EVALUATION OF THE SLUDGE BLINDING COEFFICIENT

by

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(ABSTRACT)

The sludge blinding coefficient, β, was evaluated in this experimental study, to determine if β could be used as a useful characterization parameter for sludge filterability. Fresh activated sludge, activated sludge aged at room temperature, primary sludge, alum sludge, and a calcium carbonate slurry were filtered using a Buchner funnel apparatus and varing size filter media at various pressure differentials. Particle size measurements were also performed on the above mentioned sludges using an automated particle size analyzer to examine the impact of particle size and size distribution on β. Effects of conditioning, elutriation, supernatant removal, and replacement on β were also studied.

In general, β correlated well with the average specific resistance, indicating that it could be useful in predicting a sludge filtration pattern. β was found to increase as the mean particle size of a sludge decreased, or the particle size distribution of a sludge widened. Conditioning, elutriation, supernatant removal, and replacement were found to reduce β by improving the mean particle size of a sludge and narrowing a sludge particle size distribution. In addition, β was found to increase by the applied pressure differential and filter media pore sizes for a few sludges.

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I. INTRODUCTION

One of the major problems associated with water and wastewater treatment is the handling and disposal of sludges. Many of the sludge handling and disposal problems stem from a poor understanding of sludge properties. This results in misapplication of dewatering processes and undue expense due to excessive use of conditioning chemicals and the handling of poorly dewatered sludges.

Currently, most treatment plants dewater sludges by one of several filtration processes. Recent studies (2, 4, 8) suggest that among several factors influencing sludge dewatering, filtration of a sludge may be affected by blinding of the sludge cake and filter medium. Blinding is the clogging of the pore openings in either the sludge cake or filter medium and is thought to be induced by several mechanisms. The most important blinding mechanism is the migration of fine particles through the sludge cake resulting in the eventual clogging of the available pore openings in either the sludge cake or the filter medium. Particle deformation and fragmentation are two other mechanisms thought to induce blinding.

The influence of blinding on the filtration of a sludge was ignored in the original development of sludge filtration theory (1). In recent years; however, a number of equations (2, 4, 5, 8) have been developed to account for the blinding effect on filtration. Among these, the equation developed by Huang (4) appears to be most promising. Huang modified the traditional sludge filtration equation and introduced a parameter commonly referred to as the "sludge blinding coefficient" or β to predict sludge blinding.

The goals of this study were to determine if the sludge blinding coefficient, β, could be a useful characterization parameter for a sludge and to determine why variations in β occur. It was suspected that the sludge particle size or size distribution might play a role in β; therefore, sludge particle size measurements were also conducted using an automated particle size analyzer. Finally, since it is not clear if blinding is a cake or a medium phenomenon, filter tests were performed using varing filter media sizes and a variety of sludges in an attempt to separate cake and media effects.

II. BACKGROUND

As stated previously, blinding is defined as the clogging of the available pore space in the sludge cake or the filter medium. Blinding is thought to be induced by three mechanisms. The most important mechanism is the migration of fine particles in a heterogeneous sludge through the sludge cake and the eventual blinding of either or both the medium and cake. The other two mechanisms of blinding are particle fragmentation and particle or floc deformation. Figure 1 shows the modes of the sludge cake blinding mechanisms as predicted by Huang (4).

The effect of blinding on sludge filtration has traditionally been ignored. The most common differential equation used to describe sludge filtration is expressed as follows:

$$\frac{dV}{dt} = \frac{\Delta P\ A}{u\ (R_c + R_m)} \qquad (1)$$

where:

V = Volume of filtrate in cubic centimeters;

t = Filtration time in seconds;

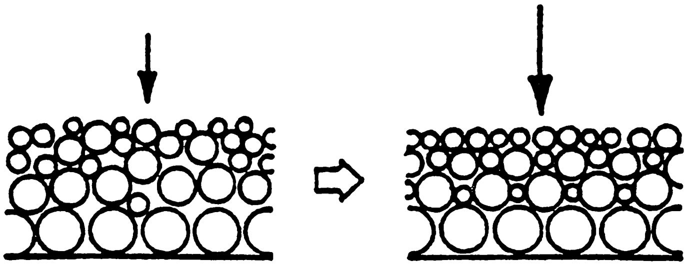
ΔP = Overall pressure drop across the sludge cake and filter medium in dynes per square centimeter;

A = Filtration area in square centimeters;

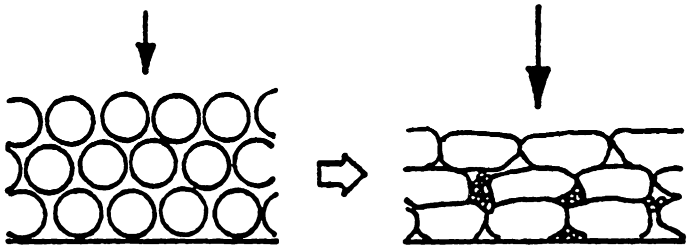
u = Filtrate viscosity in grams per centimeter per second;

R_c = Sludge cake resistance in centimeters^{-1}; and

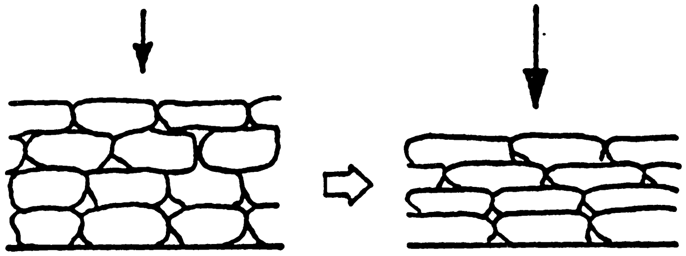
R_m = Filter medium resistance in centimeters^{-1}.



(1) Particle Rearrangement due to Sliding When Higher Vacuum or Pressure Applied



(2) Particle Fragmentation When Higher Vacuum or Pressure Applied



(3) Particle Deformation When Higher Vacuum or Pressure Applied

Figure 1 - MODES OF SLUDGE CAKE BLINDING MECHANISM

[After Huang (4)]

R_m, the medium resistance, is usually considered constant in this equation and is ignored. R_c, the cake resistance, is expressed as:

$$R_c = r\ w \qquad (2)$$

where:

r = Average specific resistance in centimeters per gram; and

w = Mass of dry solids per unit area of filter in grams per square centimeter.

It is difficult to measure w continuously and it is therefore usually expressed as:

$$w = \frac{c\ V}{A} \qquad (3)$$

where:

c = Mass of dry solids deposited per unit volume of filtrate collected in grams per cubic centimeter; and

V = Volume of filtrate in cubic centimeters.

Based on the above assumptions, Equation (1) can be written as:

$$\frac{dV}{dt} = \frac{\Delta P\ A^2}{u\ (r\ c\ V + R_m\ A)} \qquad (4)$$

This differential equation is solved by assuming that ΔP, the overall pressure differential across the sludge cake and filter medium, and r, the average specific sludge resistance, are constant. Based on these assumptions, the following equation is obtained from the integration of Equation (4):

$$\frac{t}{V} = \frac{u\ r\ c}{2\ \Delta P\ A^2}\ (V) \qquad (5)$$

Equation (5) is commonly used to characterize the filtering properties of a sludge using the single parameter, r, which is defined as the average specific resistance to cake filtration. A standard Buchner funnel test (9) is used to generate data to plot t/V versus V and generate a straight line with slope equal to ($u\ r\ c/2\ p\ A^2$) which is designated as b. Figure 2 shows a typical plot for the determination of b.

The average specific resistance then can be calculated as:

$$r = \frac{2\ b\ p\ A^2}{u\ c} \tag{6}$$

c, the weight of dry cake deposited per unit volume filtrate, is calculated as:

$$c = \frac{W_s - W_c}{100\ (W_c - W_s)} \tag{7}$$

where:

W_c = Final sludge cake solids (percent); and

W_s = Initial sludge solids concentration (percent).

Recent work on the nature of sludge filtration has shown that Equation (6) may only be applicable to non-blinding sludges. For a blinding sludge, the porosity of the sludge cake; hence, the specific resistance varies throughout the filtration process. This is evidenced by a curvelinear relationship between t/V and V, which is not predicted by Equation (5).

Notebaert, <u>et al</u>., (8) noticed the effect of blinding on sludge filtration and revised the traditional filtration equation to account for blinding effects on the average specific resistance. Their equation may be expressed as:

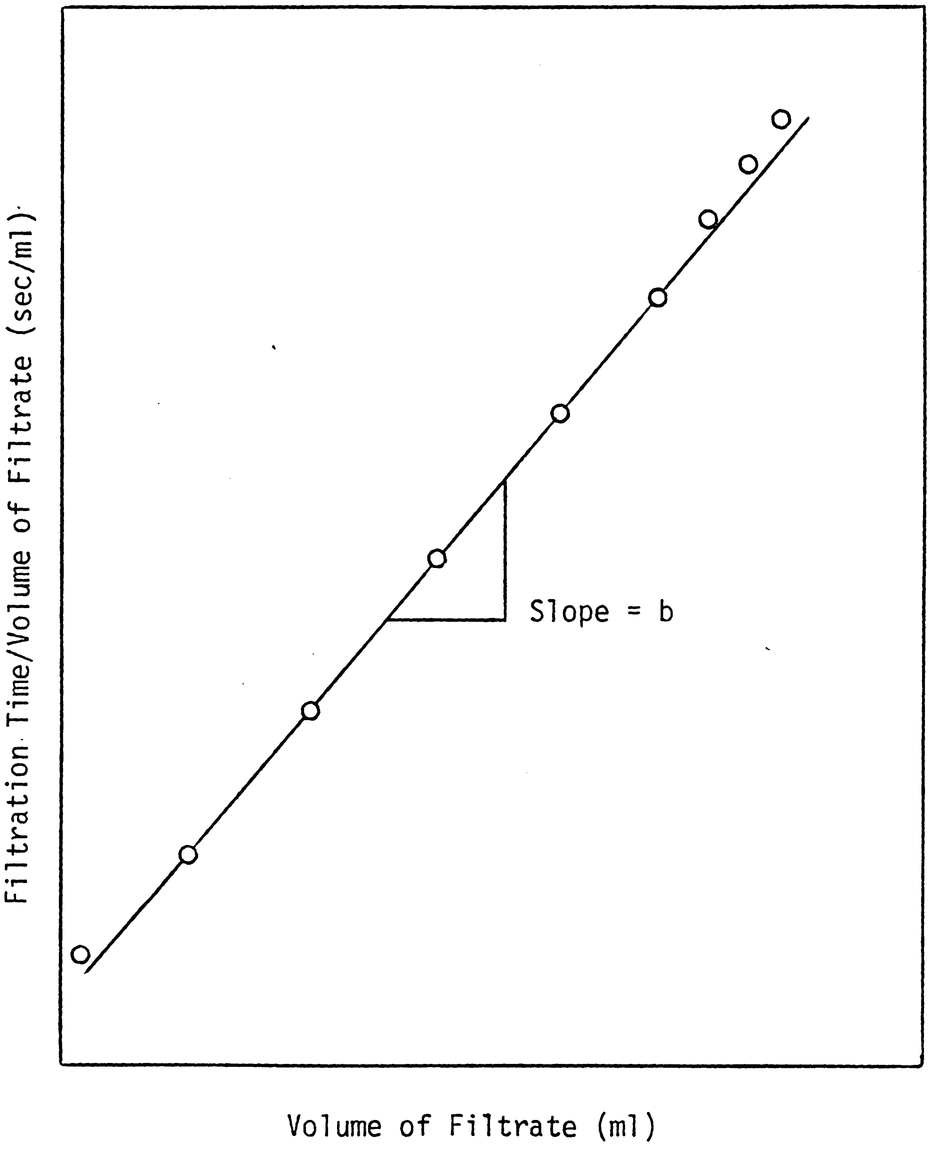


Figure 2 - Typical Data Plot Needed to Determine b.

$$t = \frac{u\ r\ c}{P(2 + X)\ A^{(2 + X)}}\ V^{(2 + X)} \qquad (8)$$

Where X is defined as a parameter indicating the correction of the exponent of V in the traditional filtration equation.

Equation (8) was used to estimate both filter medium and cake blinding as well as medium and cake resistance.

Notebaert, et al., argued that the traditional filtration equation is only applicable to a homogeneous sludge which is not subject to blinding. For a sludge with a heterogeneous structure of particles, the relationship between t/V and V appears to be curvelinear rather than linear as predicted by Equation (5). This variation from linearity was thought to be due to migration of fine particles within the sludge cake and filter medium and subsequent blinding of either or both the sludge cake and filter medium. The authors proposed that the medium will blind if the sludge is heterogeneous, containing small particles with a diameter equal to the diameter of the pores in the filter medium. When the fine particles are larger than the pores of the filter medium, blinding will only occur in the sludge cake. They argued that blinding of the filter medium is nearly independent of the applied pressure difference and the total resistance to filtration depends on the applied pressure difference only to a small extent. Therefore, the parameter, X, in Equation (8) is also independent of the applied pressure difference. Furthermore, they proposed that when (X + 2) is greater than 2, only sludge cake blinding may occur. When

(X + 2) is less than 2, only filter medium blinding may occur. Finally, when (X + 2) = 2, both medium and sludge cake blinding may occur.

Karr and Keinath (5) also demonstrated the influence of particle size distribution and blinding on filtration. The authors fractionized a sample of biological sludge into different particle size ranges and found that particle size distribution had a significant effect on sludge filtration. In studying the effect of the individual particle size fractions on sludge dewaterability, Karr and Keinath found that supracolloidal particles (size range from 1.2 to 104 microns) had the greatest effect on filtration. They attributed this observation to the ability of the supracolloidal particles to migrate throughout the sludge cake and filter medium and cause blinding. They also found that sludge particle rigidity had a significant effect on its dewaterability and that sludges with fragile particles were often difficult to dewater.

To predict blinding for a sludge they proposed a sludge blinding index which is calculated from the following equations:

$$BI = \left(\frac{r_1 - r_2}{r_2}\right)\left(\frac{c_2}{c_2 - c_1}\right)100 \qquad (9)$$

Where r_1 and r_2 are the specific resistances at two different solids concentrations, and c_1 and c_2 are the weight of dry solids deposited per unit volume of filtrate at those solids concentrations.

This index has a scale from zero to 100 percent. Zero percent indicates no blinding, while 100 percent indicates total blinding. The rationale for this designation was the assumption that for a non-blinding sludge the specific resistance is independent of the sludge solids concentration; therefore, the product $(r_1 - r_2)$ and the blinding index is equal to zero percent. For a blinding sludge on the other hand, the specific resistance is dependent on the solids concentration. For a completely blinded sludge, they argued that the product $(r_1 - r_2)/r_2$ and $c_2/(c_2 - c_1)$ become inverse of each other and cancel one another. This results in a blinding index equal to 100 percent.

Huang (4) also studied the effect of blinding on sludge filterability, and in an attempt to account for blinding during filtration, he proposed the following equation:

$$r = a\, V^{\beta} \tag{10}$$

By substituting Equation (10) into Equation (4) and neglecting the medium resistance, he obtained the following equation:

$$t = \frac{a\, u\, c}{(\beta + 2)\Delta P\, A^2}\, V^{(\beta + 2)} \tag{11}$$

Taking the natural logarithm of both sides of Equation (11) results in the expression:

$$\ln t = (\beta + 2) \ln V + \ln \frac{a\, u\, c}{(\beta + 2)\Delta P\, A^2} \tag{12}$$

A plot of ln t versus ln V generates a straight line with slope equal to $(\beta + 2)$ and an intercept equal to $\ln (a\, u\, c/(\beta + 2)\Delta P\, A^2)$; therefore, experimental results from a Buchner Funnel test can be used to determine the constants a and β. Figure 3 presents a typical plot of ln t versus ln V.

Huang (4) defined "a" as "the average specific resistance over the

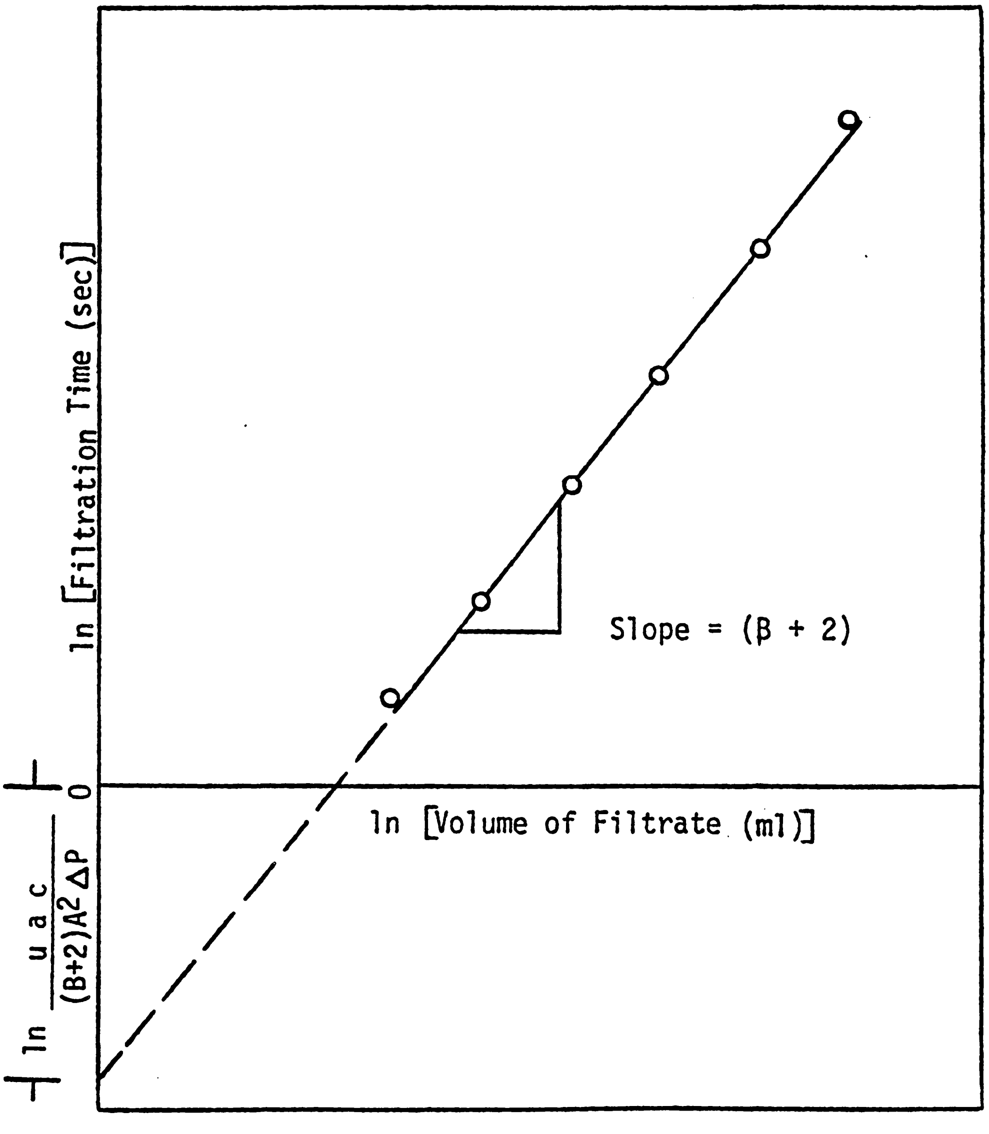


Figure 3 - Typical Data Plot Needed to Determine a and β.

cake thickness formed when the initial unit volume of filtrate is collected". He defined β as "the resistance to filtration in the cake as the filtration process proceeds". Furthermore, he proposed that when β is greater than zero, it implies that blinding has occurred in the sludge cake and/or filter medium. If β is less than zero, the implication is that blinding has not occurred. If β is equal to zero, it implies that an idealized incompressible sludge cake has been developed during the filtration process. If $\beta = -1$, it implies that the sludge cake offers no resistance to filtration. Any β value less than -1 is mathmatically impossible to obtain; hence, -1 is the lower bound of β. Huang stated that when blinding develops, the average specific resistance increases as filtration proceeds. On the other hand, for a non-blinding sludge, the average specific resistance decreases as filtration proceeds.

Work by Knocke, et al., (6), Knocke and Wakeland (7) and Goodman (2) have also shown the significance of particle size or size distribution on sludge filtration. These studies all show that particle size is more critical in the smaller size range and does not have as significant effect on filtration at higher particle size ranges. Goodman also found that as the average specific resistance increases, the sludge blinding coefficient also increases, indicating a correlation between the two parameters. The overall effect of particle size on the average specific resistance is predicted by the Kozeny equation:

$$r = \frac{36\ K\ (1 - e)}{e^3\ (\rho_p)\ (d_e)^2} \qquad (13)$$

where:

k = Kozeny particle shape factor;

e = Sludge porosity;

ρ_p = Sludge floc density in grams per cubic centimeter; and

d_e = Effective diameter (diameter of a sphere that has the same surface to volume ratio as that of a mixture of particles) in centimeters.

Equation (13) was derived by Gale (1) for flow through a non-compressible sludge cake, but was shown to be also applicable to compressible cakes. This equation shows that the relative particle size and cake porosity both affect the average specific resistance and thus sludge dewaterability. The average specific resistance increases as the particle size decreases and the porosity is reduced.

In summary, these studies suggest that blinding can significantly influence the filtration of a sludge. Therefore, to improve sludge filtration, it is essential to understand how sludge blinding occurs. One parameter that is suggested as a way to characterize blinding is the sludge blinding coefficient or β. Thus, the main objective of this study was to reevaluate β and determine if indeed β indicates sludge blinding and if so can it be used as a sludge characterization parameter.

III. METHODS AND MATERIALS

Sludge Source and Storage

This study involved the use of activated sludge, primary sludge, alum sludge, and a calcium carbonate slurry. The activated sludge and primary sludge samples were collected from the (Town of Blacksburg wastewater treatment plant). The plant consists of primary settling followed by completely mixed activated sludge process. Activated sludge and primary sludge samples were withdrawn from the waste return and sludge waste lines, respectively. Tests were performed within hours of the sample procurement on the fresh sludges and then both sludges were stored at room temperature for periodical analysis.

The alum sludge which was used was originally collected from the (Town of Blacksburg water treatment plant) and then stored at room temperature for a few years to become septic.

The calcium carbonate slurry was prepared in the laboratory using calcium hydroxide. The calcium carbonate slurry pH was approximately 11.8.

The effects of mixing, supernatant removal and replacement by tap water, elutriation, and conditioning on β were all studied. Supernatant was removed and/or replaced after allowing sufficient settling of the sludge solids in a glass beaker. Elutriation was accomplished by repeated replacement of the sludge supernatant. Alum sludge and the stored activated sludge were mixed with the calcium carbonate slurry in various proportions, then tested. Finally, Betz 1195 polymer was used to condition the storage activated sludge and primary sludge.

Specific Resistance and Blinding Tests

A standard Buchner Funnel apparatus with a 7 centimeter funnel was used for the specific resistance and blinding coefficient determinations. Figure 4 shows a standard Buchner funnel apparatus. Filter papers consisted of Whatman Qualitative 4 (pore opening 20 - 25 microns), Whatman Qualitative 1 (pore opening 11 microns), Whatman Qualitative 2 (pore opening 8 microns), and Whatman 42 Ashless (pore opening 2.5 microns). At the start of each test, distilled water was filtered through the filter paper to secure the filter to the funnel and also moisten the filter, funnel, and graduated cylinder to minimize experimental errors. Samples were mostly prepared in 100 ml aliquots from a well mixed sludge. Timing was initiated as soon as the desired vacuum was applied. A reading and recording of the filtrate volume was completed at 10 second intervals for the duration of each dewatering. The test duration depended on the filtration rate and varied for the different sludges. East test was normally stopped when it was felt that sufficient readings have been taken to characterize the sludge involved. The initial solids concentration and sludge cake solids concentration were determined by oven drying for each sludge. To determine filter cake solids concentration, filtration was continued until the cake started cracking.

Pressure levels used in this study ranged from 10 to 25 inch mercury. Normally two to three tests were completed for each sludge to allow for an estimate of experimental error.

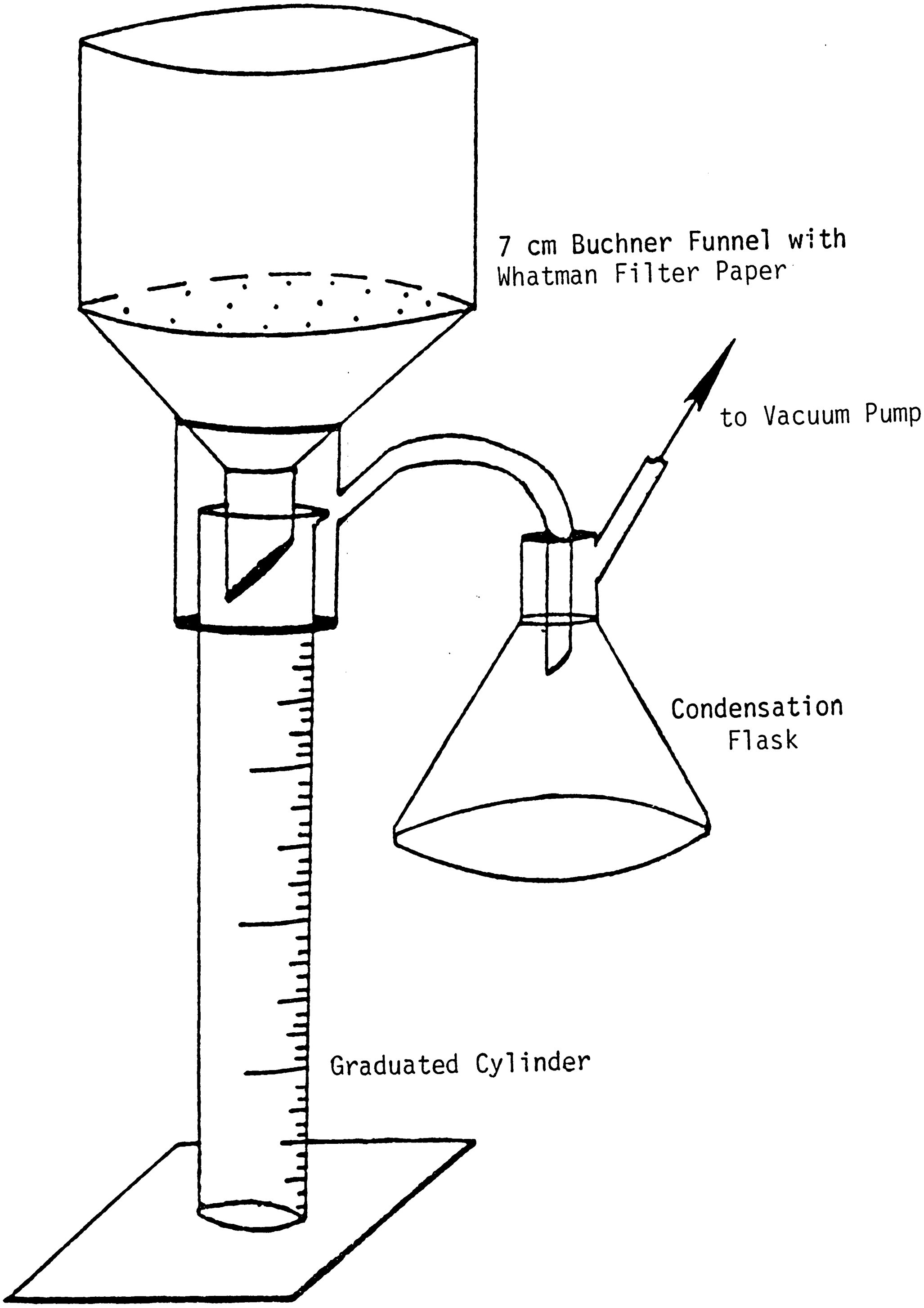


Figure 4 - Buchner Funnel Apparatus

Particle Counts

Particle counts were measured with a HIAC PC-320 12 Channel particle counter (3) employing a 5 to 300 micron sensor. This apparatus works on the light blockage principle, measuring the projected area of a particle as the particle passes through the sensor. The area is then converted electrically to an equivalent spherical diameter (a sphere with the same projected area as the particle). Electric circuitry is used to count the number of particles within a given size range preset on the counter.

The samples of sludge for particle counts were prepared by dilution with tap water to a concentration accurately detectable by the counter. High concentration of particles in the samples were avoided to minimize shading effects. Also the flow rate through the sensor was maintained at the manufacturer's recommended valves to minimize coincidence problems. A 200 ml beaker was filled with the diluted sample and placed into the sample port. A magnetic stirrer was used to keep the sample agitating gently.

The counter was set to count 10 or 15 ml samples. Two to three measurements were made for each sample to insure accuracy. Particle counts were performed on the dilution water as well and deducted from the diluted sample particle counts. Primary sludge samples after dilution were screened with a 200 micron sieve to remove larger particles and prevent the sensor from clogging. Table 1 presents the particle size ranges investigated in this study.

Table 1 - Particle Size Range Studied Using the HIAC-320 Particle Counter

Channel	Particle Size Range (microns)	Particle Surface Area (10^{-10} m^2)
1	5 - 10	1.767
2	10 - 15	4.909
3	15 - 20	9.621
4	20 - 25	15.904
5	25 - 30	23.758
6	30 - 40	38.485
7	40 - 50	63.617
8	50 - 60	95.033
9	60 - 70	132.732
10	70 - 80	176.715
11	80 - 90	226.980
12	90 - 170	530.929

IV. RESULTS AND DISCUSSION

Nature of the Sludge Blinding Coefficient

According to Huang (4) the sludge blinding coefficient, β, determines if blinding, thought to be caused by the migration of fines into the pores of sludge cakes, will be a factor in the filtration of a sludge. A positive β value indicates a blinding sludge, while a negative β value corresponds to a non-blinding sludge. A β value equal to zero may indicate an incompressible sludge.

Another characteristic of a blinding sludge that has been observed is that a plot of t/V versus V results in a curved rather than a straight line. For example, in Figure 5 data are presented for three sludges, one with a positive β value and two with negative β values. It can be seen that when β is positive, the plot of t/V versus V is curved, while for the sludges with negative β values the same plots are linear. Figure 5 also shows that b and therefore the average specific resistance increases as β increases. To illustrate the relationship between the average specific resistance and β, Figure 6 is presented. The data points for Figure 6 were obtained from an activated sludge that was permitted to become septic. As the sludge aged, the average specific resistance increased and β went from negative to positive. The average specific resistance was determined from Equation (6) and the b values were obtained from Figure 5. The b value for the blinding sludge in Figure 5 was determined from the latter part of the

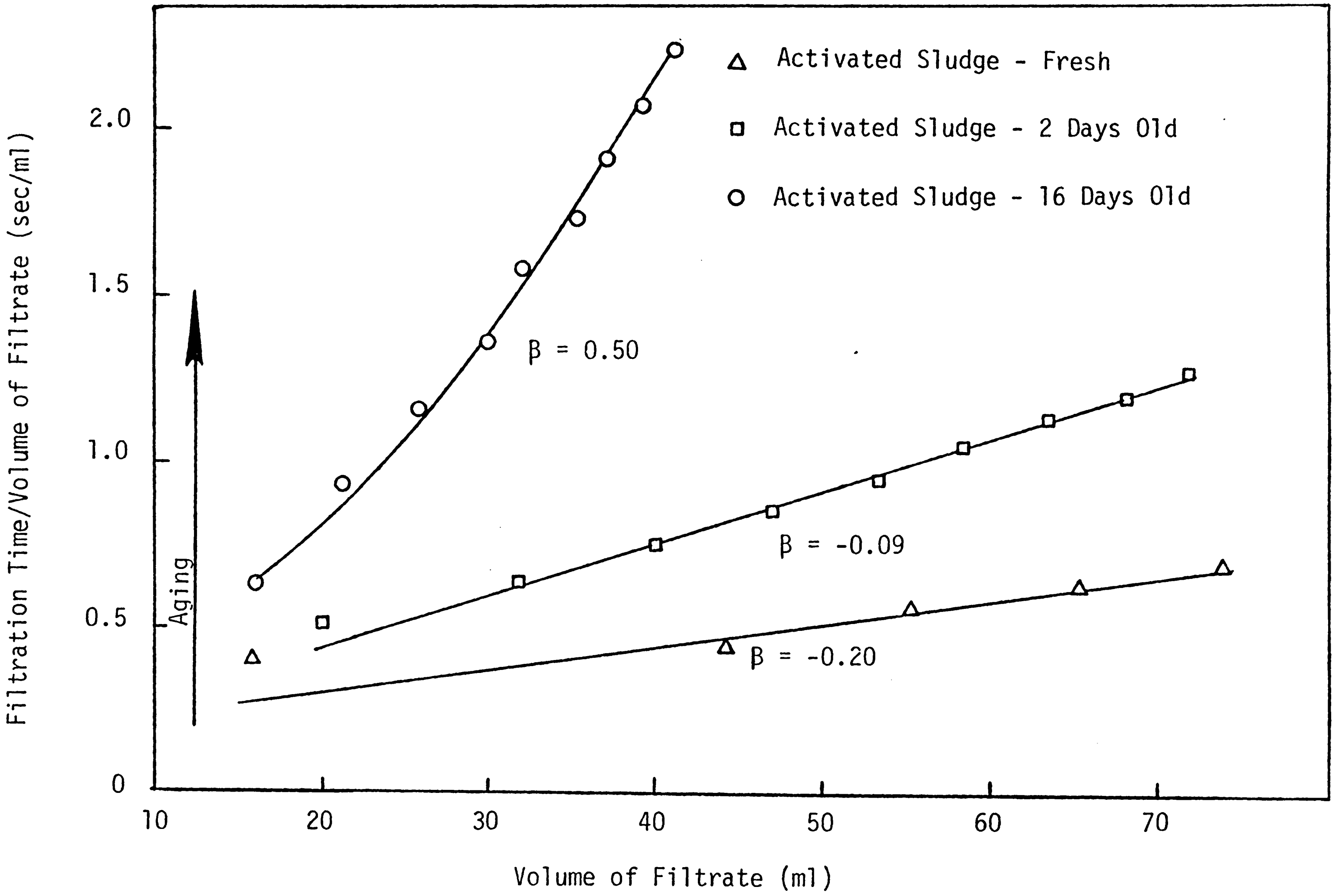


Figure 5 - Variations in the Plot of t/V Versus V for an Activated Sludge as it Ages.

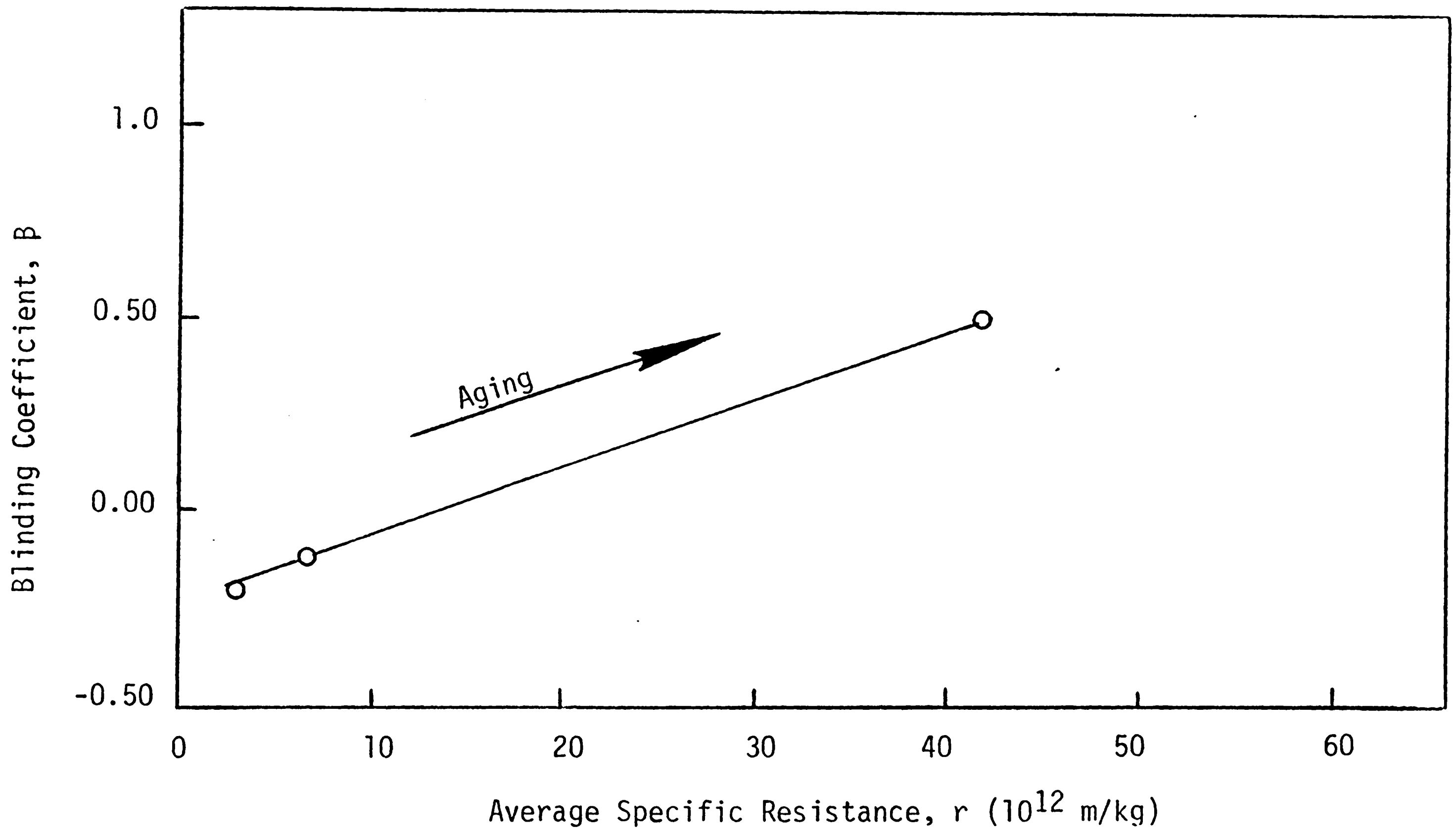


Figure 6 - Plot of the Blinding Coefficient Versus the Average Specific Resistance for an Activated Sludge as it Ages.

curve to minimize medium effects. Figure 6 indicates that a relationship may exist between the average specific resistance and β. It can be seen that as the average specific resistance increases, β goes from negative to positive.

To further investigate the relationship between the average specific resistance and β, additional data for r and β were obtained for a variety of sludges. A plot of these data are shown in Figure 7. It can be seen that the relationship between the average specific resistance and β also holds for a mixture of sludge. While this relationship is not linear as suggested in Figure 6, it is well defined for this mixture of chemical and biological sludges. This observation is in agreement with the findings of Goodman (2) that the average specific resistance increases as β increases.

Both Figures 6 and 7 show that blinding may occur when the average specific resistance value of 1.0×10^{13} m/kg is exceeded. This value is close to the values where most blinding cases were experienced in this study and also is close to the value reported by Goodman (2) to cause blinding.

In his definition of β, Huang (4) stated that when β is positive, the average specific resistance increases as the filtration operation proceeds, while when β is negative the average specific resistance decreases as the filtration operation proceeds.

Figure 5 shows that for a blinding sludge, the value of b and therefore, the average specific resistance, increases as the filtration operation continues. However, for the non-blinding sludge, no

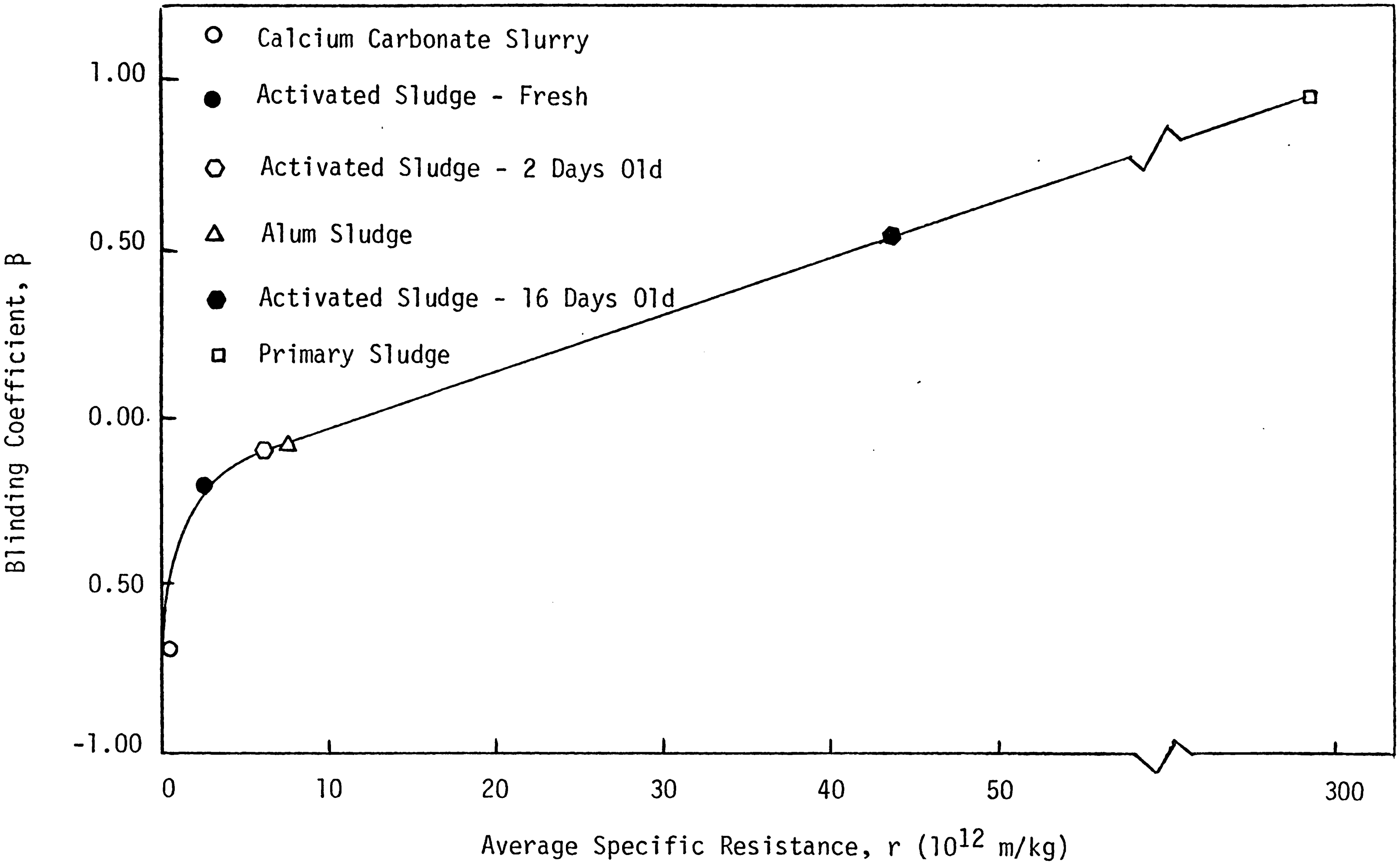


Figure 7 - Plot of the Blinding Coefficient Versus the Average Specific Resistance for the Sludges Shown.

significant change is noticed in b. Figure 8 presents the average specific resistance distribution for a blinding and two non-blinding sludges as the filtration operation proceeds. This figure was prepared using a and β values from the plot of ln t versus ln V and Equation (10). As expected, the average specific resistance increases for the blinding sludge and decreases for the non-blinding sludges. The rate of variation in the average specific resistance depends on β; therefore, for the larger (absolute) values of β, the change in the average specific resistance with the filtrate volume is greatest.

Huang (4) stated that a blinding coefficient of zero corresponds to an incompressible sludge. Sludge compressibility is normally quantified by performing several average specific resistance measurements at different pressure levels and then plotting the natural logarithm of the resistance versus the natural logarithm of the pressure. The slope of the resultant plot is equal to the sludge coefficient of compressibility or "S". A "S" value near zero indicates an incompressible sludge.

Figure 9 presents the plot of ln r versus ln p for an alum sludge with a blinding coefficient approximately equal to zero. As can be seen, this figure does not show an incompressible sludge. When β is near zero, two possibilities exist. First, as Huang proposed, the sludge may be incompressible as sketched in Figure 1. Alternatively, if each layer of the filter cake are compressed in a similar fashion blinding may not develop, although compressibility may occur because

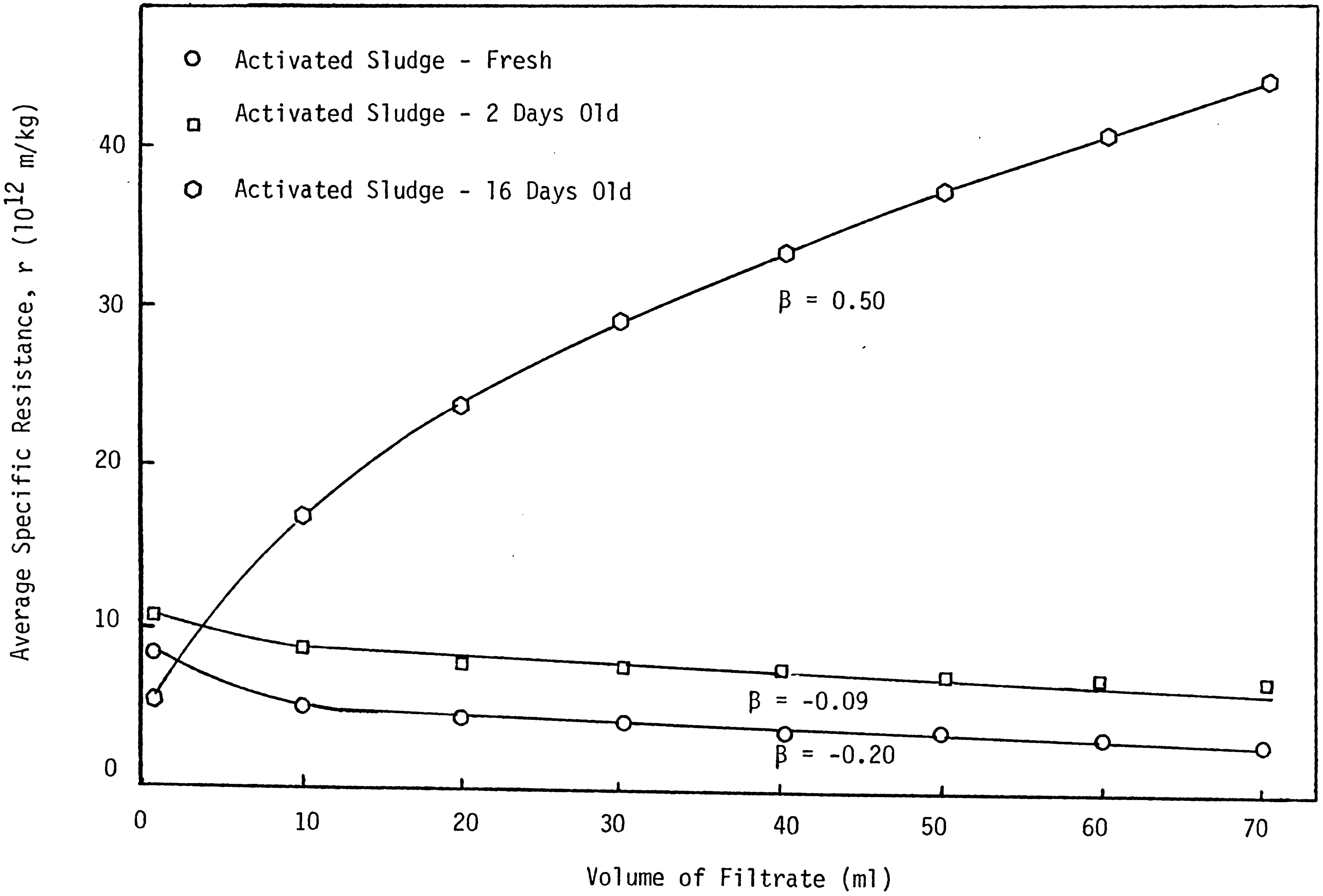


Figure 8 - Distribution of the Average Specific Resistance in Filter Cake.

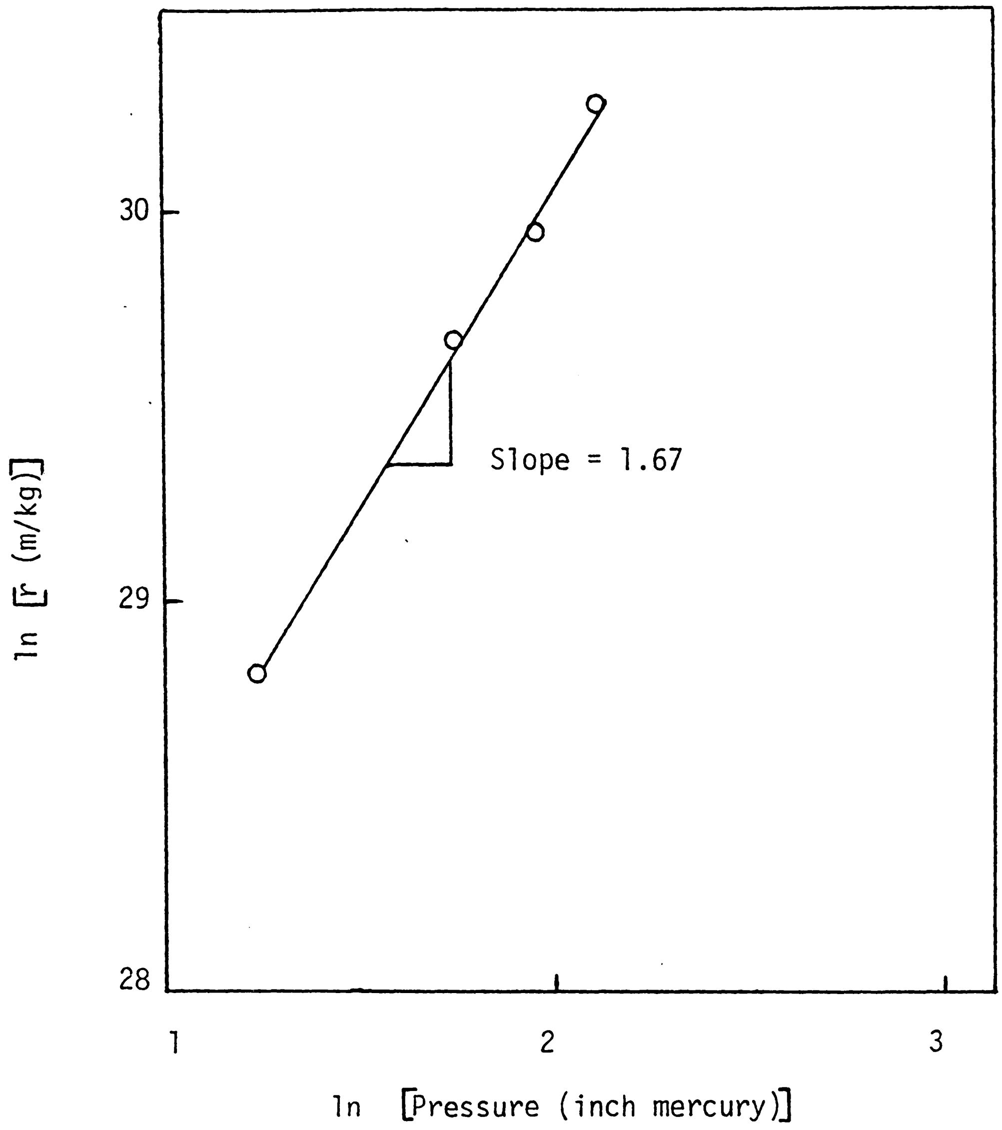


Figure 9 - Plot of the ln r Versus the ln P for an Alum Sludge with $\beta = 0$.

particle migration does not occur. Therefore, nothing appears to be unique about a β value at or near zero and it would be expected that most sludges would be compressible to some degree no matter what value of β was measured.

Particle Size and Sludge Blinding Coefficient

Particle size is believed to have a major effect on the average specific resistance. According to the Kozeny equation and as verified by Knocke, et al., (6) and others, it has been shown that the average specific resistance increases as the mean particle size decreases. In order to show the effect of particle size on the average specific resistance and β, Table 2 is provided. The data for this table were generated using Whatman Qualitative 2 filters and 20-inch mercury vacuum to conduct the Buchner Funnel tests. Equation (6) was used to determine the average specific resistance.

Table 2 shows that a relationship between the mean particle size on the basis of surface area, average specific resistance and blinding coefficient may exist for sludges of a similar nature. For example, Figure 10 shows that as the mean particle size of activated sludge decreases, the average specific resistance and β increases. However, when sludges of a dissimilar nature are involved, a consistent relationship between the mean particle size and average specific resistance is not evident. Table 2 shows that alum sludge has a larger mean particle size than the calcium carbonate slurry; however, the average

Table 2 - Particle Size Effects on the Average Specific Resistance and Blinding Coefficient

Sludge Type	Mean Particle Size (microns)	r (m/kg)	β
Activated - Fresh 6/11/84	39	2.81×10^{12}	-0.20
Activated - Stored 7 Days	36.5	2.57×10^{13}	0.33
Activated - Stored 16 Days	36	4.16×10^{13}	0.50
Primary	20	2.65×10^{14}	1.0
Alum	15	7.88×10^{12}	-0.09
Calcium Carbonate	9.5	4.87×10^{10}	-0.67
Mixture Activated and Calcium Car.	64	7.23×10^{10}	-0.55

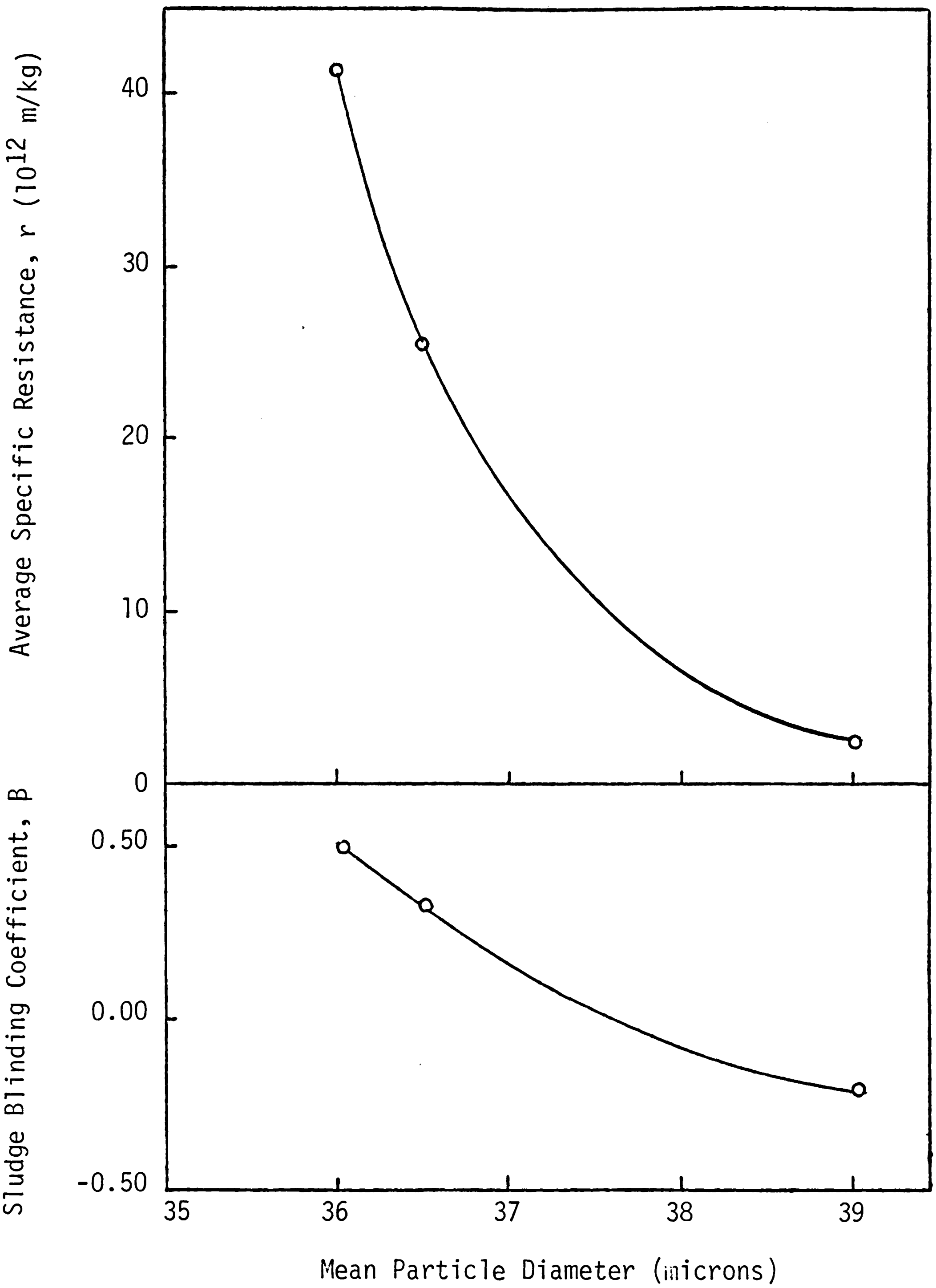


Figure 10 - Effect of the Mean Particle Size on the Average Specific Resistance and Sludge Blinding Coefficient for an Activated Sludge as it Ages.

specific resistance and blinding coefficient for alum sludge is also larger than those for the calcium carbonate slurry. Table 2 also shows shows that the blinding coefficient consistently follows the average specific resistance.

Most literature sources reviewed had dealt only with the effect of particle size on the filtration of the same or similar sludges. As stated previously, the average specific resistance appears to decrease as the particle size increases, but only for the sludges of a similar nature. When a variety of sludges are involved, filtration characteristics should not be compared based only on the particle size of the sludges. Other properties of the sludge such as sludge floc density, floc compressibility, floc regidity, blinding, and sludge particle size distribution may also need to be considered (7).

Particle Size Distribution and Sludge Blinding Coefficient

Because the particle size distribution was thought to play a more important role in sludge filtration than has previously been reported, this parameter was investigated more closely. In particular, it was thought possible that small particles in a heterogeneous sludge could penetrate the sludge cake and filter medium and eventually blind them. On the other hand, in a homogeneous sludge (one with nearly uniform-sized particles) the uniformity of the sludge particles may preclude migration of particles and thus minimize the opportunity for blinding to occur. This could explain the difference between alum sludge and the calcium carbonate slurry.

In order to study the effect of particle size distribution on blinding and the sludge blinding coefficient, particle counts were performed on some of the sludges. Figures 11 and 12 present the particle size distribution and relative size fraction on the basis of surface area for these sludges. Table 3 shows the mean particle size, the ratio of the 90 percent diameter to 50 percent diameter (D_{90}/D_{50}), average specific resistance, and blinding coefficient for the sludges shown in Figures 11 and 12. The ratio of (D_{90}/D_{50}) was chosen to indicate the uniformity of the sludges. The filter tests were all conducted at 20-inch mercury vacuum except for the activated sludge collected on April 2, 1984, which used a 25-inch mercury vacuum. All filters used were Whatman Qualitative 2 filters except that Whatman Qualitative 4 filters were used for the 4 and 10 days old activated sludge collected on April 2, 1984. The sludge collected on April 2, 1984 were characterized during the initial phase of this study before the pressure and filter media were standardized.

Data presented in Figures 11 and 12 and in Table 3 generally indicate a wider distribution of particles for the difficult to dewater sludges only when comparing sludges of similar nature. For example, particle distribution for both activated sludges collected on April 2 and June 11, 1984 widens as the sludge ages. Thus, the belief that heterogeneous sludges with small particles are more subject to blinding may be valid when comparing identical sludges. It can be seen

Table 3 - Influence of Particle Size Distribution on the Average Specific Resistance and Blinding Coefficient

Sludge Type	Mean Particle Diameter (microns)	D_{90}/D_{50}	r (m/kg)	β
Act. - 1 Day Old - 4/2/84	30	2.43	1.33×10^{13}	0.0
Act. - 4 Days Old - 4/2/84	28	2.54	2.51×10^{13}	0.33
Act. - Fresh 6/11/84	39	2.10	2.8×10^{12}	-0.20
Act. - 7 Days Old - 6/11/84	36.5	2.30	2.57×10^{13}	0.33
Act. - 16 Days Old - 6/11/84	36	2.33	4.61×10^{13}	0.50
Alum	15	3.87	7.88×10^{12}	-0.09
Cal. Carbonate	9.5	2.11	4.87×10^{10}	-0.67
Primary	20	1.95	2.65×10^{14}	1.0

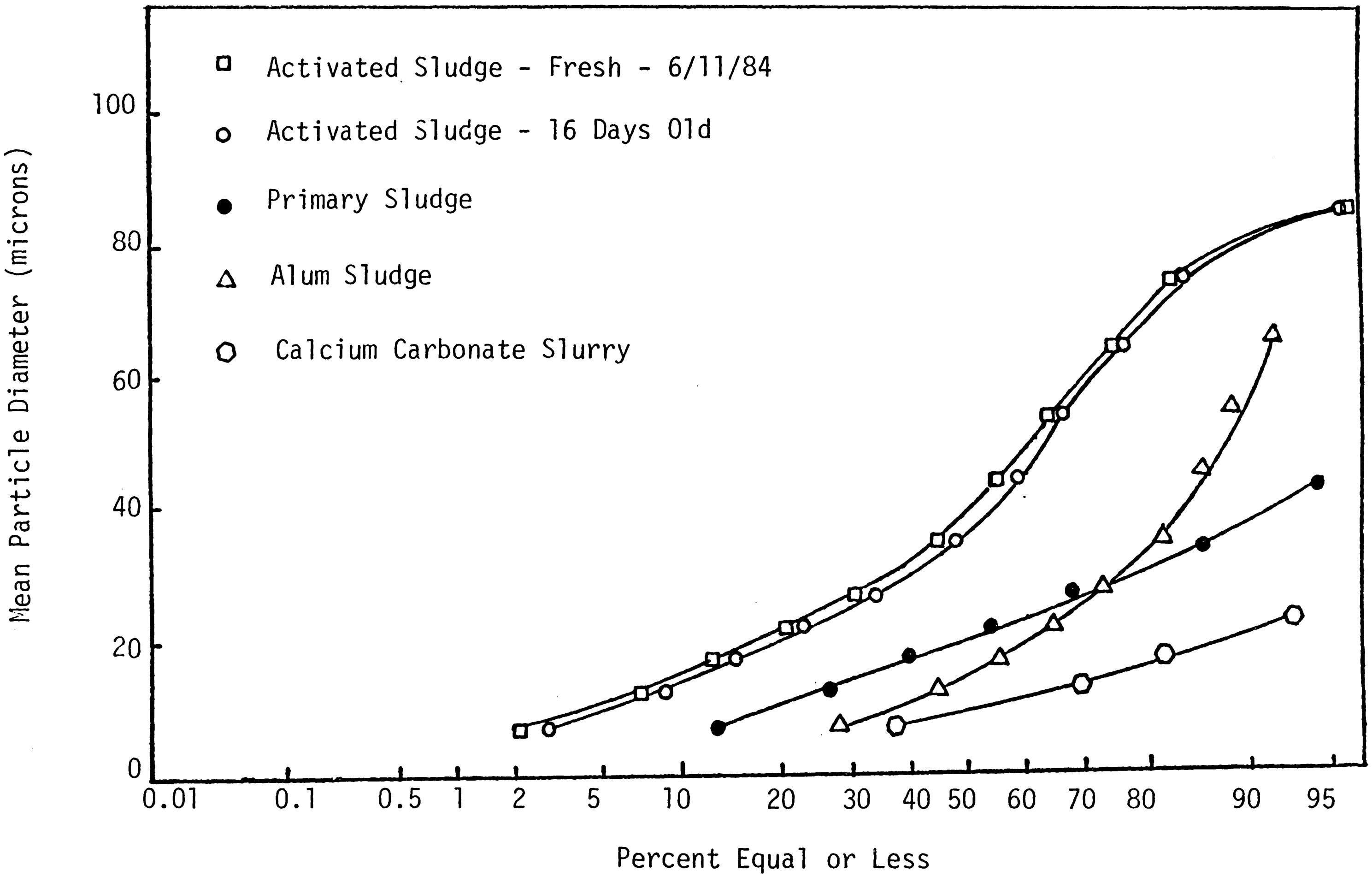


Figure 11 - Particle Size Distribution of Several Sludges Studied.

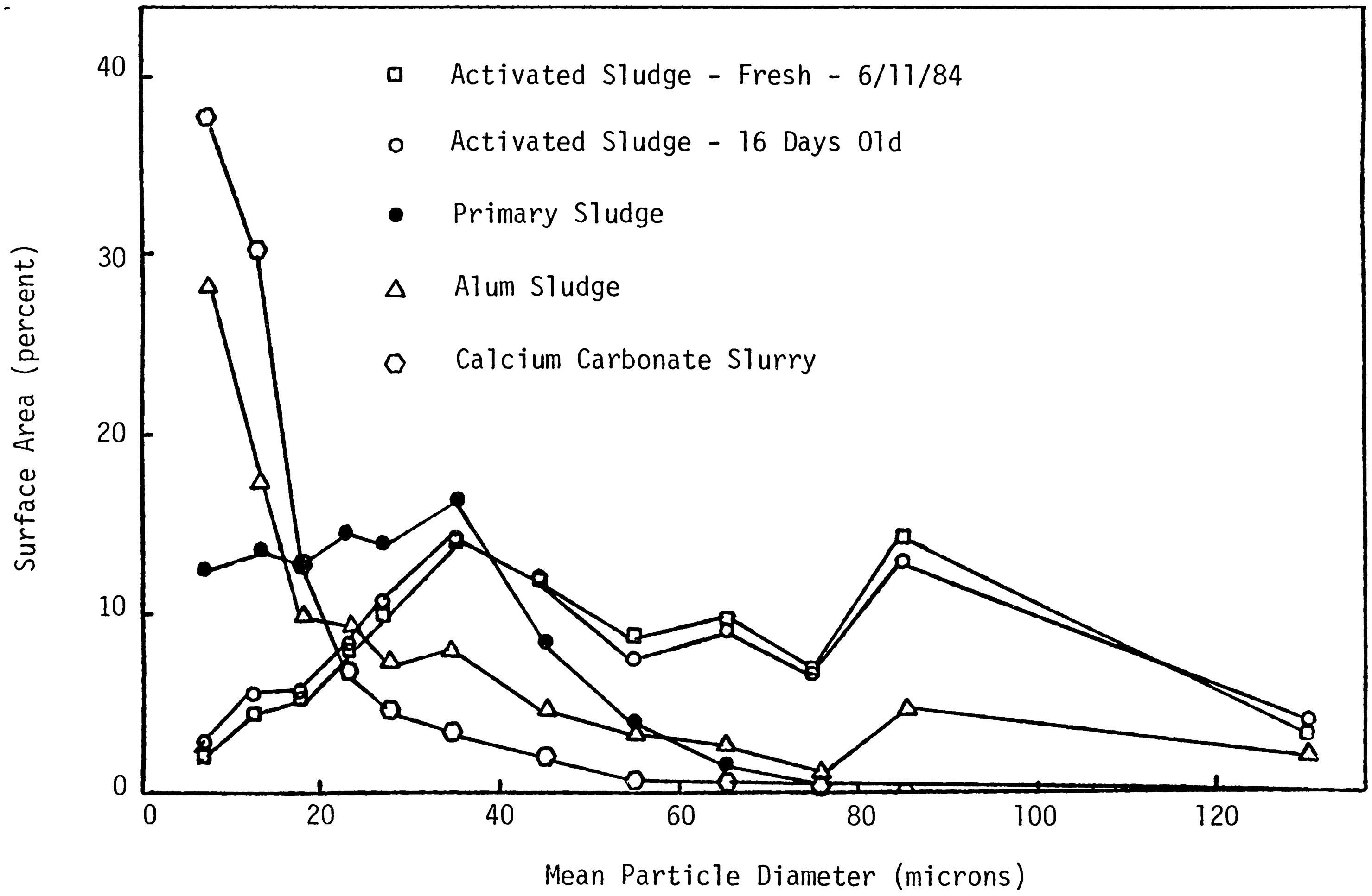


Figure 12 - Relative Fraction of the Particle Surface Area for Several Sludges Studied.

from Table 3 that the sludge average specific resistance and blinding coefficient follows the (D_{90}/D_{50}) ratio when sludges of the similar nature are involved. For instance, data in Figure 13 shows that the average specific resistance and blinding coefficient increase as the (D_{90}/D_{50}) ratio increases for the activated sludge collected on June 11, 1984 as this sludge ages. The average specific resistance and blinding coefficient for the activated sludge collected on April 2, 1984 also increases as the (D_{90}/D_{50}) ratio increases.

To minimize the effects of other factors influencing filtration, and just to concentrate on the effect of particle size distribution, activated sludges of the same origin were compared. Figures 14 and 15 show the particle size distribution and relative size fraction for the selected sludges. These figures show that as the sludge ages the fraction of small particles increases. This change is small and results in a more heterogeneous sludge which is harder to dewater.

Figure 16 presents a plot of β versus the (D_{90}/D_{50}) radio for the sludges studied in this section. The sludges are grouped to reflect differences in either the parent sludge or the mean particle size. This figure indicates that blinding is induced as the (D_{90}/D_{50}) ratio increases. Again the use of (D_{90}/D_{50}) ratio should be limited to similar sludges to be objective because as sludge filtration may also be affected by other factors such as sludge compressibility, density, particle shape, particle fragility, and sludge solids concentration. However, the data supports the concept of particle size distribution being influencial in filtration of identical sludges.

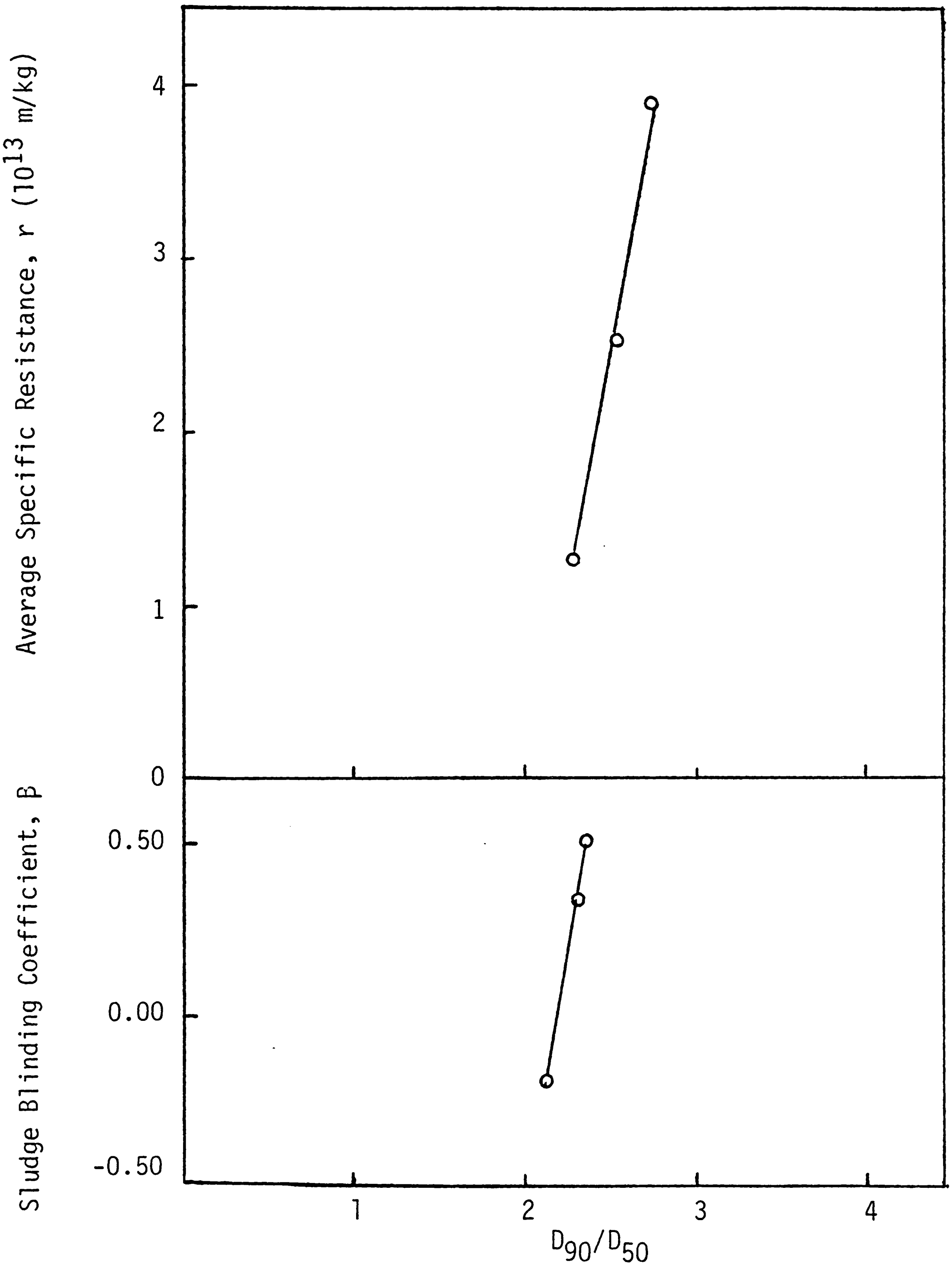


Figure 13 - Plot of the Average Specific Resistance and Blinding Coefficient Versus (D_{90}/D_{50}) Ratio for an Activated Sludge as it Ages.

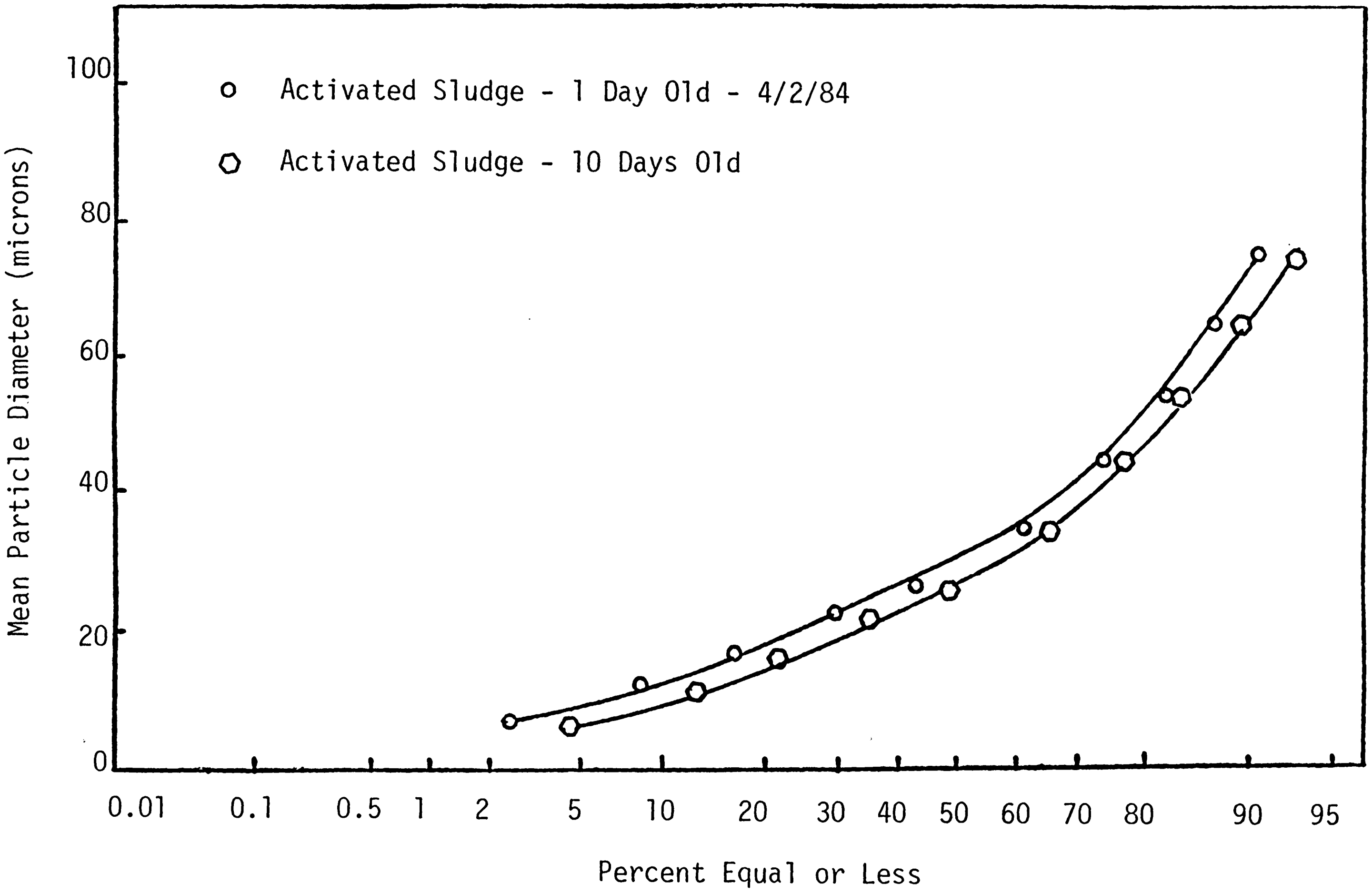


Figure 14 - Variations in the Particle Size Distribution for an Activated Sludge as it Ages.

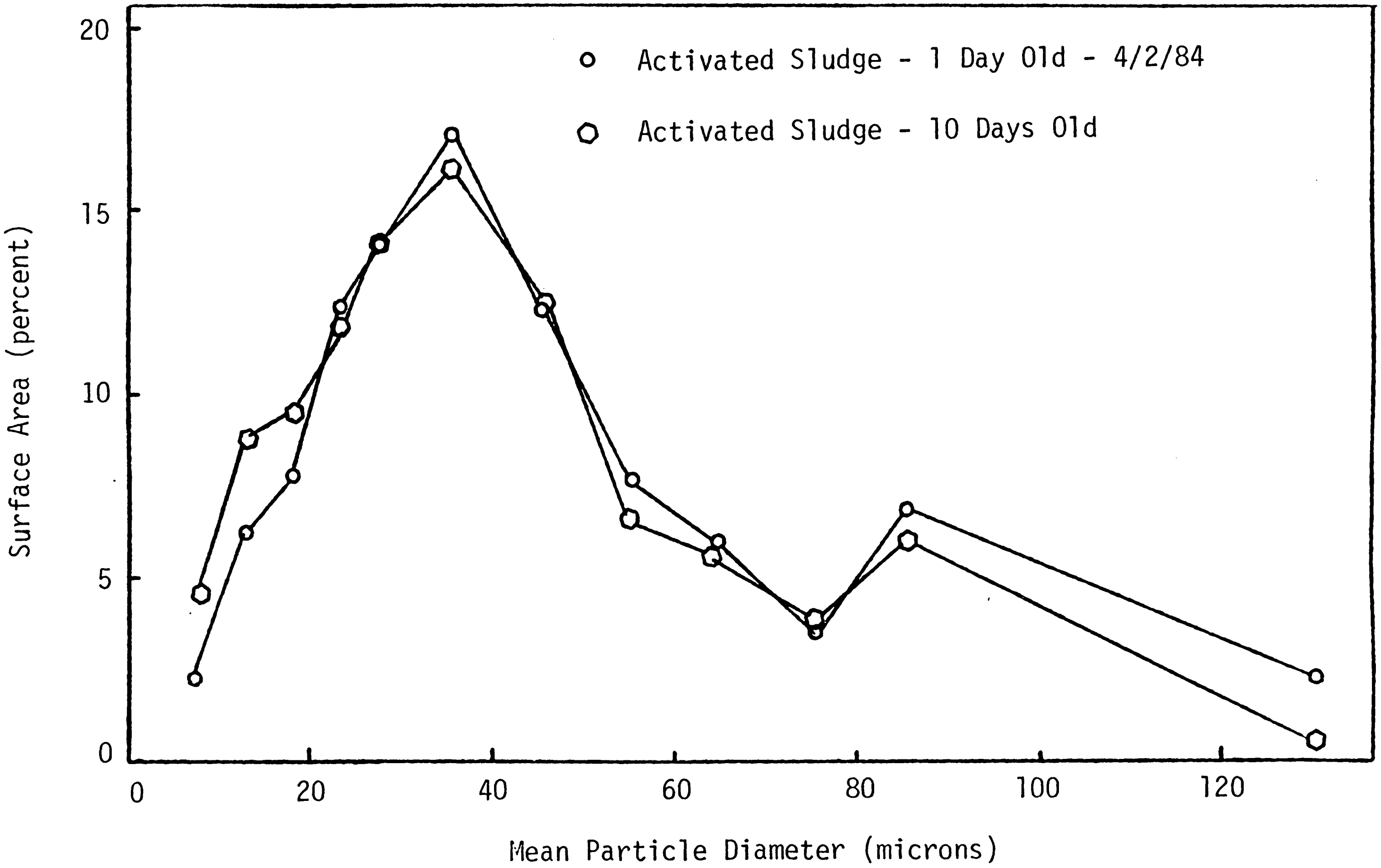


Figure 15 - Variations in the Particle Size Fraction for an Activated Sludge as it Ages.

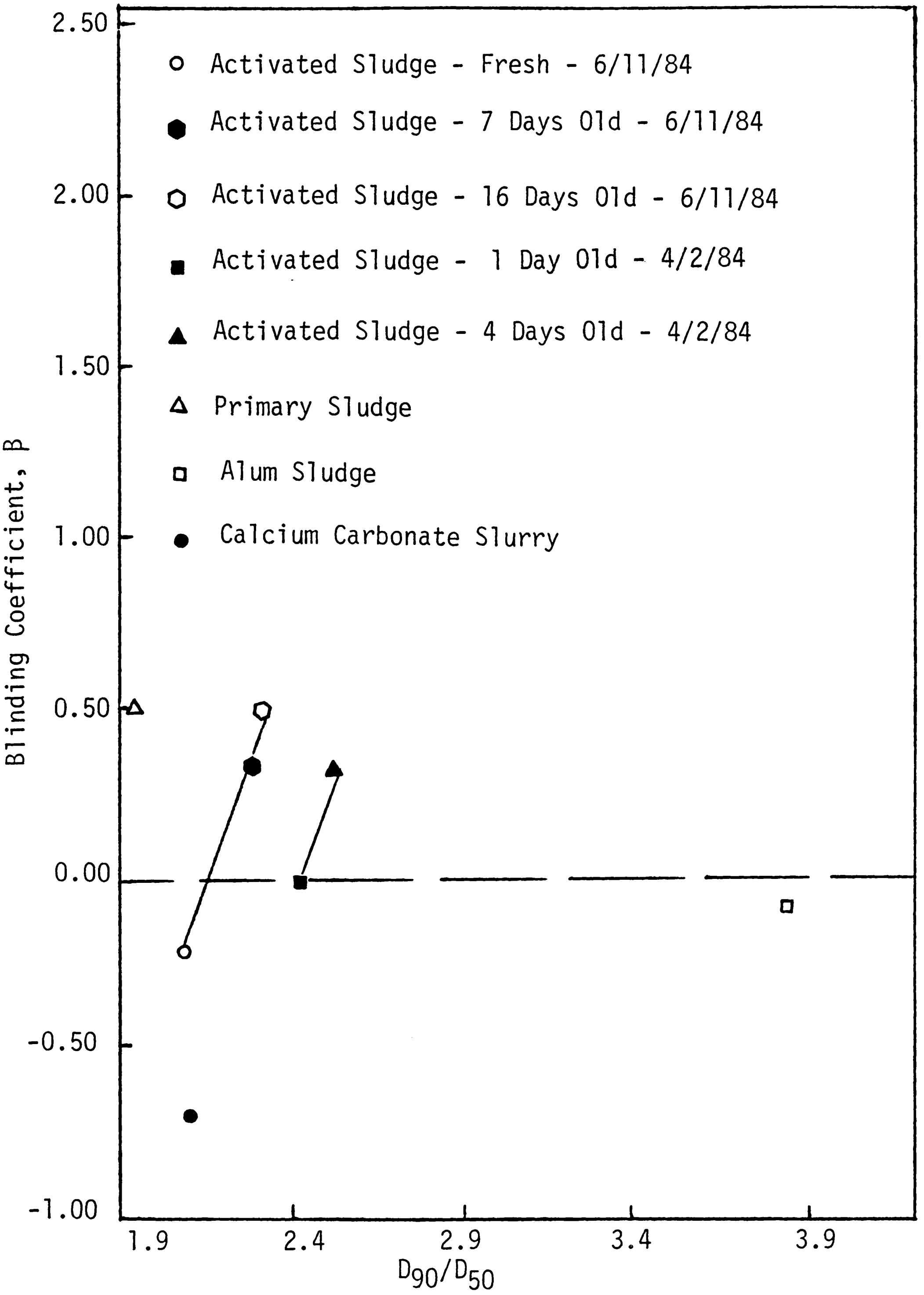


Figure 16 - Plot of the Blinding Coefficient Versus the (D_{90}/D_{50}) Ratio for Several Sludges Studied.

Pressure and Sludge Blinding Coefficient

Both Notebaert, et al., (8) and Goodman (2) indicated that pressure has little to no effect on the sludge blinding coefficient. However, data from this study suggests that changes in pressure may influence the blinding properties of compressible and fragile sludges. In Table 4 some of the data generated at various pressure levels are presented. The alum and 4 days old activated sludge in this table were tested using Whatman Qualitative 4 filters. The remainder of the tests were conducted using Whatman Qualitative 2 filters.

The data presented in the Table 4 do not show any significant changes in the average specific resistance and blinding coefficient when the applied pressure level changes except for the aged activated sludges. Both the average specific resistance and blinding coefficient increase as the applied pressure level increases for the aged activated sludges. The increase in the average specific resistance and blinding coefficient due to an increase in the pressure level, may be due to several factors. One possibility is that as more fines are produced due to aging, increased pressure can force these fines into pores, thereby increasing blinding. Another possibility is that floc particles become more fragile as they age. Further study will be needed to precisely define these effects.

Figure 17 presents the plot of the blinding coefficient versus applied pressure for the data presented in Table 4. Again, it can be seen that except for the aged activated sludges, pressure has little

Table 4 - Influence of Pressure on the Average Specific Resistance and Blinding Coefficient

	Pressure Differential (in. Hg)							
	10		15		20		25	
Sludge Type	r (m/kg)	β	r (m/kg)	β	r (m/kg)	β	r (m/kg)	β
Act. - Fresh 6/11/84	1.51×10^{12}	-0.11	2.11×10^{12}	-0.19	2.61×10^{12}	-0.20	4.01×10^{12}	-0.14
Act. - 7 Days Old - 6/11/84	7.02×10^{12}	-0.14	1.20×10^{13}	-0.07	2.57×10^{13}	0.33	2.91×10^{13}	0.5
Act. - 4 Days Old - 4/2/84	1.0×10^{13}	0.5	1.5×10^{13}	0.5	2.0×10^{13}	0.6	2.5×10^{13}	0.88
Alum	5.02×10^{12}	0	7.53×10^{12}	0	1.0×10^{13}	0	1.25×10^{13}	0

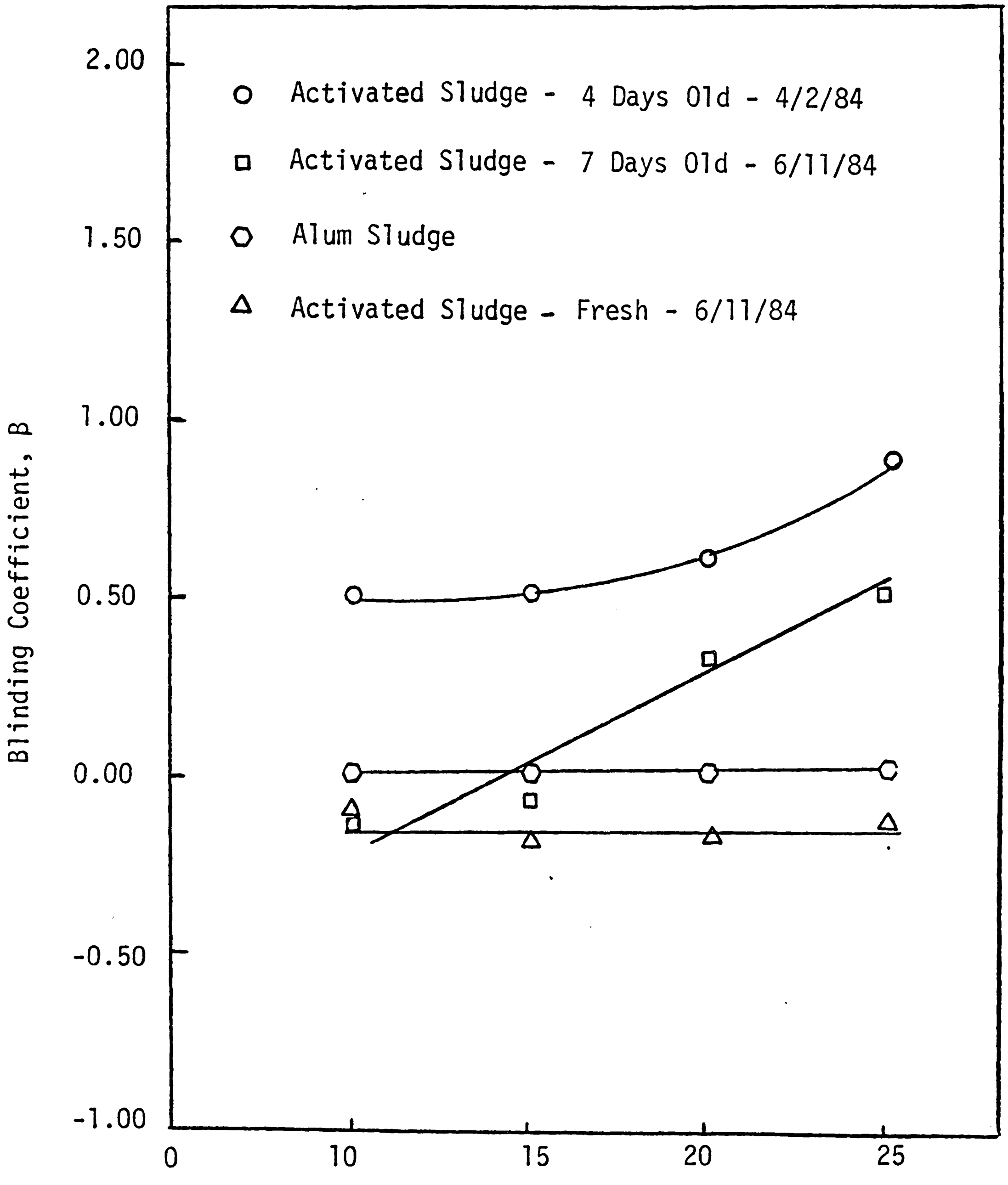


Figure 17 - Effect of Pressure on the Blinding Coefficient.

effect on the average specific resistance and the blinding coefficient. Pressure therefore appears to cause blinding to increase for sludges which have a tendency to blind. Consequently, pressure may be important for process selection based on the nature of the sludge.

Media Effects on the Sludge Blinding Coefficient

The effect of the filter medium on filtration has been mainly ignored in sludge studies. Notebaert, *et al*., (8) reemphasized the importance of the medium in filtration and argued that blinding of the medium may occur when a heterogeneous sludge contains particles equal in size to the pore openings of the medium. Since most sludges are heterogeneous in nature, the effect of the medium should not be ignored in filtration.

The effect of medium on filtration was studied using Whatman Qualitative 4 (pore size 20 - 25 microns), 2 (pore size 8 microns), 1 (pore size 11 microns), and Whatman Ashless 42 (pore size 2.5 microns) filters. Table 5 presents some of the data generated. It can be seen that for the activated and primary sludges the blinding coefficient increases as the filter pore size increases. No significant change is noticed in the blinding coefficient for the rest of the sludges. Also the change in the average specific resistance appears to be minor.

The increase in blinding with increasing medium pore sizes is the opposite of what may have been expected. However, several explanations are possible. First, the medium can affect sludge filtration by controlling the rate of filtration. When the medium pore size is small,

Table 5 - Media Effects on the Average Specific Resistance and Blinding Coefficient

	Filter Pore Sizes (microns)							
	2.5		8		11		20 - 25	
Sludge Type	r (m/kg)	β	r (m/kg)	β	r (m/kg)	β	r (m/kg)	β
Act. - Fresh 6/11/84	1.81×10^{12}	-0.73	2.81×10^{12}	-0.20	-----	-----	2.71×10^{12}	0.0
Act. - 25 Days Old - 6/11/84	1.81×10^{13}	-0.13	1.47×10^{13}	-0.07	-----	-----	1.81×10^{13}	0.4
Primary	-----	----	2.65×10^{14}	1.0	-----	-----	4.24×10^{14}	2.25
Alum	8.48×10^{12}	0.25	7.88×10^{12}	-0.09	-----	-----	7.63×10^{12}	0.0
Alum - Diluted	-----	-----	1.88×10^{13}	-0.33	1.88×10^{13}	-0.33	-----	-----

the rate of filtration; hence, filter cake formation may be slow and particle movement through the cake will be limited. This is the same effect which occurs under low pressure. When medium pore sizes are large, larger particles can migrate to the surface of medium and plug the filter pores. Smaller particles would not be expected to plug the pores since they would be screened out by the sludge cake before reaching the filter medium surface. The significant factor in medium effects is that increasing the filter medium size can for certain sludges, reduce rather than increase filtration rate. This effect appears to be due to increased medium blinding.

Conditioning Effects on the Sludge Blinding Coefficient

Conditioning is believed to improve sludge filtration by enlarging the sludge particle size. Some of the sludges involved in this study were conditioned using Betz 1195 polymer. As expected, the addition of polymer markedly improved the filtration rate. Table 6 presents some of the data generated in this study. It can be seen that both the average specific resistance and blinding coefficient improve by conditioning of the sludge. Particle counts were not possible on the conditioned sludges due to the large size of particles involved.

In addition to polymer conditioning, calcium carbonate sludge was added to several sludges to test for its conditioning effect. Lime is often used as a conditioning agent, but the mechanism which accounts for its benefits is not known. This portion of the study may provide some insight into the mechanism of lime sludge conditioning. Calcium carbonate was added to alum sludge and stored activated sludge to study

Table 6 - Influence of Conditioning and Mixing on the Blinding Coefficient and Average Specific Resistance

Sludge Type	r (m/kg)	β	Mean Particle Size (microns)	D_{90}/D_{50}
Primary	2.65×10^{14}	1.0	----	----
Conditioned	5.57×10^{12}	-0.6	----	----
Act. - 9 Days Old - 6/11/84	2.33×10^{13}	0.76	----	----
Conditioned	1.51×10^{12}	-0.5	----	----
Cal. Carbonate	4.87×10^{10}	-0.67	9.5	2.11
Alum	8.48×10^{12}	0.25	15	3.87
Mixture Alum and Cal. Carb.	2.04×10^{10}	-0.8	13	2.54
Act. - 25 Days Old - 6/11/84	1.13×10^{14}	1.0	38	2.20
Mixture - Act. and Cal. Carb.	7.23×10^{10}	-0.55	64	1.32

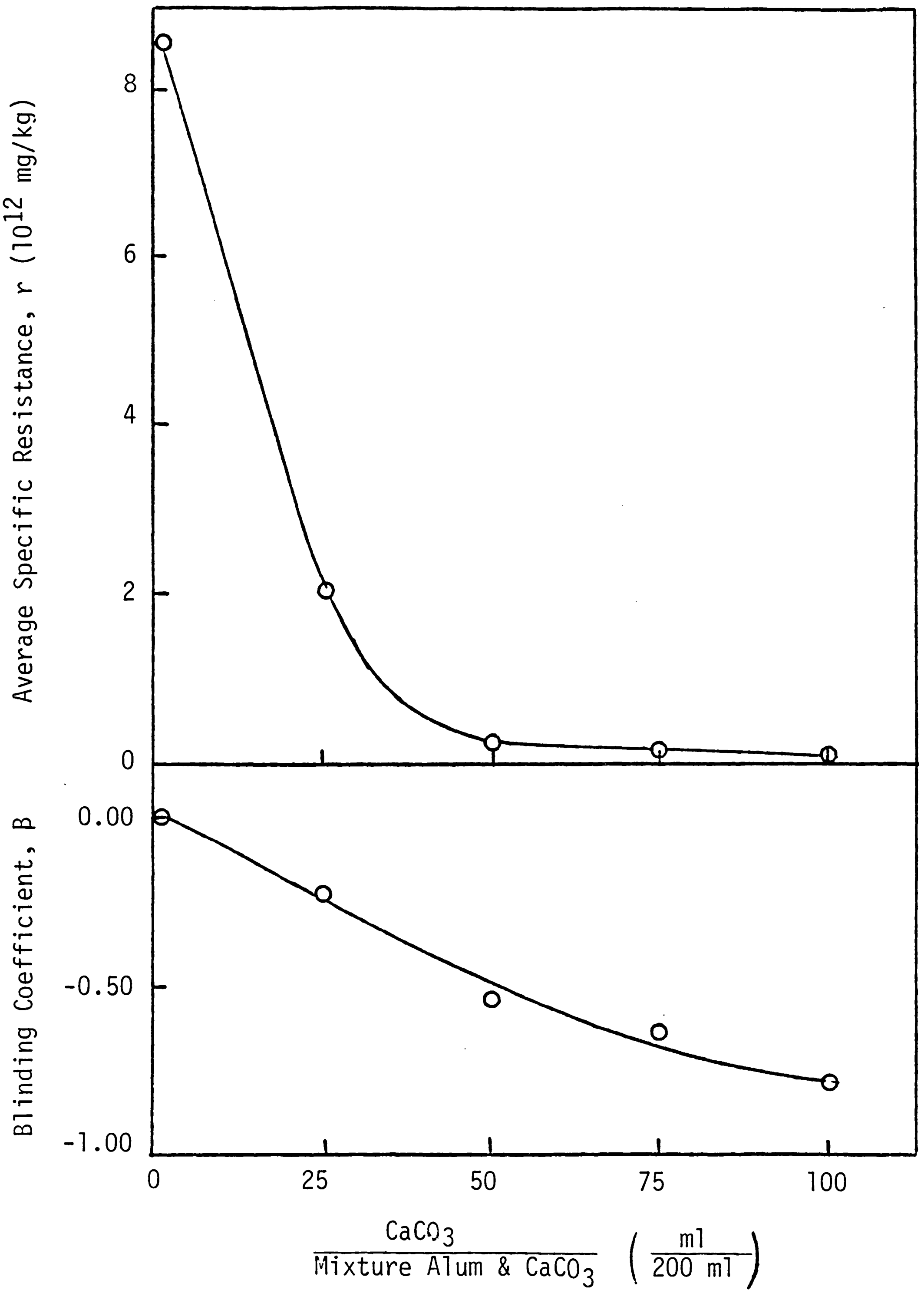


Figure 18 - Effect of the Calcium Carbonate Slurry Addition on the Average Specific Resistance and Blinding Coefficient for an Alum Sludge.

the response. All of the sludges mixed with the calcium carbonate had poor filtering properties. As can be seen from Table 6, calcium carbonate addition improved the mean particle size of the aged activated sludge significantly. For alum sludge the particle size distribution narrowed significantly, while the mean particle size decreased slightly. Figure 18 shows the trend in the blinding coefficient and average specific resistance as a result of the calcium carbonate addition to the alum sludge. It can be seen that both the average specific resistance and blinding coefficient initially decrease and then level off.

Supernatant Replacement and Elutriation Effects on the Sludge Blinding Coefficient

Supernatant replacement and elutriation are believed to improve filtration by removing small suspended solids which are reported to be the main cause of blinding (5). To study the effect of supernatant replacement and elutriation on filtration, the supernatant of several sludges was replaced by tap water. Elutriation was achieved by successive replacement of the supernatant. Each sludge, supernatant replaced sludge, and elutriated sludge were tested under the same condition.

Table 7 presents some of the data obtained in this study. It can be seen that both supernatant replacement and elutriation slightly improve filtration. The average specific resistance and blinding coefficient both decrease slightly. As stated previously, the improvement

Table 7 - Effects of Supernatant Replacement and Elutriation on the Average Specific Resistance and Blinding Coefficient

Sludge Type	r (m/kg)	β	Mean Particle Diameter (microns)	D_{90}/D_{50}
Primary	2.65×10^{14}	1.0	20	1.95
Supernatant Replaced Primary	7.36×10^{13}	1.0	20	1.80
Act. - 16 Days Old - 6/11/84	4.61×10^{13}	0.5	36	2.33
Supernatant Replaced	1.08×10^{13}	-0.14	36	2.22
Act. - 22 Days Old - 6/27/84	2.4×10^{13}	-0.13	35	2.34
Supernatant Replaced	7.99×10^{12}	-0.25	30	2.20
Elutriated - Act. 16 Days Old - 6/11/84	1.40×10^{13}	0.0	34	2.29
Act. - 11 Days Old - 6/11/84	1.57×10^{13}	0.40	35	2.34

Table 7 - Effects of Supernatant Replacement and Elutriation on the Average Specific Resistance and Blinding Coefficient (cont'd)

Sludge Type	r (m/kg)	β	Mean Particle Diameter (microns)	D_{90}/D_{50}
Elutriated - Act. 11 Days Old - 6/11/84	9.03×10^{12}	0.22	41	1.98
Alum	7.63×10^{12}	0.0	19	3.84
Elutriated	1.0×10^{13}	0.0	16	3.25

in the rate of filtration as a result of supernatant replacement and elutriation is probably due to the suspended solids removal by these two mechanisms. Consequently, supernatant replacement and elutriation may improve filtration of the sludges that contain substantial amount of suspended solids; however, these methods may not be effective for sludges which contain few suspended solids. Even for the sludges that contain substantial amounts of suspended solids, for elutriation to improve filtration, substantial amounts of water appears to be necessary.

Comparison of Sludge Blinding Coefficient and Sludge Blinding Index

Sludge blinding index was developed by Karr and Keinath (5) to predict and quantify the degree of blinding which may be induced by the filtration of a sludge. This index is determined based on the following expression:

$$BI = \left(\frac{r_1 - r_2}{r_2}\right) \left(\frac{c_2}{c_2 - c_1}\right) 100 \qquad (9)$$

Where r_1 and r_2 are the average specific resistance of the sludge at two different solids concentrations, and c_1 and c_2 are the weight of dry solids in the filter cake per unit volume of filtrate at those solids concentrations. This index has a scale that ranges from zero percent for a non-blinding sludge to 100 percent for a completely blinding sludge.

Karr and Keinath developed the sludge blinding index assuming that for a non-blinding sludge the average specific resistance is independent of the sludge solids concentration. Thus, the product $(r_1 - r_2)$ and hence the blinding index is zero percent for a non-blinding sludge. For a blinding sludge on the other hand, they stated that the specific resistance of the sludge depends to the solids concentration of the sludge, and thus r_1 and r_2 are different. When a sludge is completely blinding the products $(r_1 - r_2/r_2)$ and $(c_2/c_2 - c_1)$ become the exact inverse of each other and cancel one another and result in a blinding index equal to 100 percent.

This study and work by others have shown that under some conditions, the specific resistance varies with the sludge solids concentrations. The overwelming evidence is that the specific resistance increases as the solids concentration increases, although this study indicated that when a sludge is very dilute, medium effect may predominate the cake resistance and increase the overall resistance. Thus, the assumption that the specific resistance is independent of the sludge solids concentration is probably invalid. For a blinding sludge on the other hand, it has been shown that the plot of t/V versus V is curvelinear; hence, selecting a proper slope to calculate b and the average specific resistance is very difficult, and perhaps misrepresents the sludge filtration properties.

Mathematically, assuming that the average specific resistance of the concentrated sludge is larger than that of the less concentrated sludge, the blinding index will be negative. In fact, Goodman (2) showed that blinding indices well outside the zero to 100 percent range are possible.

Table 8 presents the blinding coefficient and index for some of the sludges studied. It can be seen that the two blinding parameters for some sludges do not agree. Also, for the nine days stored activated sludge, the blinding index is outside the scale designated by Karr and Keinath.

In some instances it appears that β may not be constant but rather may vary with the filtrate volume. It can be seen in Figure 19 that a plot of t/V versus V for some sludges is curvelinear rather than linear. The significance of this occurrence is not clear and needs further study. Overall, the concept of the sludge blinding coefficient is mathematically sound and in practice it seems to describe the filtration pattern. The Karr and Keinath sludge blinding index on the other hand, was developed empirically and as shown here and by Goodman (2), often results in values well outside the scale prescribed for it. Therefore, the sludge blinding coefficient should be the parameter of choice to predict blinding.

Table 8 - Comparison of the Sludge Blinding Coefficient and Sludge Blinding Index

Sludge Type	Solids Concentration (Percent)	c	r (m/kg)	BI	β
Act. - 10 Days Old - 4/2/84	0.9	0.01	4.07×10^{13}	-21	0.56
Act. - Diluted	0.17	0.002	2.22×10^{13}		
Act. - 9 Days Old - 6/11/854	0.76	0.008	2.33×10^{13}	58	0.8
Act. - Diluted	0.37	0.004	3.01×10^{13}		
Act. - 9 Days Old - 6/11/84	0.50	0.005	4.01×10^{13}	-122.2	1.33
Act. - Diluited	0.27	0.003	2.21×10^{13}		
Act. - 22 Days Old - 6/27/84	0.31	0.003	1.81×10^{13}	53	0.4
Act. - Concentrated - 6/27/84	0.56	0.006	1.43×10^{13}		
Alum	4.83	0.06	6.69×10^{12}	0.0	0.0
Alum - Diluted	0.37	0.004	6.52×10^{12}		

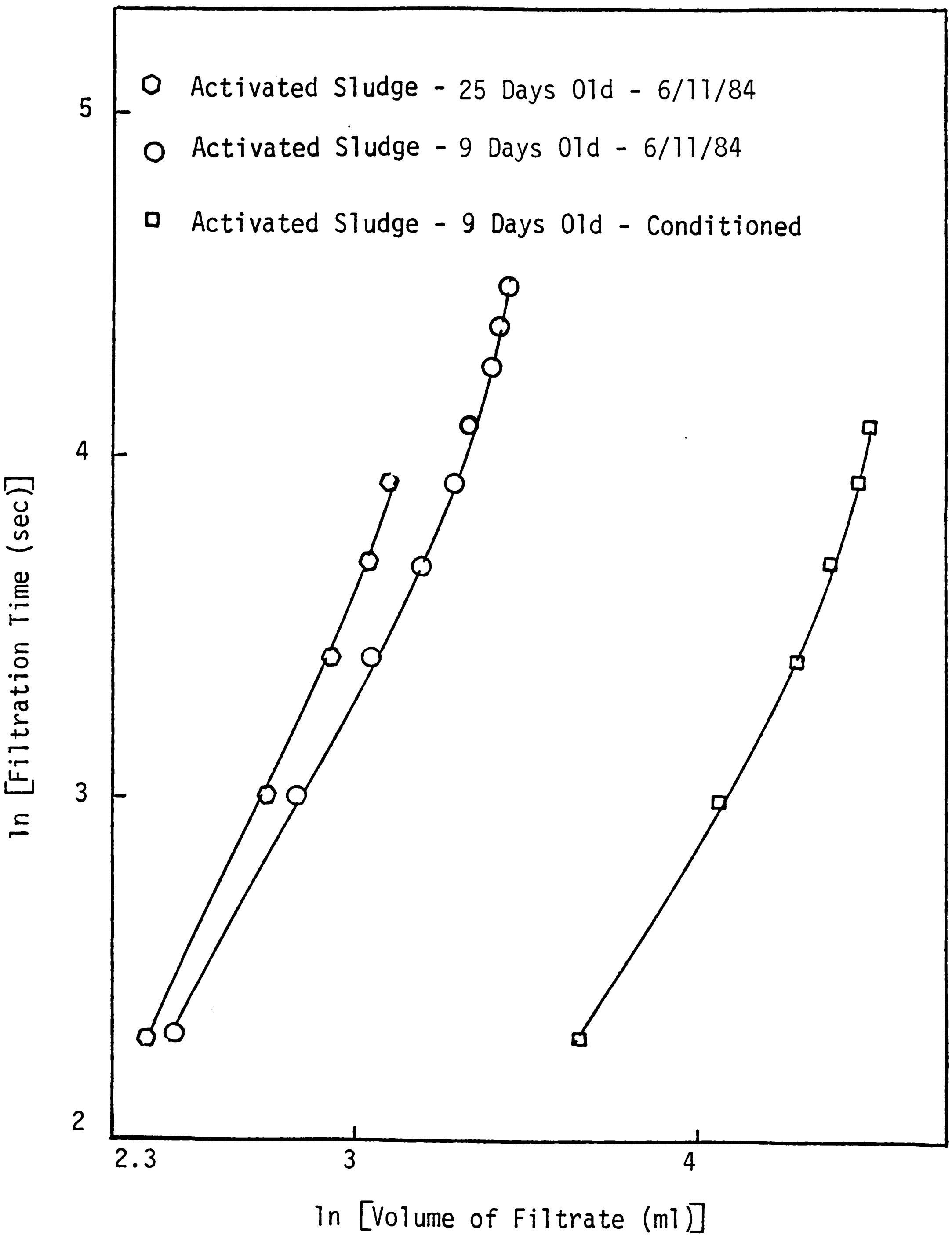


Figure 19 - Plot of ln t Versus ln V for Several Sludges.

V. SUMMARY AND CONCLUSIONS

The sludge blinding coefficient, β, was examined in this study to determine if β could be a useful characterization parameter for sludge dewatering properties. Activated sludge, activated sludge aged at room temperature, primary sludge, alum sludge, and a calcium carbonate slurry were tested at various pressure levels and various size filter media using a standard Buchner funnel apparatus to study β. Particle counts were also performed on the above mentioned sludges using an automated particle counter to determine the impact of particle size and size distribution on β. Effects of conditioning, elutriation, supernatant removal and replacement on β were also studied.

In general, β correlated well with the sludge average specific resistance, indicating that it can be useful in predicting a sludge filterability. Conditioning, elutriation, supernatant removal and/or replacement, filter medium, and pressure were all found to affect sludge filtration. These effects were noticed by changes in β and the sludge average specific resistance. Conditioning, elutriation, supernatant removal and replacement improved sludge filtration, β, and the average specific resistance.

Overall, the following conclusions can be formulated from this study:

1. The sludge blinding coefficient, β, appears to adequately describe incremental changes in sludge filtration rates with the filtrate volume.

2. The particle size distribution appears to be an important factor in determining the value of β. As the particle size distribution increases, as indicated by increasing values of (D_{90}/D_{50}), β or blinding also increases.
3. Increased filtration pressure increased β for sludges which tend to blind.
4. It appears that blinding and sludge compressibility are separate phenomena. When $\beta = 0$, no information about compressibility can be assumed.

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