sludge and probably be of no concern to a treatment plant operator. In fact, even at a carbohydrate concentration of 45.1%, Forster's sludge yielded a SVI of only 190.

In light of the findings of this study and the lack of strong supportive evidence from other works, the correlation between SVI and carbohydrate content should be considered of no importance.

### Volatile Suspended Solids and the Sludge Volume Index

For the samples collected from the municipal facilities, a moderate correlation was seen between SVI and VSS ($r = 0.531$, $i = 0.554$), though inclusion of the lab samples considerably reduced it (r = 0.277). For the curvilinear relationship, 30.7% of the variance in SVI was due to changes in VSS.

The percent VSS is not a factor frequently associated with the settling characteristics of a biological sludge, yet it can be seen through this study that some correlation does exist. Since the percent volatility describes a condition rather than a physical characteristic of the sludge, it is likely that the VSS is actually linked indirectly to the SVI. In looking at the data in Table I, it appears that the filament length is the physical characteristic through which the percent VSS is related to the SVI. In general, the municipal sludges with the higher percent VSS are also those with the greater filament lengths (r = 0.377). Therefore, the percent VSS serves as a rough indicator to the degree of filamentous growth. The same can not be said for the laboratory sludges, which experienced up to 89% VSS with little or no evidence of filaments. Thus, for municipal sludges, the relationship between VSS and filament length approximates the relationship of VSS and SVI yet the same correlations are mutually reduced for laboratory sludges.

## Bound Water and the Sludge Volume Index

A moderate correlation (r = 0.569) was observed between the SVI and bound water content of the municipal sludges with 32.3% of the variance being accounted for by changes in the percent bound water though, once again, inclusion of the lab data reduced the correlation (r = 0.370). Since the correlation reported by Heukelikian and Weisberg (1956) was based on zoogleal forms of activated sludge, it was deemed appropriate to examine the possibilities of establishing a stronger correlation for this work by omitting some of the more filamentous data. By excluding the three most filamentous samples from the statistical analysis, the correlation coefficient for SVI versus bound water was increased from 0.569 to 0.714, thereby indicating a fairly strong correlation.

As stated by Sezgin et al. (1978) and confirmed through this work, non-filamentous bulking is not common in most cases of activated sludge operation and is encountered more frequently in laboratory studies using a simple waste than in full-scale municipal operations. Thus, the importance of the effect bound water has on bulking in general is to be questioned.

It should be noted that the bench-scale sludges in this study tended to have a higher bound water content than the municipal sludges. Heukelikian and Weisberg stated that increases in bound water result from the excessive supply of available food, thereby suggesting that cellular storage of excess substrate is directly related to the amount of bound water. Since a synthetic waste which was easy to metabolize was fed to the bench-scale systems, it is highly probable that cellular storage and, thus, bound water was greater for the laboratory than for the municipal sludges. It may be concluded from this that, though bound water is not a major factor in sludges fed a complex municipal waste, it can become significant in situations where high loading of simple wastes exists.

## Electrophoretic Mobility and the Sludge Volume Index

Regardless of sample source (lab or field), no correlation could be found between the SVI and electrophoretic mobility data.

The electrophoretic mobility, a measure of a sludge's surface charge, has been implicated in a variety of ways to both flocculation and bulking. It has been shown to be directly (Forster, 1968) as well as inversely (Magara et al., 1976) related to the SVI. Pavoni et al. (1972) reported that surface charge reduction was not necessary for biological flocculation and, in fact, that negatively charged cells could be flocculated by negatively charged polymers.

If the surface charge itself is important as a repelling force, it could only be of significance in cases of truly non-filamentous sludges. Otherwise, the filaments themselves would act as a physical barrier to agglomeration by bridging between floc particles, thereby negating any possible effects of the charge. If the surface charge is actually indicative of a component or group of components which are directly responsible for bulking, those components have yet to be positively identified and, if proven to exist, must be of such magnitude that they supersede the myriad other properties known to be present in a biological sludge.

It is acknowledged that practically any property, including surface charge, can be associated with sludge bulking if closely controlled laboratory conditions are maintained. However, if the same does not hold true under actual field conditions, it is of little use to the environmental engineer.

## Filament Length and the Zone Settling Velocity

A moderate correlation was found to exist between the ZSV and filament length of municipal sludges ($r = 0.561$, $i = 0.749$) with 56.1% of the curvilinear variance in ZSV being due to differences in filament length. A slightly lower correlation ($r = 0.488$) resulted when laboratory sludges were included in the analysis.

Since both the ZSV and SVI are measures of sludge thickening properties, the similarity in correlations to the filament length is expected. However, the correlation with respect to the ZSV is not quite as perfect as the one which exists for the SVI. Two different possibilities come to mind as to the reason for this. First, the measurement of ZSV is not as simple a laboratory procedure as is the determination of SVI and is, therefore, more prone to error. Especially for rapidly settling sludges, it is often difficult to discern a distinct sludge blanket prior to the beginning of compaction, thereby making the calculations an approximation at best. Second (and hopefully the correct reason), the resultant SVI is more a function of compaction difficulties, as may be experienced with the overabundance of extended filaments, than is the ZSV, which is governed more by frictional resistance to settling. It appears, therefore, that the existence of filaments does increase the frictional resistance but not to the degree that it hinders compaction.

## Bound Water and Specific Resistance

A correlation could be established for this relationship, regardless of sample source. This was of no surprise to the author despite the implication of several publications (Karr and Keinath, 1978; Wu et al.,1982; An Analysis of Research Needs . . . , 1982) that bound water is related to dewaterability.

On the face of it, it appears to be only logical that the two factors are associated in some way. However, if the term "bound water" and the process of dewatering are accurately understood, the dissociation becomes apparent. Vesilind (1979) cites four categories into which the water portion of sludge may be placed. The first two, free and floc water, are removable by gravitational settling and mechanical dewatering, respectively. The third, capillary water, adheres to the particles and can be removed by extreme compaction. The last, and most tightly bound, is the bound water which is held by chemical bonds to the individual particles. Therefore, even after a sludge has been mechanically dewatered, the bound water remains, requiring a process such as incineration to remove it.

Generally, those authors who imply the bound water-dewaterability relationship have not performed the research themselves but cite the work of Heukelekian and Weisberg (1956). However, it is too often overlooked that Heukelekian and Weisberg were studying the effects of bound water on sludge bulking and in no way examined filtration or dewaterability. Therefore, for lack of any supportive evidence, the association between bound water and the specific resistance to filtration should be considered nonexistent.

## Sludge Protein and Specific Resistance

Regardless of sample source (lab or field), no correlation was found between the specific resistance and sludge protein data.

To the author's knowledge, no reasons have been proposed regarding why sludge protein might have an effect on dewaterability. It was examined in this study because of the conflicting findings of Randall et al. (1971), who found a weak inverse relationship, and Wu et al. (1982), who found a direct relationship.

No plausible reason is evident for an association of any sort and, as a result of the lack of correlation in this study, it is concluded that the sludge protein content is not an important variable in the dewatering process.

## Sludge Carbohydrate and Specific Resistance

Again, regardless of sample source, no correlation was found between the specific resistance and sludge carbohydrate data.

Perhaps due to its association with the extracellular slime layer of activated sludge, carbohydrate has been implicated as a factor affecting dewaterability. Both Randall et al. (1971) and Wu et al. (1982) have found a direct relationship between the sludge carbohydrate content and the dewatering characteristics. However, in the study of Randall et al., sludges from two different treatment facilities gave distinctly different plots, thereby suggesting the nonexistence of a universal relationship.

Since the data presented here represents sludges from several treatment facilities, it would appear to be consistent with Randall et al. that no correlation could be established. If the sludge carbohydrate content is to be used as an operational parameter in the dewatering process, the relationship would have to be established for each individual plant. More than likely, this would not be practical.

## Supracolloidal Particles and Specific Resistance

The strongest correlation observed for specific resistance was with respect to the supracolloidal particle fraction of the sludge. The linear correlation for the field data was 0.522, with inclusion of the laboratory data raising the correlation slightly to 0.567. The curvilinear relationship for the field data was somewhat better than the linear relationship, giving an index of correlation value equal to 0.575.

Particle size is suggested by both the U.S. Environmental Protection Agency (1982) and the Water Pollution Control Federation (An Analysis of Research Needs . . . , 1982) as being the single most important factor influencing dewaterability. It is believed that, as particle size decreases, resistance to filtration increases. The reasons for this effect, as given in the EPA's manual, include increased interparticle repulsion due to the larger area of electrical charges, greater frictional resistance to water movement, and greater adsorption of water due to the increased number of potential sites on the particle. In addition to, or perhaps instead of, these reasons, Karr and Keinath (1978) stated that the resistance to filtration is increased by small particles as a result of their blinding the sludge cake and filter medium.

The implication of blinding as the major factor was based on the finding by Karr and Keinath that all reductions in particle size do not affect filtration rates. It was found that only the supracollodial particles (1 to 100 μ in size) had a significant effect and that particles both larger and smaller than the supracolloids did not. Since the pore size of the filter medium was in the range of 1 to 100 μ, it was believed that the supracolloids would become entrapped within the pores, whereas smaller particles would pass through the filter and larger ones remain perched on the filter surface.

The determination of particle size for this study was made by means of microscopic measurements, a method adopted because of its compatibility to both particle and filament sizing. Though adequate for analyzing filamentous growth, the magnification used was only reliable for sizing particles greater than 15 μ in diameter. Thus, considerable oversight of the smaller supracolloidal particles may have occurred, thereby making their impact on filtration unaccounted for. As a result, the correlation values presented here should be viewed as only approximates, with the true values possibly being higher or lower.

## Electrophoretic Mobility and Specific Resistance

A slight correlation ($r = 0.403$) was observed between the specific resistance and electrophoretic mobility values for the field sludges but inclusion of the laboratory data reduced the correlation to an inconsiderable level ($r = 0.228$).

As stated in the EPA's design manual (1982), the particle surface charge affects dewatering by hindering compaction due to the repulsive forces and by weakly binding water to the particle surface. However, as mentioned previously in this discussion, water which is bound directly to the particle is not generally removed by conventional dewatering processes. Therefore, this effect should not be considered significant.

One of the reasons surface charge has been implicated is based on the observation that, when conditioning a sludge with polymers, optimal dewatering rates are achieved when the charge is reduced to zero. However, as found by Roberts and Olsson (1975), it is the charge on the colloidal particles (smaller than 10 μ) for which neutralization is most important. It is this author's belief that it is not as much charge neutralization as it is polymer bridging of the colloidal particles (thus preventing blinding of the medium) which most impacts dewatering rates.

The fact that a slight correlation is seen between specific resistance to filtration and electrophoretic mobility is possibly due to the apparent increased mobility of small particles as compared to large ones. Thus, the greater the fraction of small, colloidal particles becomes, the greater both the specific resistance and electrophoretic mobility are.

### Filament Length and Specific Resistance

No correlation was seen to exist between the specific resistance and filament length for either the laboratory or field data.

Wu et al. (1982) reported that the excessive growth of filamentous microorganisms resulted in poor filtering properties. It was suggested that the filaments physically clog the draining pores in much the same way as do the colloidal particles. However, if Sezgin et al.'s (1978) description of the filament as a "backbone" is accepted, an opposite effect would be expected.

This author has frequently observed bulking sludges which were quite filamentous yet dewatered rapidly. In fact, if a generality were to be made, it would be contrary to the conclusions of Wu et al. Therefore, it is suggested that filament length not be considered to be of major importance in evaluating a sludge's dewatering properties.

### Zone Settling Velocity and Specific Resistance

No correlation was observed between the specific resistance and ZSV values for either the field or laboratory sludges.

The findings of Novak et al. (1977) suggested a direct relationship between thickening velocities and filtration rates. In other words, the sludges which settle slowly are also the ones to dewater slowly. However, these results were based on very little data (three data points) and have not been supported by subsequent research. Therefore, based on the paucity of past evidence and the lack of correlation in this present study, the association between ZSV and specific resistance should remain indeterminate.

## Collective Comparison of Correlations

### Thickening

There is a strong indication that the length of the filaments is the most important factor in determining the gravitational thickening rates. With the exception of sludge protein content, no other property appears to have as great an influence as does the excessive growth of filaments. Due to the relatively low quantity of protein data, results regarding it are inconclusive. As to the surface charge, the role it plays in affecting thickening is, if anything, indeterminate. Bound water does appear to be of some importance in non-filamentous bulking though, it should be mentioned, this form of bulking does not seem to be either common or troublesome to municipal treatment facilities.

With regard to the five sludges collected from the bench-scale systems, their thickening characteristics were generally independent of any trends exhibited by the municipal sludges. Caution should be taken, however, in extrapolating any conclusions from these findings. The units fed the heavy metals produced sludges that were atypical in comparison to sludges grown on synthetic substrate alone. In order for more reliable conclusions to be drawn, a larger sampling of sludges should be made and a variety of synthetic substrates used.

As mentioned at the outset, the sludge volume index was selected as the test for measuring thickening due to its widespread use as well as its simulation of the most common form of thickening, gravitational. However, if dissolved air flotation or any other form of thickening is to be employed, these findings may not be applicable and independent tests should be run.

## CHAPTER VI

## CONCLUSIONS

1. When filaments are present, the extent of their growth governs the gravitational thickening of sludge.

2. The effect surface charge has on gravitational thickening is not universal and, therefore, knowledge of a sludge's surface charge is of no benefit in predicting thickening rates.

3. Under non-controlled environmental conditions, the carbohydrate content of a sludge has no impact on the gravitational thickening rates.

4. The bound water content of a sludge does not affect the vacuum filtration rates of that sludge.

5. The chemical constituents, protein and carbohydrate, have no direct effect on the vacuum filtration rates of a sludge.

6. The particle size distribution of a sludge affects the rate at which water can be removed by vacuum filtration.

7. Filaments do not govern vacuum filtration rates.

# CHAPTER VII

# RECOMMENDATIONS

1. Efforts should be made to identify a component unique to filamentous bacteria which may be used to expedite future quantification of filaments.

2. A larger sample population should be used to determine the correlation between SVI and sludge protein content. If a strong correlation is found, research into the causes should be performed.

3. No more research should be devoted to the attempt to establish surface charge as being a controlling factor in sludge thickening.

4. Improved particle fractioning and measuring techniques need to be developed in order that the impact of particle size on dewatering can be more reliably evaluated.

5. Bench-scale units should be operated using a variety of synthetic wastes as well as actual domestic wastewater and comparative evaluations (similar to those in this study) performed to determine the appropriateness of using synthetic wastewater to simulate actual sewage.

# BIBLIOGRAPHY

An Analysis of Research Needs Concerning the Treatment, Utilization, and Disposal of Wastewater Treatment Plant Sludges. Washington, D.C.: Water Pollution Control Federation, 1982.

Bisogni, J.J. Jr. and A.W. Lawrence. "Relationships Between Biological Solids Retention Time and Settling Characteristics of Activated Sludge." Water Research, 5 (1971). 753-673.

Christensen, G.L. "Units for Specific Resistance." J. Water Pollution Control Federation, 55 (1983) 417-419.

Coackley, P. and B.R.S. Jones. "Vacuum Sludge Filtration. Part 1 - Interpretation of Results by the Concept of Specific Resistance." Sewage and Industrial Wastes, 28 (1956), 963-975.

Ezekiel, M. and K.A. Fox. Methods of Correlation and Regression Analysis. New York: John Wiley and Sons, Inc., 1959.

Finstein, M.S. and H. Heukelekian. "Gross Dimensions of Activated Sludge Flocs with Reference to Bulking." J. Water Pollution Control Federation, 39 (1967), 33-40.

Forster, C.F. "The Surface of Activated Sludge Particles in Relation to their Settiling Characteristics." Water Research, 2, (1968), 767-776.

Forster, C.F. "Activated Sludge Surfaces in Relation to the Sludge Volume Indes." Water Research, 5 (1971), 861-870.

Forster, C.F. and J. Dallas-Newton. "Activated Sludge Settlement—Some Suppositions and Suggestions." Water Pollution Control, 79 (1980), 338-351.

Gulas, V., M. Bond, and L. Benefield. "Use of Exocellular Polymers for Thickening and Dewatering Activated Sludge." J. Water Pollution Control Federation, 51 (1979), 798-807.

Heukelekian, H. and E. Weisberg. "Bound Water and Activated Sludge Bulking." Sewage and Industrial Wastes, 28 (1956), 558-574.

Karr, P.R. and T.M. Keinath. "Influence of Particle Size on Sludge Dewaterability." J. Water Pollution Control Federation, 50 (1978), 1911-1930.

Magara, Y., S. Nambu, and K. Utosawa. "Biochemical and Physical Properties of an Activated Sludge on Settling Characteristics." Water Research, 10 (1976), 71-77.

Metcalf and Eddy, Inc. Wastewater Engineering: Treatment, Disposal, Reuse. 2nd Ed. New York: McGraw-Hill Book Company, 1979.

"New WPCF Reports Emphasize Needs of Research." Water Pollution Control Federation Highlights. 19, 7 (July, 1982), 1.

Novak, J.T., H. Becker, and A. Zurrow. "Factors Influencing Activated Sludge Properties." J. Environmental Engineering Division, ASCE, 103 (1977), 815-828.

Pavoni, J.L., M.W. Tenney, and W.F. Echelberger, Jr. "Bacterial Exocellular Polymers and Biological Flocculation." J. Water Pollution Control Federation, 44 (1972), 414-431.

Pipes, W.O. "Microbiology of Activated Sludge Bulking." Advances in Applied Microbiology, 24 (1978), 85-127.

Ramanathan, M., A.F. Gaudy, Jr., and E.E. Cook. Selected Analytical Methods for Research in Water Pollution Control. Stillwater, Oklahoma: Center for Water Research in Engineering, Oklahoma State University (1968).

Randall, C.W., J.K. Turpin, and P.H. King. "Activated Sludge Dewatering: Factors Affecting Drainability." J. Water Pollution Control Federation, 43 (1971), 102-122.

Roberts, K. and O. Olsson. "Influence of Colloidal Particles on Dewatering of Activated Sludge with Polyelectrolyte." Environmental Science and Technology, 9 (1975), 945-948.

Sezgin, M., D. Jenkins, and D.S. Parker. "A Unified Theory of Filamentous Activated Sludge Bulking." J. Water Pollution Control Federation, 50 (1978), 362-381.

Sezgin, M., D. Jenkins, and J.C. Palm. "Floc Size, Filament Length, and Settling Properties of Prototype Activated Sludge Plants." Progress in Water Technology, 12 (1980), 171-182.

Sezgin, M. "Variation of Sludge Volume Index with Activated Sludge Characteristics." Water Research, 16 (1982), 83-88.

Somers, J.A. "The Relation Between Sludge Volume Index and Sludge Content in the Activated Sludge Process." Water Research, 2 (1968), 563-573.

Standard Methods for the Examination of Water and Wastewater. 14th Ed. New York: American Public Health Association, 1976.

Steiner, A.E., D.A. McLaren, and C.F. Forster. "The Nature of Activated Sludge Flocs." Water Research, 10 (1976), 25-30.

Tenney, M.W., W.F. Echelberger, Jr., J.J. Coffey, and T.J. McAloon. "Chemical Conditioning of Biological Sludges for Vacuum Filtration." J. Water Pollution Control Federation, 42 (1970), R1-R20.

U.S. Environmental Protection Agency. Process Design Manual for Dewatering Municipal Sludges. Concinnati, Ohio: Center for Environmental Research Information, EPA-625/1-82-014, 1982.

Vesilind, P.A. Treatment and Disposal of Wastewater Sludges. Revised Edition. Ann Arbor, Mich: Ann Arbor Science Publishers, Inc., 1979.

Wu, Y.C., E.D. Smith, and R. Novak. "Filterability of Activated Sludge in Response to Growth Conditions." J. Water Pollution Control Federation, 54 (1982), 444-456.

Zeta-Meter Manual. 3rd Ed. New York: Zeta-Meter, Inc., 1975.

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