Laboratory Evaluation of Conditioning Requirements for Sludge Dewatering using a Belt Filter Press

by

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(ABSTRACT)

The purposes of this study were to develop a reliable bench-scale testing procedure to adequately predict polymer conditioning requirements for full-scale belt filter presses, and to determine the additional polymer demand exerted by applied pressure during the expression stage of a dewatering process. Bench-scale experiments performed with anaerobically digested, alum and secondary sludges used a high-speed mixer to gauge mixing intensity effects, and a wedge zone tester to gauge applied pressure effects on conditioning requirements. Full-scale experiments varied sludge throughput, belt speed, and polymer dose to evaluate polymer performance.

The polymer requirements to optimize performance of a full-scale belt filter press can be predicted with a bench-scale mixing device, where the shear (Gt) of the mixer matches that of the full-scale press. An estimate of the Gt value of the full-scale belt filter presses used in this study was 10,000. Alternatively, a bench-scale wedge zone

tester, operated in an applied pressure range between 5 psi and 20 psi, can predict polymer doses for optimum belt filter press performance.

The range of applied pressures used to simulate the expression phase of a dewatering process did not exert a significant additional polymer demand for optimum conditioning. The shear (Gt) associated with mixing sludge and polymer during conditioning can exert a greater polymer demand than the expression phase of the wedge zone tester.

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INTRODUCTION

Dewatering of municipal and industrial sludges is a necessary step in water and wastewater treatment. Sludges are generally high in water content, accounting for 90% to 99% of the sludge volume. Removal of this water greatly reduces the quantity of these residual materials. This in turn saves on transportation and ultimate disposal costs.

Dewatering is often accomplished using mechanical dewatering equipment. Belt filter presses are one of the processes commonly used for sludge dewatering. These machines were originally designed for the pulp and paper industry, but are now widely used for sewage sludge dewatering. Sludges are dewatered in a belt filter press first with the aid of gravity, and then under pressure and shear. For optimum dewatering, conditioning of the sludge is required.

Organic polyelectrolytes, known as polymers, have been used extensively in the water and wastewater industries for sludge conditioning. These substances act as coagulants and thereby allow more rapid dewatering from sludge. In this manner polymer conditioning of sludges improves process performance, and often increases the solids concentration of the dewatered sludge.

One purpose of this study was to develop a reliable bench-scale method of predicting polymer doses for optimum belt filter press performance. This investigation also sought to determine if a laboratory-scale wedge zone device could predict the performance of full-scale belt filter presses. A major goal was to elucidate the conditioning requirements exerted by different applied pressures, and to gauge which operating parameters significantly affect belt filter press performance. Correlation of mixing intensity effects and applied pressure effects on conditioning requirements was also investigated. The study was undertaken with two proposed objectives:

1. Determine the relationship between the shear (Gt) imparted by bench-scale mixing device, the bench-scale filter press wedge zone tester, and several full-scale belt press units.

2. Evaluate the additional polymer demand exerted by applied pressure in the expression phase during dewatering in a belt filter press.

LITERATURE REVIEW

This chapter will review five separate literature topics associated with sludge dewatering using a belt filter press. The first section will describe the physical and operational aspects of a belt filter press. Polymer conditioning of sludge will be covered second. This section will examine polymer and sludge characteristics which affect conditioning and the mechanisms which promote it. Next, the effects of mixing intensity and shear will be discussed. The relationship between mixing energy (G), mixing time (t), and polymer dose will be detailed. Following this, the concepts of filtration and expression and how they apply to sludge dewatering will be explained. The final topic covered will be laboratory attempts to predict full-scale dewatering equipment performance. Results obtained from bench-scale presses and their relationship to full-scale units will be addressed.

The Belt Filter Press

The belt filter press is one of the most commonly used mechanical devices for sludge dewatering (1). Dewatering of sludge occurs as the filter cake is sandwiched between two tensioned, porous belts. These belts are passed over a series of rollers of successively smaller diameter which increase the applied pressure used to squeeze out water. Sludges are dewatered in a belt filter press first with the aid of gravity, and then under pressure and shear (2).

Three distinct zones of dewatering are incorporated into a belt filter press, shown in Figure 1. Removal of free water occurs in the gravity drainage zone. Superflocculation of the sludge is required for this zone to ensure satisfactory press performance (1 - 3). Superflocculation occurs when sludge flocs are visibly separated from the bound water, and the dewatering rate is maximized. The wedge zone is the area where the upper and lower belts first come together to sandwich the sludge under low pressure. This is a critical stage because here the cake is prepared to withstand the high pressure zone. Both shear and high pressure are used in this final zone for further water removal (1, 2).

Shear is generated by the movement of the upper and lower belts, relative to each other, and is believed to cause further water removal (1). This same physical process which may aid dewatering, may also require additional polymer requirements to prevent floc rupture from deteriorating dewatering performance. The high pressure

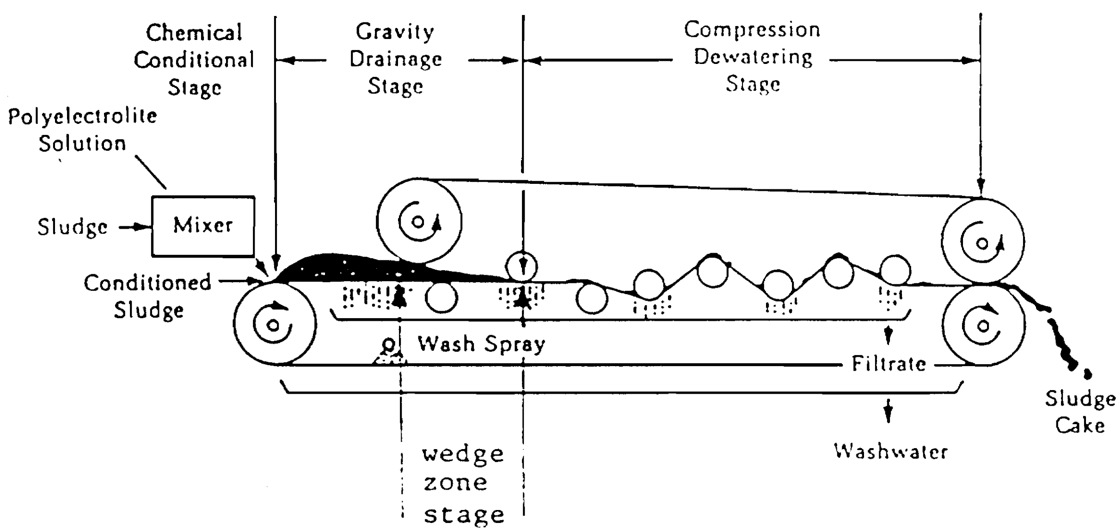

Figure 1. Belt filter press schematic. From EPA (1).

forces simply squeeze the sludge for further water removal. Conditioning requirements may also increase to protect the sludge from these pressure forces.

There are a number of machine and process variables that affect belt filter press performance. Belt tension, belt speed and location of the polymer feed are three of the major machine variables. Belt tension controls the magnitude of the applied pressure, whereas belt speed controls the overall residence time of the sludge in the press. The polymer feed location controls the amount of mixing the sludge and polymer undergo before they reach the press. Sludge throughput and polymer feed rate are two significant process variables. Throughput controls the mass loading onto the press, and polymer feed rate controls the conditioning dose. An estimation of the variables which control dewatering has yet to be clearly defined.

Polymer Conditioning of Sludge

Chemical or physical treatment of sludge prior to dewatering is usually required to improve both the rate and extent of water removal. The three most common conditioning methods are inorganic chemical addition, organic polymer addition, and thermal processing. Conditioning with polymers instead of inorganic chemicals or thermal processing has several advantages. Little additional sludge mass is created with the use of polymers. If ultimate disposal is incineration, polymers do not lower the heat value of sludge. Finally, polymer conditioning lends itself to cleaner material handling procedures and reduced operation and maintenance costs (1).

Organic polymers are long chain, water soluble molecules used for conditioning. They are constructed by combining smaller monomers into a much larger molecule. Characteristics used for polymer classification include charge, charge density, molecular weight and their physical form. Polymers usually come in liquid or dry powder form (2).

Research studies using organic polymers examined have the mechanisms of coagulation which improved the dewatering rate of sludge (4 - 7). An increase in particle size is the primary objective of conditioning. Polymers accomplish this through either charge neutralization or interparticle bridging (1, 4, 5). A polymer in solution will promote desorption of the bound water attached to sludge particles. Charge neutralization of the sludge by the polymer will reduce the electrostatic forces between the sludge particles. Flocculation of these destabilized particles by interparticle bridging will then be able to occur.

Physical properties of the sludge slurry seem to govern which dewatering mechanisms are occurring. Novak and Haugan (4) described a biological sludge as an anionic slurry, which required cationic polymers to promote charge neutralization (4). Chemical sludges are thought to require a polymer to promote interparticle bridging (5).

Several important parameters have been seen to affect sludge conditioning. Polymer molecular weight and sludge pH were judged by Novak and O'Brien (5) to be the most important parameters affecting conditioning. As polymer molecular weight increased, polymer dose requirements decreased. Researchers have generally agreed that a high molecular weight polymer (greater than 10^6) worked most effectively with chemical and biological sludges. Spinosa *et al.* (6) found that polymers with molecular weights between 2 to 4 million produced the highest cake solids and dewatering rates with a beltpress.

Additional sludge and polymer characteristics were studied to gauge their effects on dewaterability. Novak and O'Brien (5) concluded that as the solids contents of a sludge increased, the amount of polymer (expressed in mg/L) required for conditioning also increased. The effects of the charge density of the polymer was unclear. No trend between charge density and the dewatering rate was found by Cole and Singer (7). Also, neutralization of the charged sludge particles was not required for optimum conditioning. However, Spinosa *et al.* (6) found that a polymer's charge density would affect the type of dewatering equipment it could be used with.

Previous research on polymer conditioning of sludges has defined many areas of concerns. Polymers promote particle growth either by charge neutralization or interparticle bridging, and the mechanism seems to be dependent on the sludge type. It was shown, that in general, the pH and the polymer molecular weight have the most significant effects on conditioning performance. For some sludges, a polymer with a molecular weight of at least 10^6 was reported to be required to promote rapid dewatering. The effect of charge density was unclear. Research up to this point in time was just beginning to incorporate mixing effects into conditioning requirements.

Effects of Mixing Intensity and Shear on Sludge Dewatering

A significant amount of research has been conducted to characterize the effects of mixing on sludge dewatering properties. A variety of sludges conditioned with different polymers have been shown to respond similarly during mixing experiments. The most important parameters controlling dewatering were shown to be the mean velocity gradient, G (t^{-1}), mixing time (t), and polymer dose (8). The mixing energy input (Gt) is a dimensionless parameter used as a measure of shear encountered during conditioning. High Gt mixing conditions, and the subsequent polymer demands, were compared to high shear encountered in mechanical dewatering equipment (9).

An early investigation by Novak and Haugan (4) of the effects of mixing proposed a floc surface model to describe polymer conditioning of activated sludge. Activated sludge was shown to be comprised of anionic biocolloids which cationic polymers could neutralize and then coagulate. Mixing energy input was considered in this model. The authors found that the amount of polymer required for sludge conditioning increased as mixing turbulence increased. As the mixing energy increased, more biocolloids were released from the sludge, which further increased the polymer demand. At low mixing speeds, polymer requirements were nearly independent of sludge solids concentration. In addition, a polymer conditioned sludge was shown to be quite fragile due to its rapid deterioration from mixing, and high compressibility. However, sludges conditioned under high intensity mixing were shown to resist further deterioration.

A successive group of studies were performed by Werle *et al.* (8), Novak *et al.* (9), Novak and Bandak (10), and Novak and Lynch (11) to investigate the effects of mixing intensity and shear on polymer conditioning of sludge. The experimental methods for these studies were basically the same. A high-speed bench-scale mixing device was used to control the mixing energy input (Gt). The sludge dewatering rate was measured with a Capillary Suction Time (CST) apparatus. Polymer dose, mixing time (t), and mixing energy (G) were all varied to evaluate their effects on the dewatering rates for a variety of sludges.

Common results were found throughout this group of investigations which essentially extended the work of each previous study. First, mixing energy and mixing time were shown to control conditioning performance, and that the product of Gt was an important measure of shear (8). As Gt increased, more polymer was required for optimum conditioning, as shown in Figure 2. Second, standard jar test mixing devices were shown to underpredict conditioning requirements because of the low Gt they imparted (4). Third, overdosed conditions were observed for some sludges which was hypothesized to be due to excessive surface coverage and charge reversal by the polymer (9). Finally, these studies concluded that because these sludges could be adequately conditioned at high Gt values, they could also be

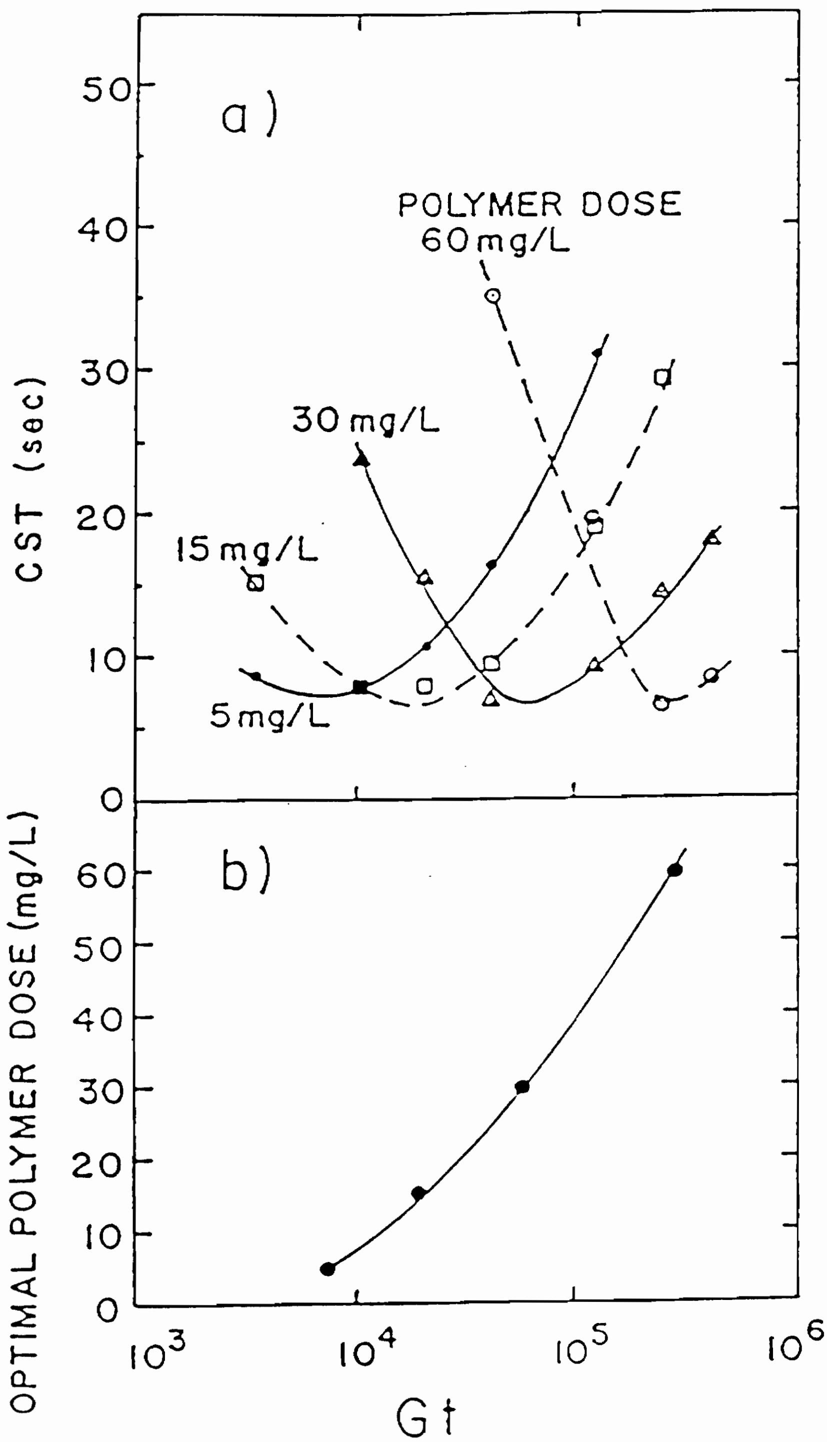

Figure 2. Effect of Gt on the polymer conditioning requirements of alum sludge. From Novak and Bandak (10).

conditioned for high shear equipment (8, 9). Another conclusion was that selection of a specific polymer product, similar to polymer dose, was more important at high Gt values than at low Gt values (9).

After acquiring a reasonable knowledge of mixing intensity effects, shear effects were then investigated. Novak and Bandak (10) found that proper conditioning increased the physical stability of sludge. Mixing requirements were represented by the equation:

$$G^x t = k \qquad [1]$$

where G is the mixing energy, t is the mixing time, and k is a constant associated with each polymer dose. The magnitude of the exponent x was proposed as a measure of the sensitivity of a sludge to shear. The value of the exponent for unconditioned sludges was 2.8 and decreased as the polymer dose increased. A decrease of this exponent indicated an increase in the physical stability of the sludge and its resistance to shear.

Shear effects on sludge dewatering were further studied by Novak and Lynch (11) using additional laboratory techniques. A high-speed mixer was used to conduct mixing intensity experiments as before. Additionally, Buchner funnel drainage tests were performed at several different applied pressures. The results from these two tests produced similar responses, as shown in Figure 3. The authors concluded that an increase in pressure was equivalent to an increase in Gt. Buchner funnel refiltration experiments were also performed to establish shear during dewatering. Results indicated that water flowing through a filter cake imparts enough shear to exert a further polymer demand. The applied vacuum differential which was used to draw water through the cake increased this demand.

The goal of understanding both mixing intensity and shear effects was to develop a reliable bench-scale method of predicting polymer doses for optimum performance of full-scale mechanical dewatering equipment. With this objective in mind, researchers attempted to determine a unique Gt value for a specific dewatering device. If a unique Gt could be identified, then a bench-scale mixing device set for that Gt could be used to find an optimum polymer dose. Costly full-scale testing would not be necessary to determine optimum conditioning requirements (12).

Studies by Zoccola (12), Lynch (13), and Reitz (14) attempted to correlate bench-scale mixing results to the performance of pilot-scale filter presses. Two general results were found in each of these investigations. First, polymer conditioning requirements increased for the press as

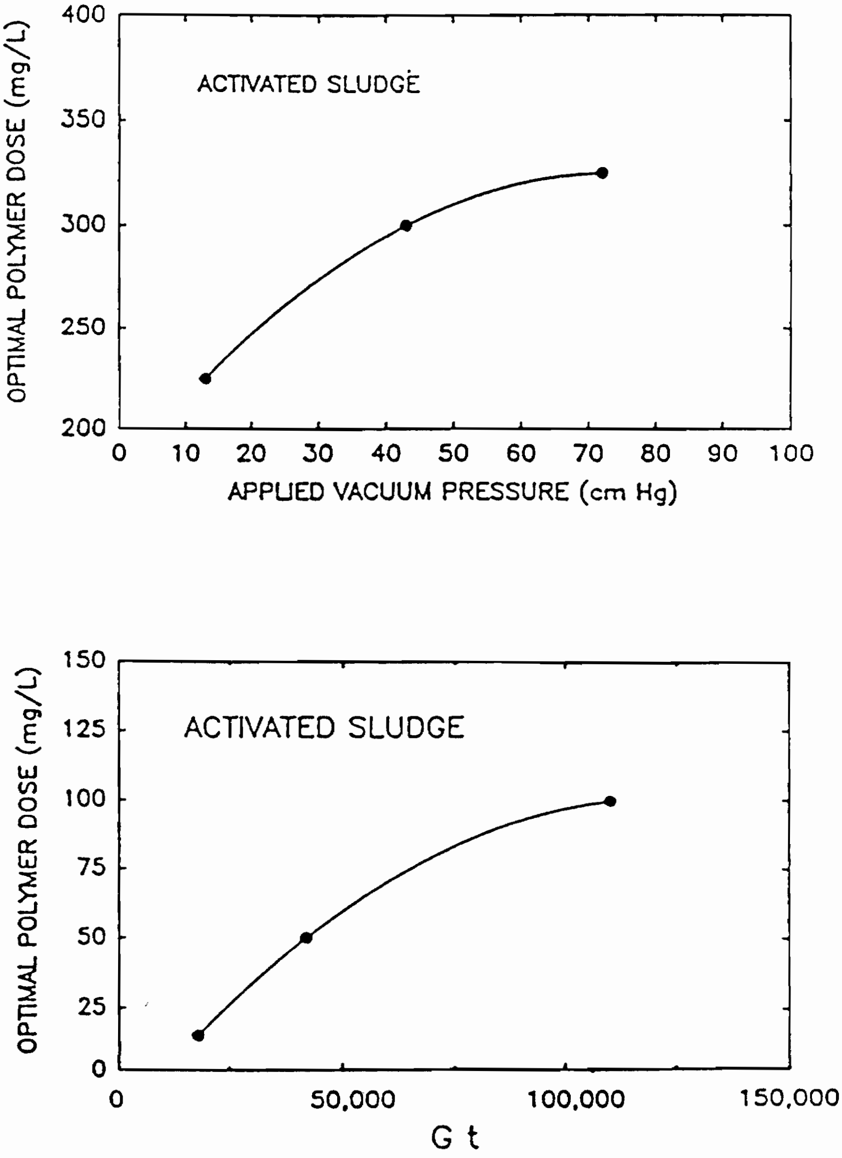

Figure 3. Effects of applied vacuum pressure, and Gt on polymer conditioning requirements of alum sludge. From Novak and Lynch (11).

the polymer mixing intensity increased. Second, it was difficult to define a unique Gt value for each filter press.

Two of these studies experimented with a pilot-scale plate and frame press (12, 13). Zoccola (12) was unable to define a specific Gt for the press. However, Lynch (13) estimated the Gt value for a pilot-scale plate and frame press to be between 15,000 and 40,000. A Gt value of 5,000 was selected for mixing the polymer and sludge before being fed into the press in order to minimize shear effects during the conditioning step. With this variable fixed, Lynch was better able to quantify the Gt value of the press.

A pilot-scale belt filter press was investigated by Reitz (14). Comparison of the optimum dose response to mixing allowed Reitz to conclude that the shear exerted by a belt filter press was roughly equivalent to a Gt value of 45,000. However, this high Gt value for the press contradicted other results found in the study regarding conditioning requirements. The conditioning requirements for the different dewatering zones encountered in a belt filter press were analyzed separately. The first two zones encountered in a belt filter press (gravity drainage and wedge) were simulated with a wedge zone tester. The high pressure zone was simulated with the pilot-scale belt filter press. Reitz found that the optimum polymer doses for all three zones were essentially the same. A high Gt value does not seem appropriate for the gravity drainage or wedge zones, which were also shown to be predictive gauges of press performance.

These studies highlight the difficulties encountered in correlating mixing intensity results to mechanical dewatering performance. While a high Gt does simulate high shear, the assumption that it simulates high shear equipment may be inaccurate. In fact, the Gt value associated with the mixing during conditioning of the sludge and polymer might control overall dewatering performance. This was suggested by Reitz, and would agree with work that showed superflocculation of the sludge was required for optimum filter press performance (1 - 3).

Filtration and Expression

Sludge dewatering with a belt filter press occurs in two distinct regions. Filtration, or free drainage, occurs between the time the conditioned sludge is fed onto the belt until it enters the wedge zone of the press. Expression occurs when applied pressure is exerted for further water removal. These two stages are shown schematically in Figure 4. Research in this area has focused on cake formation.

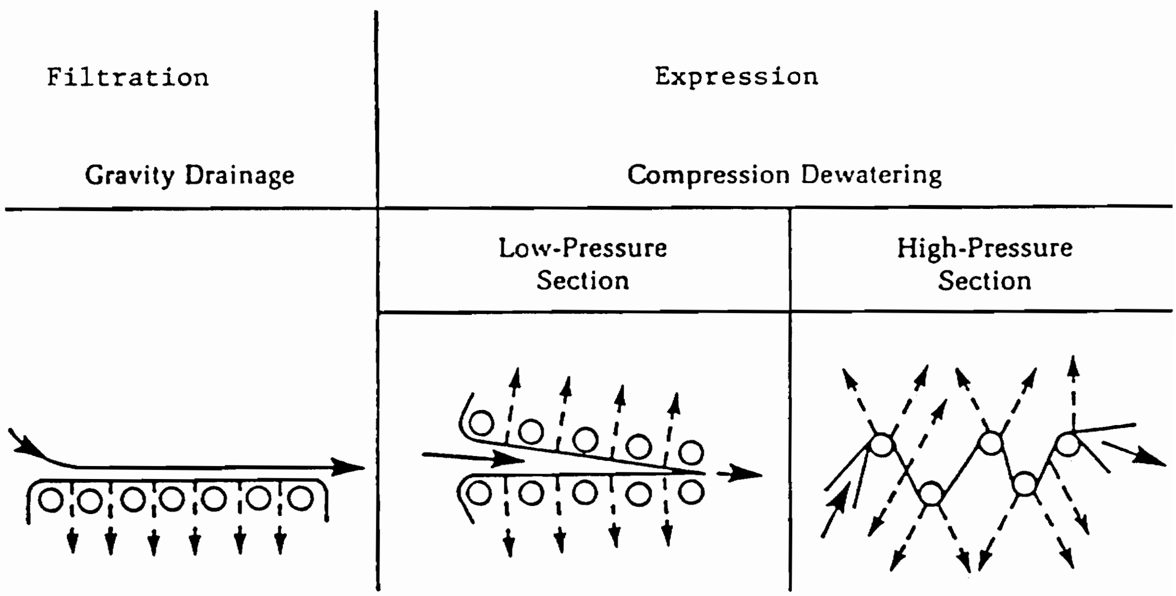

Figure 4. Location of filtration and expression stages that occur within a belt filter press. From EPA (1).

More recent work has studied how cake properties respond under applied pressure.

Cake formation has been described by first principles of filtration theory. Specific resistance of a cake to flow was clarified as a measure of sludge filterability by Gale (15). Physically it can be viewed as the pressure required to produce flow through a cake. The compressibility of filter cakes formed from sludge caused serious deviations of behavior compared with an ideal incompressible cake.

Further research was concerned with cake properties and their response to filtration and expression. A common result was found by two distinctly different studies. Both found that applied pressure had a very limited effect on sludge dewatering (16, 17). This was attributed to the high compressibility of a well conditioned, superflocculated sludge slurry. Tiller and Yeh (16) performed experiments to determine the relationship between the nature of particles and the best dewatering procedure. A hydraulic press was used with pretreated slurries to gauge the effects of applied pressure on cake porosity. For a beltpress, a superflocculated slurry was shown to work best in this study.

The other study, conducted by Bierck and Dick (17), used an X-ray absorbance technique to measure suspended solids concentration in a filter cake as it formed at different pressure differentials. An unconditioned activated sludge was shown to behave as a highly compressible cake. A highly compressed skin of the activated sludge cake absorbed most of the applied pressure and seemed to control filtration. Because of this skin formation, pressure had little effect on the filtrate rates of the activated sludge cakes. Conditioned sludges have also been shown to produce this compressible skin (18).

Research in the area of filtration and expression of sludges has not thoroughly investigated polymer conditioning requirements. Specifically, information is needed to reveal if the expression stage of a dewatering process exerts a further polymer demand which needs to be accounted for to optimize overall dewatering. This can be best accomplished if the individual steps in dewatering; mixing, filtration, and expression are clearly separated. A bench-scale mixer and filter press are capable of this and have been used in several studies.

Laboratory Attempts To Predict Full-Scale Performance

Several researchers have used laboratory-scale filter presses to evaluate machine parameters and conditioning requirements which optimize sludge dewatering (3, 18, 19). In most cases, a bench-scale piston press was used to simulate a full-scale unit. All these studies found that polymer conditioned sludges produced highly compressible cakes, and that a polymer dose capable of superflocculating the sludge was required to promote good dewaterability.

Baskerville *et al.* (3) concluded that the factors which affected belt press performance were polymer dose, rate of gravity drainage, and rate of drainage under compression. The rate of gravity drainage was used to determine the allowable sludge loading at a selected dose. Compression drainage was used to predict final cake solids.

The operating variables of a piston press (rate of pressure application, amplitude and duration of applied pressure, shear, and sludge loading) were studied by Halde (18), rather than conditioning requirements. Longer pressing times and higher pressures produced drier cakes, and filtrate solids were not greatly affected by pressure or time. However, the specific time of pressure increase affected both cake and filtrate solids. A gradual rise of pressure was shown to work most effectively.

Zall *et al.* (19) compared different conditioners for use with an oily sludge and a plate and frame press. Filter press yields were measured when this sludge was conditioned with an organic polymer, lime or fly ash. The inorganic conditioners were called skeleton builders because of the strengthened cake structure they produced. The authors found that polymer conditioned sludges were highly compressible and performed poorly with an oily sludge. Skeleton conditioners produced a more incompressible cake capable of maintaining its high porosity and generating a much higher filter press yield.

Information on the conditioning requirements for these laboratory-scale presses was limited. A polymer dose capable of producing a superflocculated sludge prior to gravity drainage was the only requirement. Further polymer demands generated within the expression phase were not considered. An understanding of applied pressure effects on conditioning requirements is required to better predict belt filter press performance.

Summary

A significant amount of literature is available dealing with sludge dewatering. However, information is still needed to confidently predict conditioning requirements for a full-scale belt filter press. In particular, information is required in the following areas:

- evaluation of the polymer conditioning requirements within the separate stages of filtration and expression encountered in dewatering equipment;
- determination of the polymer demand exerted during the expression stage which may need to be accounted for to optimize overall dewatering; and,
- the development of a reliable bench-scale testing procedure to determine optimum polymer requirements for full-scale equipment.

METHODS AND MATERIALS

One purpose of this study was to develop a laboratory-scale approach to predict polymer dose requirements for a full-scale belt filter press. Another purpose was to determine the effects of applied pressure on conditioning requirements for sludge dewatering. Bench-scale testing included mixing intensity experiments and wedge zone experiments. Full-scale results were obtained at two wastewater treatment facilities. This chapter describes the materials, equipment and procedures used to conduct these experiments.

Sludge Samples

Sludge samples were obtained from a municipal wastewater treatment facility, an industrial water treatment facility, and an industrial wastewater treatment facility. One batch of sludge was collected from the Peppers Ferry Regional Wastewater Treatment Plant (Peppers Ferry) in Radford, Virginia; two batches were collected from the water treatment plant of a munitions manufacturer in Southwest Virginia; and two batches were collected from the Ronile, Inc. wastewater treatment plant, in Rocky Mount, Virginia. Dry solids concentrations of the sludges were measured in accordance with *Standard Methods For the Examination of Water and Wastewater* (20).

Anaerobically digested sludge from Peppers Ferry was obtained from a sampling valve on a pipe in the sludge storage building that carried sludge from the sludge storage basin to the belt filter press. The sludge was collected in five-gallon carboys. The dry solids content of the sludge averaged 3.4%. The complete test matrix was completed over a two day period to minimize changes of sludge characteristics.

Alum sludge from the munitions manufacturer was obtained from a sludge storage lagoon. The solids content of the first and second batches of sludge averaged 3.4% and 3.6%, respectively. The first test matrix was completed over a two day period. The second test matrix was completed over a two week period. Because of the long storage time in the lagoon and the chemical nature of the sludge, the sludge properties were presumed to be unchanged over the storage period. Identical experiments repeated with the same batch of sludge over this two week period generated similar results, which confirmed this assumption.

Secondary sludge from the Ronile, Inc. wastewater treatment plant was obtained from the outlet valve on a pipe that carried sludge from the settling basins to the sludge drying beds. The sludge was collected in a bucket and then poured into five-gallon carboys. Two batches of sludge were used to complete the test matrix during one day of on-site testing. Solids content of the two batches averaged 3.2% and 2.5%, respectively.

Polymer Selection and Preparation

Several manufacturers' polymers were used in this study. Stockhausen D4160 polymer was used for conditioning the anaerobically digested sludge obtained from Peppers Ferry. The Stockhausen product was supplied in a dry powder form and is a high molecular weight, moderate charge density, cationic polymer. Betz 1120 polymer was used with the alum sludge. The Betz product was supplied in a dry powder form and is a high molecular weight, moderate charge density, anionic polymer. Ronile, Inc. sludge was conditioned with Nalco 90WP030 polymer. The Nalco product is an experimental, high molecular weight, cationic, liquid polymer.

Polymer densities of stock solutions were selected so that the volumetric amount of polymer added to a sludge would not exceed 20%. For example, if a 250 mL sludge sample was to be conditioned, a maximum of 50 mL of polymer could be added. If the required polymer dose was to be 400 mg polymer/L sludge, a polymer density of 2 g polymer/L solution would be required to fulfill the volumetric requirement. This requirement was imposed in order to avoid an inappropriate dilution of the sludge slurry.

Stock polymer solutions were prepared on the day or the day before they were used for sludge conditioning and were kept refrigerated up to two days for later use. These solutions were prepared in 1 liter, round plastic stirring jars and stirred with a Nalco caged impeller mixing paddle powered by a Cole-Palmer variable speed motor mounted on a ring stand. Tap water was used to prepare the stock solutions.

Dry powder polymer solutions were prepared by weighing the appropriate amount of dry powder and then pouring it into the stirring jar along with 1 L of tap water. A graduated cylinder was used to measure the water volume. After the polymer was added to the water, the mixer was turned on until a mild vortex was formed in the polymer solution. Mixing continued until the dry powder was completely dissolved, typically requiring 12 to 24 hours.

Liquid polymer solutions were prepared by measuring the appropriate volume of water and pouring it into the stirring jar. Polymer was injected into the stirring jar with a 1 mL plastic syringe. The solution was mixed as previously described. To determine the dry weight of polymer in the solution, Nalco stated that a 1% solution by volume equals 10,000 mg/L. This enabled dry polymer solids to be calculated from liquid polymer doses.

Bench-Scale Mixing Device

A bench-scale high speed mixer was used for mixing the polymer and sludge. The mixing energy (G) was calibrated to the rotational frequency (rpm) of the mixer. A Cole-Palmer variable speed stirring motor was mounted onto a ring stand and positioned above the mixing chamber. The motor speed was controlled by a Fischer Scientific Variable Autotransformer wired directly through the Cole-Palmer speed controller. The motor rotated a 2 inch by 0.5 inch metal paddle. A cylindrical, Plexiglass, baffled mixing chamber measuring 3.7 inches in diameter by 8.5 inches high was used. Four, 0.5 inch baffles positioned 90 degrees apart were located lengthwise in the cylinder.

The mixer was previously calibrated by Werle *et al.* (8) and Lynch (13). This calibration allowed paddle rotational frequency to be converted to mean velocity gradient, G, according to the equation used by Stump and Novak (21):

$$G=\sqrt{\frac{2\pi gNT}{60V\nu\rho}} \qquad [2]$$

where:

G = mean velocity gradient, sec^{-1}

π = 3.143

g = acceleration of gravity, in/sec

N = paddle rotational speed, rpm

T = net torque on paddle, in-oz

V = sample volume, in^3

ν = kinematic viscosity, in^2/sec

ρ = density of water, oz/in^3

Lynch (13) measured torque with a Power Instruments Model 783 torque meter fitted between the motor and the paddle. A General Radio Strobotac strobe light was used to read the torque meter. The volume of sludge used was 0.5 liter. The kinematic viscosity was assumed to be 5.68×10^{-3} in^2/sec, and the density of water at 20 degrees C was assumed to be 0.576 oz/in^3, both from Werle *et al.* (7). Substituting these values, Equation [2] reduces to:

$$G=20.14\sqrt{NT} \qquad [3]$$

Calibration results are shown in Table 1. The rpm of the mixer for a given Variable Autotransformer setting was measured with the General Radio Strobotac strobe light. A plot of log(G) versus log(rpm) was used to determine the mean G value applied to the sludge in the mixer for the measured setting.

Bench-Scale Mixing Intensity Experiments

These experiments used the bench-scale mixing device and a Capillary Suction Time (CST) apparatus to determine the effects of mixing intensity on the sludge dewatering rate at a specific polymer dose.

The dewatering rate was measured with a Triton Type 1165 CST apparatus. The CST apparatus measures the time it takes for the sludge filtrate to travel a fixed distance through filter paper due to capillary suction forces. The device consists of a timing device, an upper plate containing probes that activate and deactivate the timing device, and a lower plate that holds the filter paper and a metal sample container (1). A 10 mm diameter sample container and Whatman #17 chromatography paper were used.

Table 1. Calibration of Bench-Scale Mixing Device. From Lynch (13).

RPM	Torque In Air (in-oz)	Torque In Sludge (in-oz)	Net Torque	G (sec^{-1})
420	0.8	1.8	1.0	410
600	1.2	2.8	1.7	640
1200	2.3	6.2	3.5	1380
1500	2.8	7.1	4.3	1620

A conditioned sludge sample was mixed at one or more of the four G values used in this study, 50 sec^{-1}, 270 sec^{-1}, 520 sec^{-1}, or 630 sec^{-1}. These values were chosen to provide a range of G values used in the various experiments. One-half liter sludge samples were poured into the mixing chamber. Polymer was then poured into the mixing chamber. The mixer was set at the specified speed and then turned on. Mixing occurred for a set time to produce a desired Gt product. A Fischer Scientific stopwatch was used to measure mixing time. The mixer was then stopped, a sample removed and placed in the CST apparatus. Samples were removed from the mixing chamber with a cut-off-tip pipette. After the CST test was completed, the mixer was restarted and the procedure continued. All mix times were cumulative.

Bench-Scale Wedge Zone Device

The wedge zone of a belt filter press was simulated with a wedge zone simulator similar to that used for field testing by the Arus Andritz company (13) (shown in Figure 5). The device consisted of a pneumatic cylinder mounted over a box type dewatering chamber which was arranged on a two-level wooden frame. The wooden frame was raised on two, 4 inch ^{x} 4 inch ^{x} 10 inch high blocks in order to provide

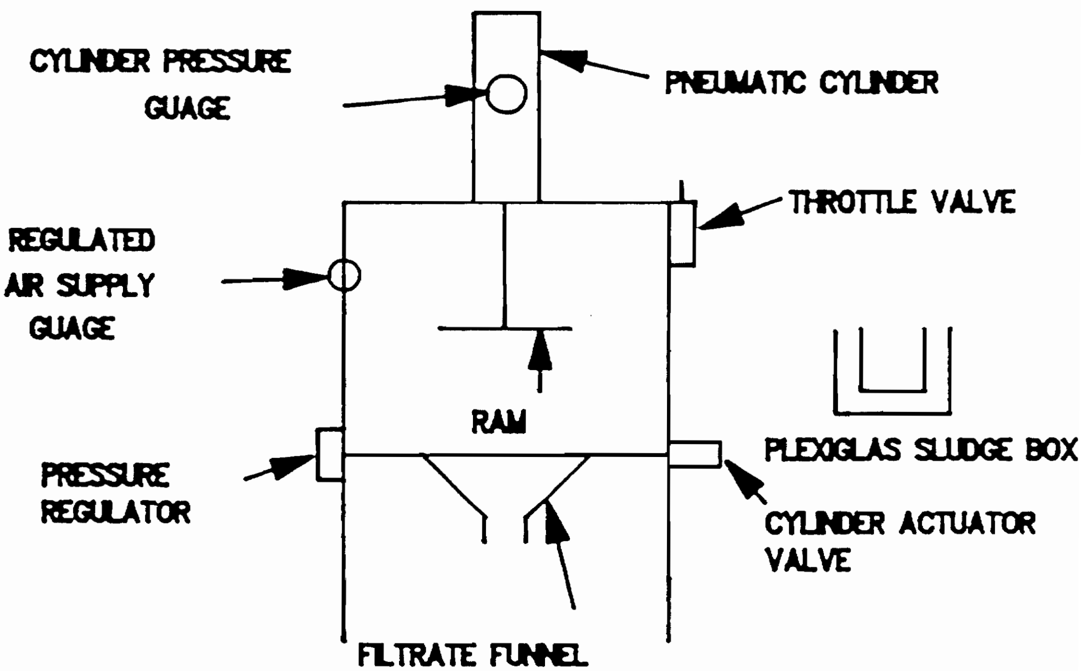

Figure 5. Wedge zone device schematic.

enough room for a 250 mL graduated cylinder to fit below the filtrate funnel. The pneumatic cylinder (Ashcroft A38) pressure was controlled with a standard air pressure regulator. Air pressure was provided by a compressed air tank attached to the pressure regulator. The on-off control of the pneumatic cylinder was set with a dual-action pneumatic switch (Atlas Copoco VA 15 HB2-5).

The dewatering chamber was a square Plexiglass box, 4 inches square by 3 and 3/8 inches deep. The box was open at the top and the bottom was sealed with a 1/16 inch rubber gasket. Both the gasket and the Plexiglass bottom were drilled with a matrix of 1/8 inch holes for filtrate drainage. A piece of belt filter fabric was placed in the box bottom, on top of which a 1/4 inch wide, square perimeter, 1/16 inch rubber gasket was fitted. This second gasket prevented sludge from escaping around the sides of the belt fabric.

The top "ram" component of the dewatering chamber was similar to the bottom, but was smaller so that it fit tightly into the bottom box. A conditioned sludge sample was poured into the bottom box. A piece of filter fabric was placed on top of the sludge sample before the top box was placed within the bottom. This sandwiched the sludge sample between the two pieces of filter fabric. Pressure was applied onto the top box after it was placed within the bottom chamber.

The applied pressure on the sludge cake was a function of the applied pressure in the pneumatic cylinder. A conversion factor of 0.31 psi applied to the sludge per psi gauge applied to the cylinder was determined by Reitz (14). The effect of the perimeter gasket on this conversion increased this conversion factor to 0.33. This was due to the decreased area of the bottom box with the addition of the gasket. The pressures used in the wedge zone experiments were 5, 10 and 20 psi applied to the sludge. These were selected in hopes of providing a wide enough range to gauge pressure effects on dewatering performance. This range is also typical of the pressures seen in the wedge zone of full-scale belt filter presses (1).

Bench-Scale Wedge Zone Experiments

These experiments used the wedge zone device to determine the conditioning requirements exerted by different applied pressures. One purpose of this study was to determine whether a laboratory-scale wedge zone device could adequately predict full-scale belt filter press performance.

Sludge dewatering performance was gauged by several parameters. Free drainage volume (the volume of filtrate to pass through the lower filter fabric in one minute under no applied pressure) was one measure. Another measure was the 3 minute discharge volume, the total volume of filtrate released from the filter cake after an additional two minutes of applied pressure (three minute cycle time). The filtrate volume after two minutes of applied pressure proved to be a clearer indicator of polymer performance than other cycle times. Cake solids of the dewatered cake was used in conjunction with the filtrate quality as the third measure.

One-quarter liter sludge samples were measured in a 500 mL beaker. Polymer was measured in a 50 mL graduated cylinder, and when necessary tap water was added to the polymer dose to increase the volume to 50 mL for every test. This was done so that all samples started with the same total volume of 300 mL.

The contents of the beaker and the graduated cylinder were then poured simultaneously into the mixing chamber. This helped ensure vertical distribution of the polymer within the slurry. The mixer was set at a speed which corresponded to a G value of 50 sec^{-1}. This low G value was selected to minimize the shear encountered in the mixing stage of the experiments. For the Ronile, Inc. sludge the mixer speed corresponded to a G value of 520 sec^{-1}. The polymer manufacturer recommended that a higher mixing intensity would be required with this polymer, Nalco 90WP030, because of the polymer's high molecular weight. Mixing occurred for 20 seconds, imparting a Gt of 1,000 for experiments with the anaerobically digested and alum sludges. For the Ronile, Inc. sludge, mixing occurred for 8 seconds, imparting a Gt of roughly 4,000.

The contents of the mixing chamber were then poured directly onto the filter fabric in the bottom dewatering chamber. Drainage time measurements began at the instant the sludge contacted the filter fabric. Cumulative filtrate volume was measured with a 250 mL graduated cylinder below the filtrate funnel at times of 10, 30 and 60 seconds. Between the 30 and 60 second readings another piece of filter fabric was placed on top of the sludge in the lower box. The upper box was then placed on top of the second piece of filter fabric. After 1 minute of free drainage an applied pressure was exerted by the pneumatic cylinder onto the upper box of the dewatering chamber. Filtrate volume continued to be measured with the graduated cylinder below the filtrate funnel and the "upper" graduated cylinder. The upper cylinder was connected to a vacuum pump and a cut-off-tip pipette which collected the filtrate pushed through the top piece of filter fabric. Measurements were taken at 30 second intervals for 4 minutes, at which time the pressure was switched off and the test completed, after a total cycle time of 5 minutes. This procedure was repeated for several polymer doses at each applied pressure.

Duplicates of every experimental condition were performed, and the data collected were averaged to reflect a more representative result. The reproducibility of these experiments was confirmed, and the expected variability was quantified by performing duplicate experiments.

Cake solids and filtrate solids were determined with the procedures described in *Standard Methods For the Examination of Water and Wastewater* (20).

Preliminary results revealed that the optimum polymer dose was barely affected by applied pressure exerted by the wedge zone tester. This led to the hypothesis that the optimum polymer dose may be more influenced by the shear imparted in the conditioning step of the procedure than the applied pressure stage. Verification of this subsequent hypothesis led to the need for experiments which varied the mixing during conditioning, also referred to as the conditioning energy. The mixing during conditioning experiments followed the exact procedures previously described with the exception of the selected G value of the mixer and the mixing time. All conditioning energy experiments were performed with the second batch of alum sludge, and were conditioned with Betz 1120 polymer. The applied pressure was held at 5 psi for this group of experiments.

Full-Scale Experiments

Experiments were performed with full-scale belt filter presses at two wastewater treatment facilities. A different polymer was used at each test site. Wedge zone experiments and mixing intensity experiments were performed simultaneously at only one of these locations. However, wedge zone and mixing intensity experiments were performed later with a batch of sludge obtained from the other facility.

Stockhausen D4160 polymer was evaluated at Peppers Ferry municipal wastewater treatment plant, Radford, VA, on February 26-27, 1990. The experimental design varied belt speed, polymer dose and sludge throughput to evaluate polymer performance. Two groups of experiments were run at different sludge throughputs. Operational parameters sampled and measured to gauge polymer performance included influent solids, gravity drainage solids, cake solids and filtrate solids. These parameters were used at each full-scale test site. A complete bench-scale test matrix was later performed in June, 1990.

The Peppers Ferry facility treats municipal wastewater with an activated sludge system. Residual streams from the primary and secondary clarifiers are thickened with a dissolved air floatation (DAF) unit. Thickened sludge from the DAF unit is stabilized in an anaerobic digester. Anaerobically digested sludge is then conditioned, and dewatered with a belt filter press.

Nalco 90WP030 was evaluated at the wastewater plant of Ronile, Inc., Rocky Mount, VA, on July 25, 1990. A three-variable experimental design was run to evaluate polymer performance. The variables used were belt speed, polymer dose and sludge throughput. A complete bench-scale test matrix, including mixing intensity and wedge zone experiments, was performed simultaneously on-site.

The Ronile, Inc. wastewater facility treats textile dying waste in an aerated lagoon. The waste stream then passes through a secondary, flocculation system. The sludge which settles out of the flocculators is comprised virtually of all color colloids and no suspended solids. Sludge drying beds are used as the primary dewatering option; however, a belt filter press is on-site for overflow conditions and winter use.

Results and Discussion

This section will present and discuss the results obtained from this study in six areas. The effects of mixing intensity on polymer requirements during bench-scale mixing experiments will be covered first. Next, the effects of applied pressure on polymer requirements during wedge zone experiments will be addressed. The third topic will involve correlating the effects of mixing intensity and applied pressure on conditioning requirements. Following this, the effects of the mixing during conditioning on wedge zone experiments will be detailed. Full-scale results from the two wastewater treatment facilities will then be presented. Finally, a comparison of laboratory-scale and full-scale results will be discussed.

Polymer Dose and Mixing Intensity

Several sludges and polymers were used in the investigation of the relationships between mixing intensity and polymer conditioning requirements. Anaerobically digested sludge from Peppers Ferry, Radford, Virginia was conditioned with Stockhausen D4160 polymer for one group of data. Alum sludge from a munitions manufacturer in Southwest Virginia was conditioned with Betz 1120 polymer for the second data set. Secondary sludge from Ronile, Inc. (Rocky Mount, Virginia) was conditioned with Nalco 90WP030 for the final group of data. For each sludge, the bench-scale mixing device and the CST apparatus were used.

Anaerobically Digested Sludge Response

Mixing intensity experiments performed with anaerobically digested sludge and Stockhausen D4160 polymer used polymer doses between 200 mg/L and 600 mg/L. The bench-scale mixing device was set at an approximate G value of 630 sec^{-1}. The mixing time was varied to yield a range of mixing energy inputs: Gt = 5,000, 10,000, 20,000, 30,000, 40,000 and 60,000. For each dose, Gt versus CST curves were generated. A minimum CST value or range corresponds to optimum dewatering conditions. The top portion of Figure 6 shows these results for several selected doses.

In general, as the mixing energy input (Gt) increased, polymer conditioning requirements for optimum dewatering also increased, as shown in the lower half of Figure 6. These results agree with the previous work of several researchers (8 - 14). An optimal dose range is used instead

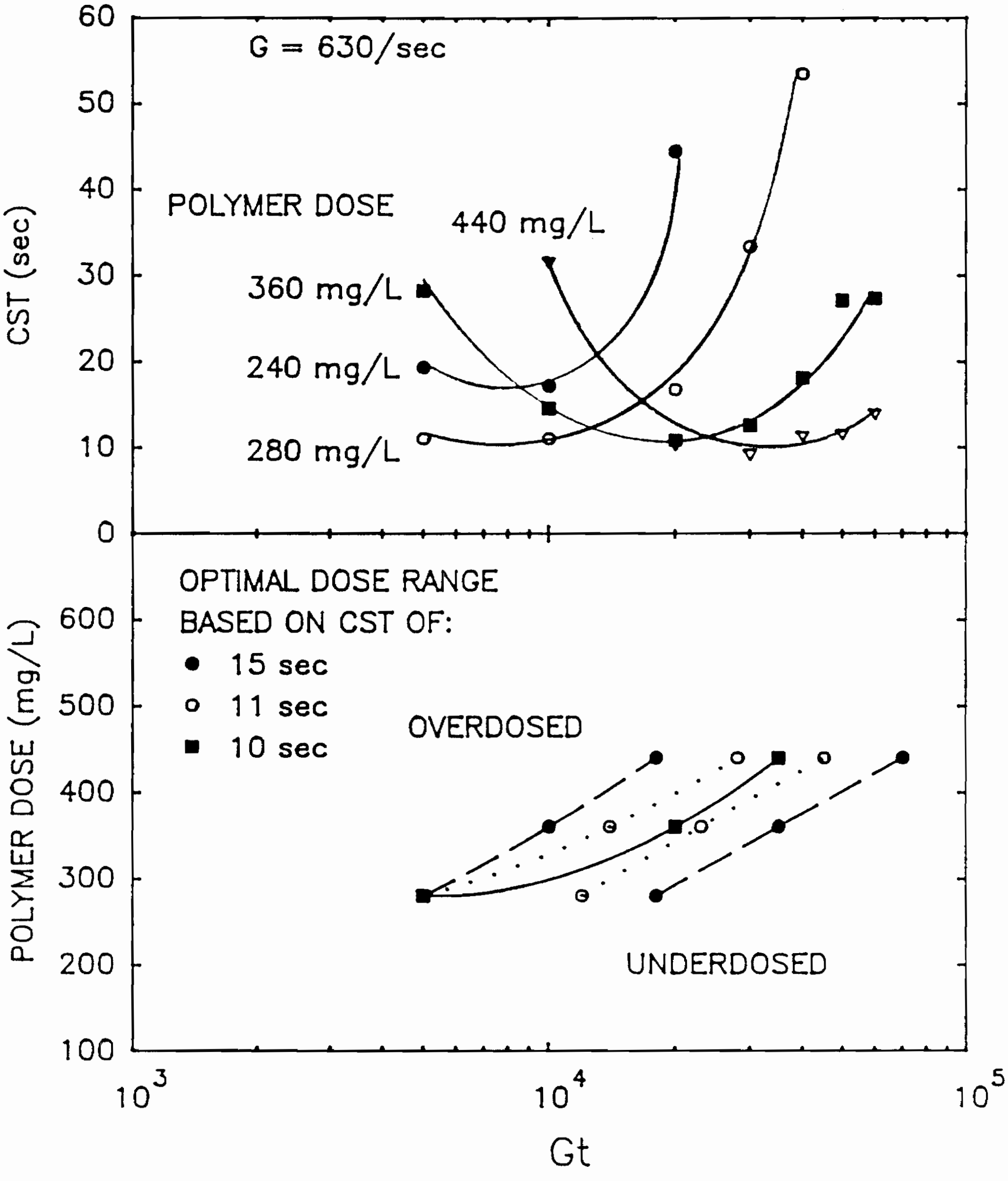

Figure 6. Effect of Gt on the dewatering rate of anaerobically digested sludge conditioned with Stockhausen D4160 polymer. Dry solids concentration averaged 3.4%.

of a single optimum dose to define the range of acceptable polymer doses for given mixing conditions. If a CST value of 15 seconds, 11 seconds, or 10 seconds is assumed to indicate a properly conditioned sludge, this range of Gt values can then be plotted as a function of polymer dose to generate the lower portion of Figure 6.

The minimum CST obtainable was roughly 10 seconds for each polymer dose. The shape of each of these curves was similar. Finally, both overdosed and underdosed regions existed. Overdosed conditions result from excessive surface coverage and charge reversal by the polymer. Underdosed conditions result from excessive mixing which causes floc rupture or disaggregation.

Alum Sludge Response

Alum sludge and Betz 1120 polymer were also used for mixing intensity experiments. This sludge was chosen because its characteristics did not change appreciably over time, so a range of studies could be conducted without regard to the possibility that the sludge was changing. The polymer was selected based on prior success with this product for conditioning alum sludges. Polymer doses ranged between 50 mg/L and 200 mg/L. The bench-scale mixing device was set at an approximate G value of 630 sec^{-1}. The mixing time was varied to yield a range of mixing energy inputs: Gt = 5,000, 10,000, 20,000 and 30,000. Figure 7 summarizes the results of the mixing intensity experiments performed with alum sludge. As with the anaerobically digested sludge, polymer conditioning requirements increased as mixing energy input increased.

Secondary Sludge Response

Mixing intensity experiments performed with secondary sludge and Nalco 90WP030 polymer used polymer doses between 400 mg/L and 800 mg/L. The bench-scale mixing device was set at an approximate G value of 520 sec^{-1}. The mixing time was varied to yield a range of mixing energy inputs: Gt = 8,000, 16,000, 23,000, 31,000 and 39,000. The general trend of increased polymer conditioning requirements for increased mixing energy was seen again in Figure 8.

The common thread between all these experiments was that as the mixing energy input increased, polymer conditioning requirements to produce an adequate dewatering rate also increased. This result was expected from the literature, and is believed to have a relationship to polymer requirements for full-scale dewatering units. If

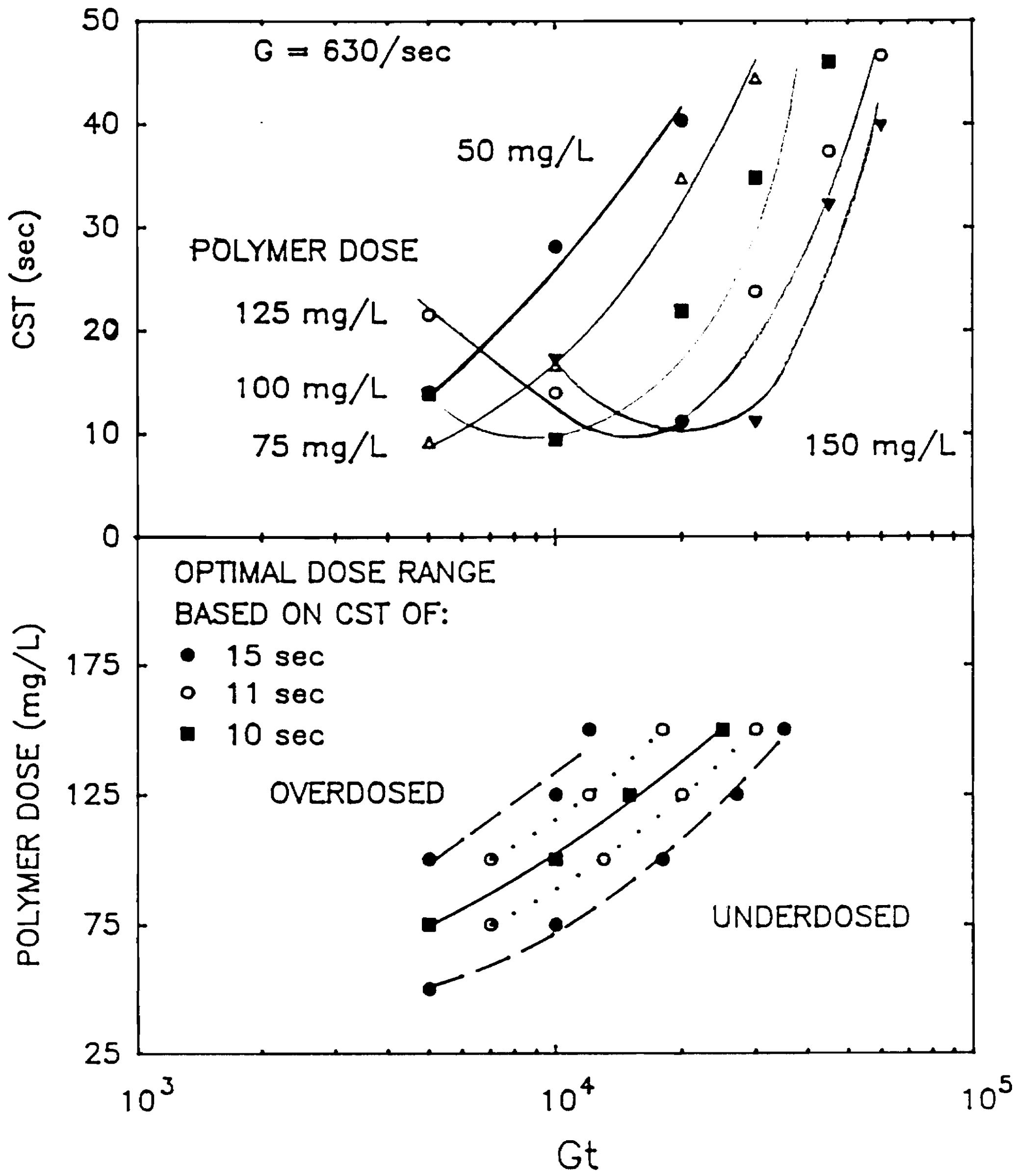

Figure 7. Effect of Gt on the dewatering rate of alum sludge conditioned with Betz 1120 polymer. Dry solids concentration averaged 3.4%.

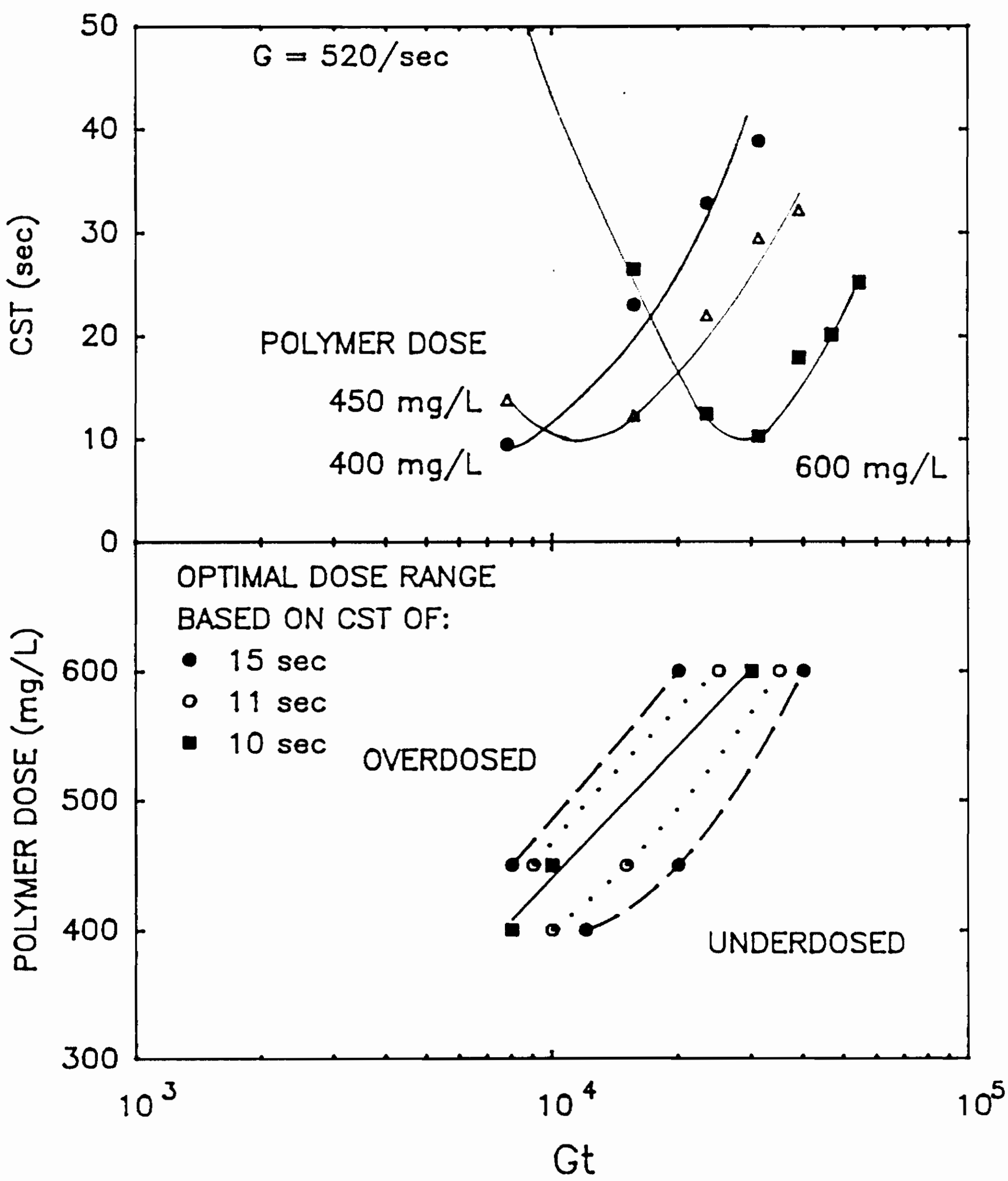

Figure 8. Effect of Gt on the dewatering rate of secondary sludge conditioned with Nalco 90WP030 polymer. Dry solids concentration averaged 3.2%.

the shear imparted by a mechanical device can be determined, the polymer dose required to optimize press performance could be predicted with these bench-scale mixing experiments. This would eliminate the need to perform costly full-scale experiments, and would allow a rapid and accurate modification of polymer selection and dose as sludge characteristics change.

Polymer Dose and Applied Pressure

The same three sludges and polymers used to investigate mixing intensity effects were also used to elucidate the conditioning requirements exerted by a range of applied pressures. The bench-scale wedge zone simulator was operated at applied pressures of 5 psi, 10 psi, and 20 psi over a range of polymer doses for each sludge. Filtrate production, cake solids and filtrate solids were each measured and used as gauges of sludge dewaterability. The bench-scale mixing device was used to condition the sludge before it was placed into the dewatering chamber of the wedge zone simulator.

Anaerobically Digested Sludge Response

Wedge zone experiments performed with anaerobically digested sludge and Stockhausen D4160 polymer used polymer doses between 100 mg/L and 500 mg/L. The bench-scale mixing device was set at an approximate G value of 50 sec^{-1}. The mixing time lasted for twenty seconds, imparting a mixing energy input of Gt = 1,000 during the conditioning step of the experiment.

The combination of cake solids and filtrate solids data versus polymer dose helped define the optimum dose for each applied pressure test, as shown in Figure 9. As the applied pressure increased, the maximum cake solids obtainable also increased. This response to the magnitude of the pressure would agree with results found by Halde (18). In general, as the polymer dose increased, cake solids increased and filtrate solids decreased.

Cake solids approached a maximum as polymer dose increased to a certain point, then declined slightly with excess polymer addition. Data from the 10 psi applied pressure test clearly displayed this trend. This characteristic shape was seen in these experiments and the inflection point of the curve tended to mark the optimum polymer dose, 250 mg/L in this case. Selection of a clear optimum dose is often difficult, and debateable.

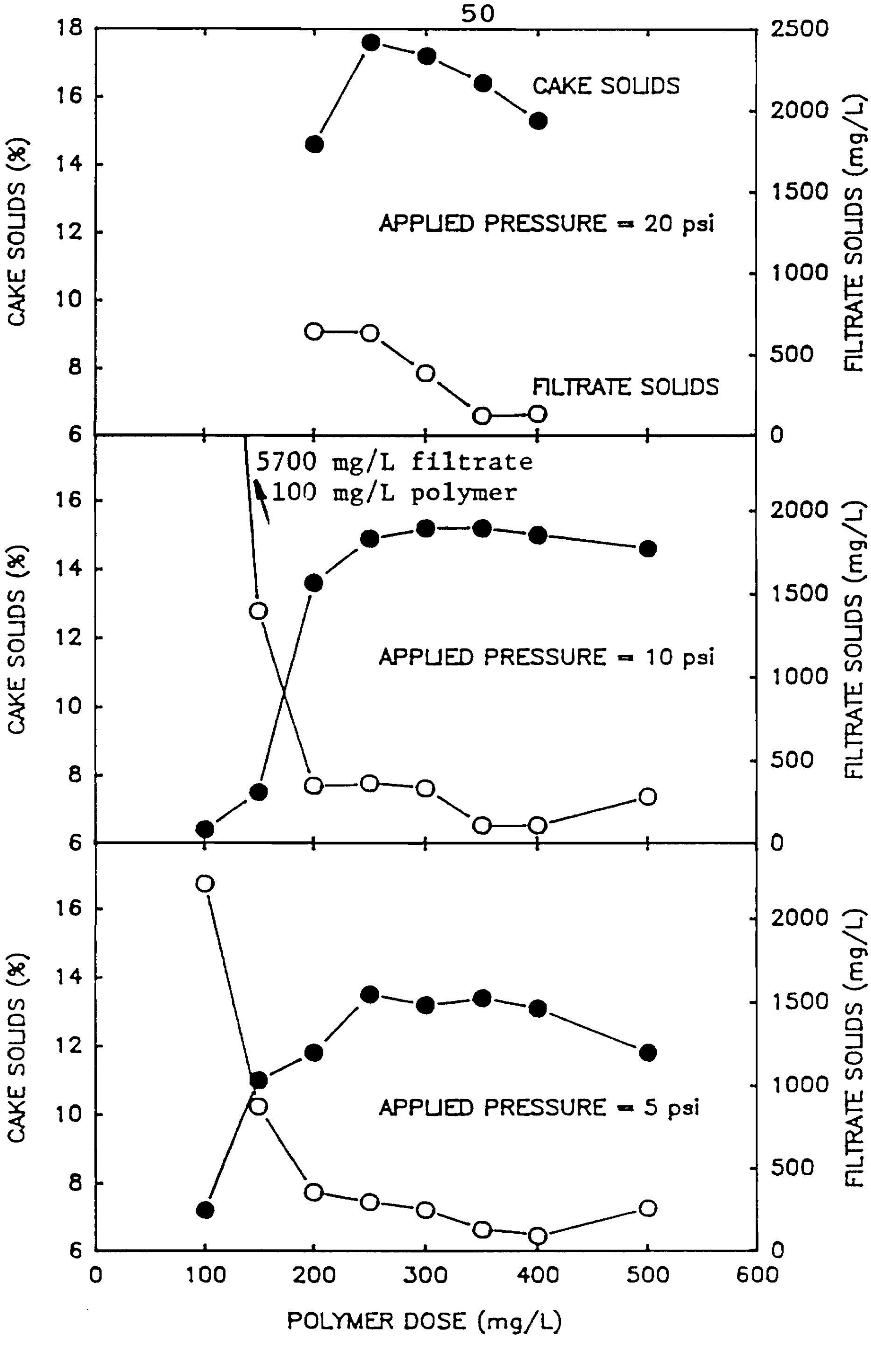

Figure 9. Cake solids and filtrate solids versus polymer dose for anaerobically digested sludge conditioned with Stockhausen D4160 polymer under three applied pressures.

The exact nature of the response seemed to be a function of the applied pressure. At the lowest applied pressure the increase in cake solids with dose was more gradual. At the applied pressure of 10 psi a dramatic increase in cake solids was observed with increasing dose. Finally, at the highest applied pressure the optimum dose was clearly defined. It can be also seen that the optimum dose for cake solids was the same regardless of the applied pressure. This was the first indication that the range of applied pressures exerted by the wedge zone simulator produced a limited additional polymer demand for optimum conditioning.

As shown in Figure 9, the filtrate solids approached a minimum as polymer dose increased. Data from the low pressure test best displayed this trend. Filtrate solids of roughly 500 mg/L were considered to be an acceptable filtrate quality. The optimum dose to attain an acceptable filtrate quality was 200 mg/L for the 5 psi and 10 psi tests. However, as the applied pressure was increased to 20 psi the polymer dose required to maintain an acceptable filtrate quality increased to 300 mg/L. It is suspected that this occurred because at the highest pressure, sludge flocs were ruptured and then forced through the filter fabric. The deterioration of filtrate quality at higher pressures suggested that some shear effects were imparted by the wedge zone simulator.

Two other measures of cake dewatering (free drainage volume and the 3 minute discharge volume) are presented in Figure 10 for the three pressure tests. These parameters were also useful for predicting an optimum dose. Both measures of filtrate production approached a maximum as the polymer dose increased, and then decreased slightly. The polymer doses capable of optimizing the free drainage volume also optimized the discharge volume. This suggests that gravity drainage should be maximized to optimize total water removal.

The shape of the curves also seemed to be a function of the applied pressure and closely resembled the cake solids response. However, the inflection points which tended to mark the optimum dose were slightly different for each parameter. As previously noted, the optimum polymer dose for cake dry solids concentration was 250 mg/L regardless of the applied pressure. The optimum dose for filtrate solids was 200 mg/L for the 5 psi and 10 psi tests, and 300 mg/L for the 20 psi test. If the free drainage volume was used the optimum dose would have been 250 mg/L. Finally, if the 3 minute discharge volume was used, the optimum dose would have been 200 mg/L regardless of the applied pressure.

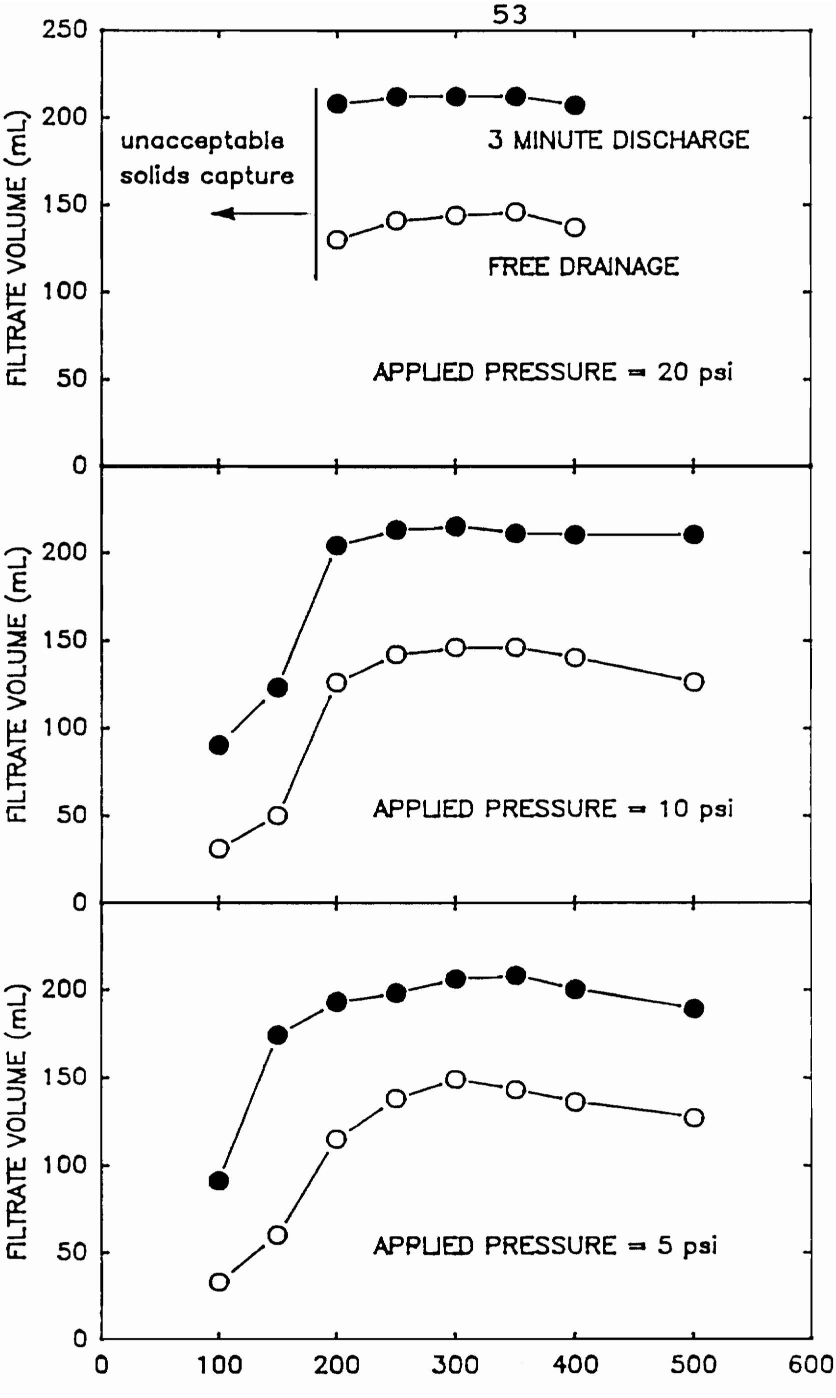

Figure 10. Three minute discharge volume and free drainage volume versus polymer dose for anaerobically digested sludge conditioned with Stockhausen D4160 polymer under three applied pressures.

A comparison of these gauges of dewaterability provides some insight into the effects of applied pressure on conditioning requirements. First, the optimum polymer dose was marginally affected by the range of applied pressures used. Second, the combination of cake solids and filtrate solids most clearly defined the optimum dose. Third, free drainage volume tended to better predict the optimum dose than the 3 minute discharge volume. Finally, the effect of applied pressure was most clearly seen as a decrease in filtrate quality, and that additional polymer was required to maintain an acceptable filtrate quality at higher pressures.

Alum sludge response

Alum sludge and Betz 1120 polymer were used to perform another group of wedge zone experiments. Polymer doses ranged between 30 mg/L and 150 mg/L. The bench-scale mixing device was set at a G value of 50 sec^{-1}. The mixing time lasted for 20 seconds, imparting a Gt of 1,000 during the conditioning step of the experiment.

Results from the experiments performed with alum sludge displayed similar responses with those performed with the anaerobically digested sludge. The combination of cake solids and filtrate solids versus data polymer dose for each applied pressure are shown in Figure 11. As polymer dose was increased to a certain point, cake solids increased and filtrate solids decreased. As the applied pressure increased, the maximum obtainable cake solids increased and, for a given polymer dose, filtrate solids increased.

The shape of both cake solids and filtrate solids versus polymer dose was similar to the other sludges tested. The shape of these curves also depended on the applied pressure. The inflection points of all three cake solids curves tended to mark the same optimum polymer dose at 80 mg/L. This supports the preliminary conclusion that the range of applied pressures exerted by the wedge zone simulator produced a limited additional polymer demand for optimum conditioning.

However, filtrate quality was seen to be dependent on the applied pressure. The optimum dose to attain an acceptable filtrate quality was 80 mg/L for the 5 psi and 10 psi tests, and 100 mg/L for the 20 psi test. At the highest pressure, ruptured sludge flocs were apparently forced through the filter fabric. Unlike the anaerobically digested sludge which could be conditioned to produce an acceptable filtrate quality even at the highest applied pressure, the alum sludge could not. This suggests that even properly conditioned alum sludge flocs are susceptible to floc rupture at the highest pressure tested.

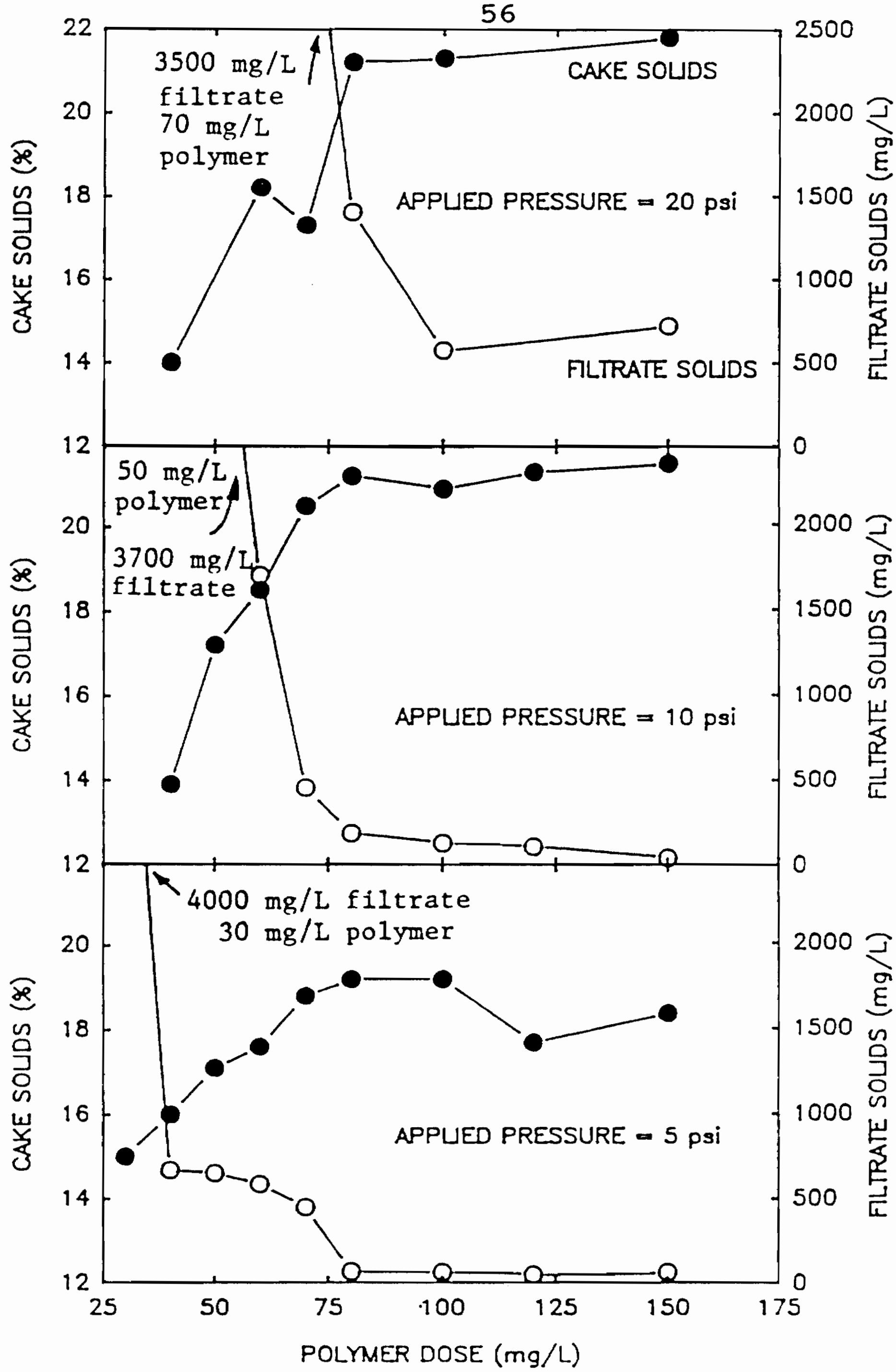

Figure 11. Cake solids and filtrate solids versus polymer dose for alum sludge conditioned with Betz 1120 polymer under three applied pressures.

A comparison of the 3 minute discharge volume and the free drainage volume obtained at the three pressures are shown in Figure 12. As polymer dose increased filtrate production increased, and then decreased slightly. The inflection point on the free drainage volume curve was more pronounced than the 3 minute discharge volume curve.

Pressure effects on the extent of dewatering of alum sludge conditioned with two different polymer doses are shown in Figure 13. Filtrate production was lowest at the highest pressure for both polymer doses. Fragile alum sludge flocs seemed to be adversely affected by the highest applied pressure. Because of the fragile nature of some sludges a high pressure dewatering process may not be a feasible option. Even a properly conditioned sludge may not yield acceptable solids capture under these conditions.

A summary of the optimum polymer doses predicted by these measures of dewaterability displayed a similar response to the anaerobically digested sludge results. First, the optimum dose was marginally affected by the range of applied pressures used. Second, the combination of cake solids and filtrate solids produced the clearest picture of conditioning requirements and optimum dose. Third, free drainage volume was an excellent indicator of optimum dose; however it cannot account for filtrate quality deterioration that may occur due to pressure effects. Finally, free

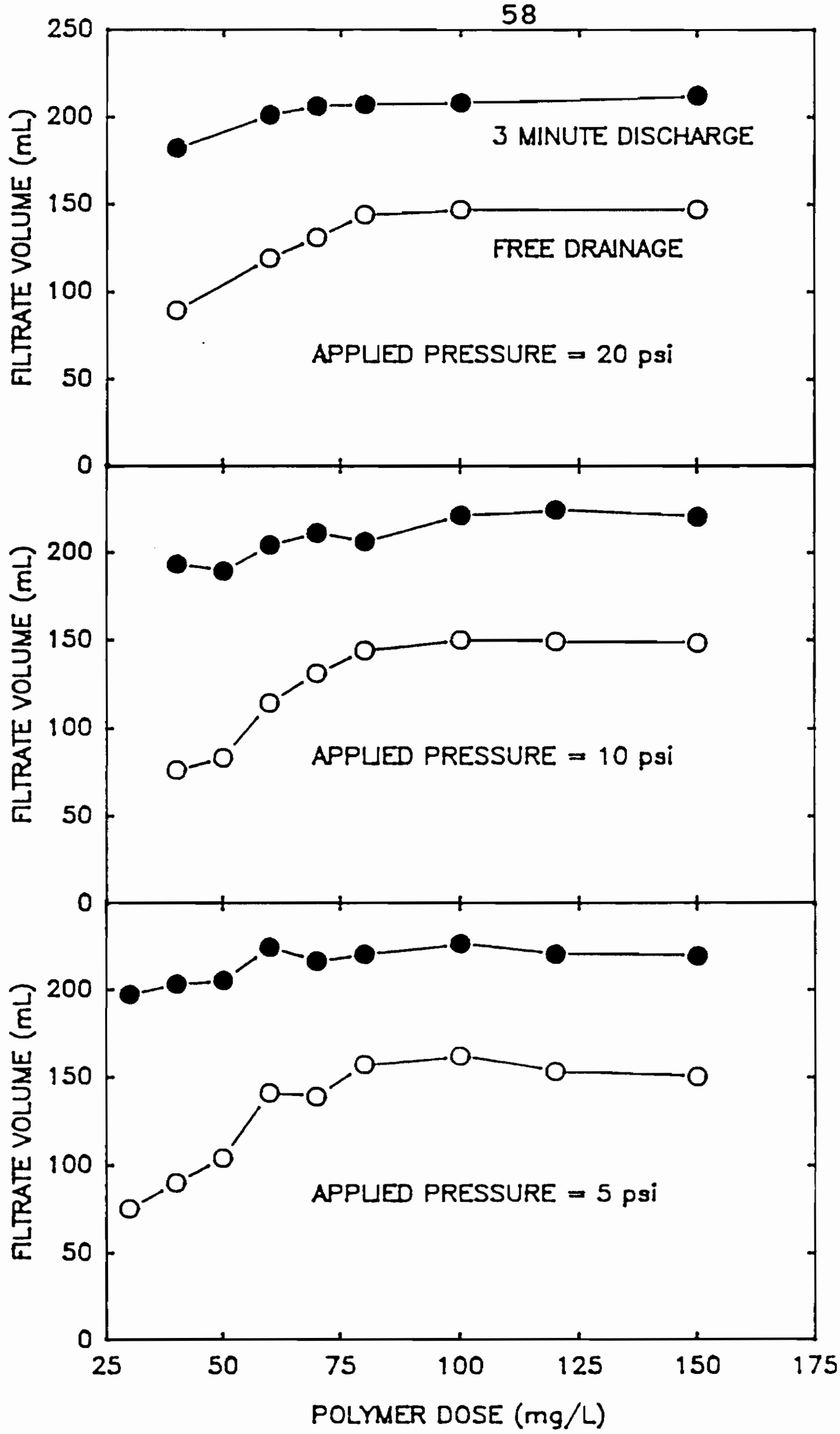

Figure 12. Three minute discharge volume and free drainage volume versus polymer dose for alum sludge conditioned with Betz 1120 polymer under three applied pressures.

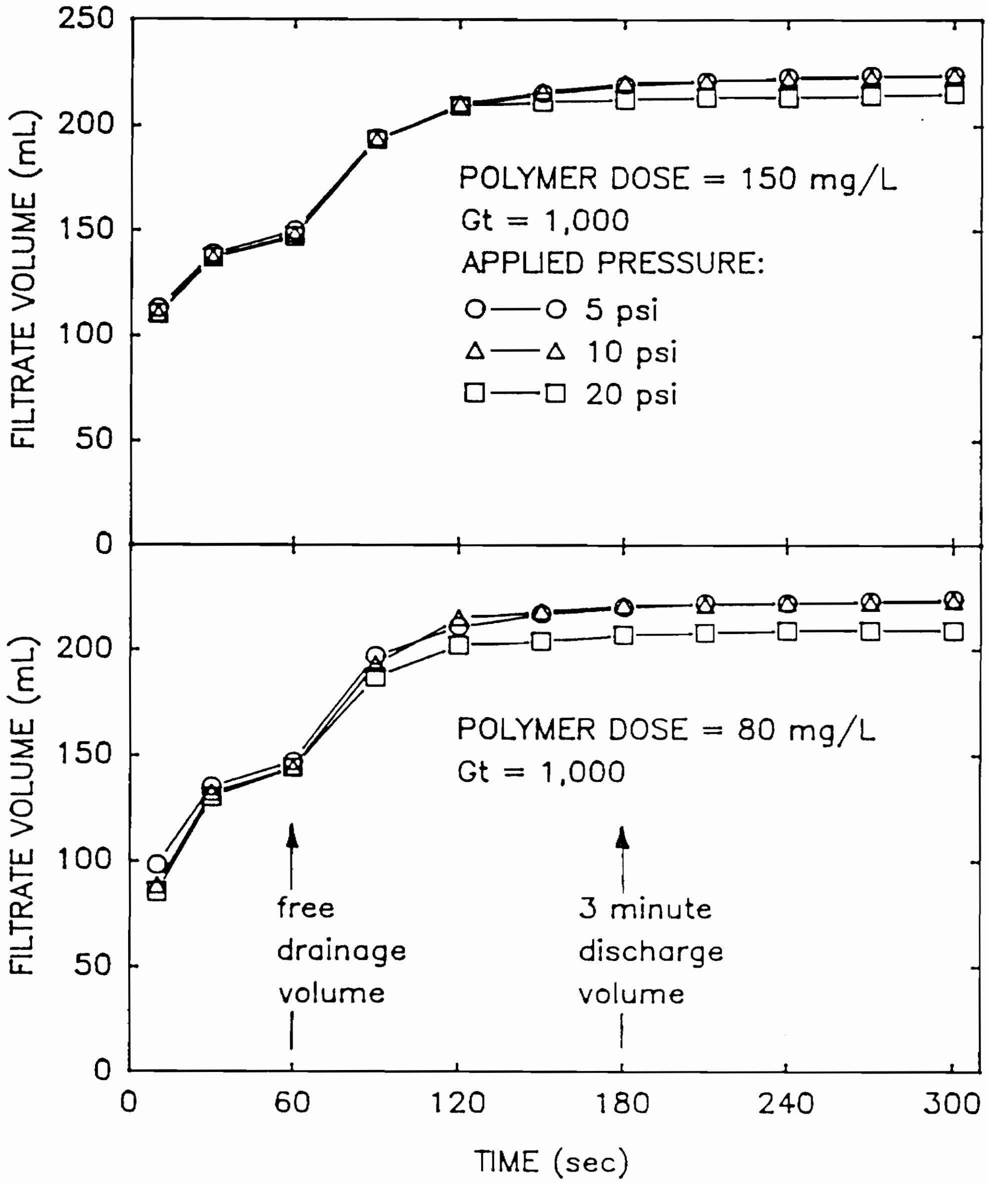

Figure 13. Filtrate volume versus time for alum sludge under three applied pressures conditioned with two doses of Betz 1120 polymer.

drainage was a better indicator of polymer performance than a press discharge volume.

Secondary Sludge Response

Wedge zone experiments performed with secondary sludge and Nalco 90WP030 polymer used doses between 300 mg/L and 600 mg/L. Two batches of sludge were used for these experiments. Influent dry solids concentrations of the two batches were 3.2 % and 2.5 %, respectively. The 10 psi applied pressure tests used the first batch at 3.2 % solids. The 5 psi and 20 psi pressure test used the second batch at 2.5 %. Polymer dose units were not converted from mg/L to lb/dry ton because the dewatering response was virtually independent of the influent dry solids concentration. This suggested that other sludge properties, such as color colloid concentration, may need to considered for initial estimates of polymer dose requirements.

The bench-scale mixing device was set at a G value of 520 sec^{-1}. The mixing time lasted 8 seconds, which imparted a mixing energy input of roughly Gt = 4,000 during conditioning. The higher G and Gt values used for this group of experiments were suggested by the polymer manufacturer. Due to the large size of the polymer molecule more vigorous mixing was required to get the polymer evenly distributed throughout the sludge samples.

Figure 14 shows cake solids and filtrate solids concentration data versus polymer dose for each applied pressure test. The results were similar to both the anaerobically digested and the alum sludges' responses. As polymer dose increased to a certain point, cake solids increased and filtrate solids decreased. As the applied pressure increased, the maximum obtainable cake solids increased, and the filtrate quality decreased.

The characteristic shape of both cake solids and filtrate solids versus polymer dose were evident again. The shape of these curves also depended on the applied pressure. At the lowest pressure, the increase in cake solids with dose was gradual with no dramatic inflection point. At the two higher pressures, a more defined increase in cake solids was observed with dose. The optimum dose for cake solids was roughly 450 mg/L regardless of the applied pressure. As seen with the other sludges tested, the range of pressures exerted by the wedge zone tester produced a limited additional polymer demand for optimum conditioning.

The deterioration of filtrate quality at higher pressures was also seen. The optimum dose to attain an acceptable filtrate quality was 400 mg/L for the 5 psi test, 450 mg/L for the 10 psi test, and 500 mg/L for the 20 psi

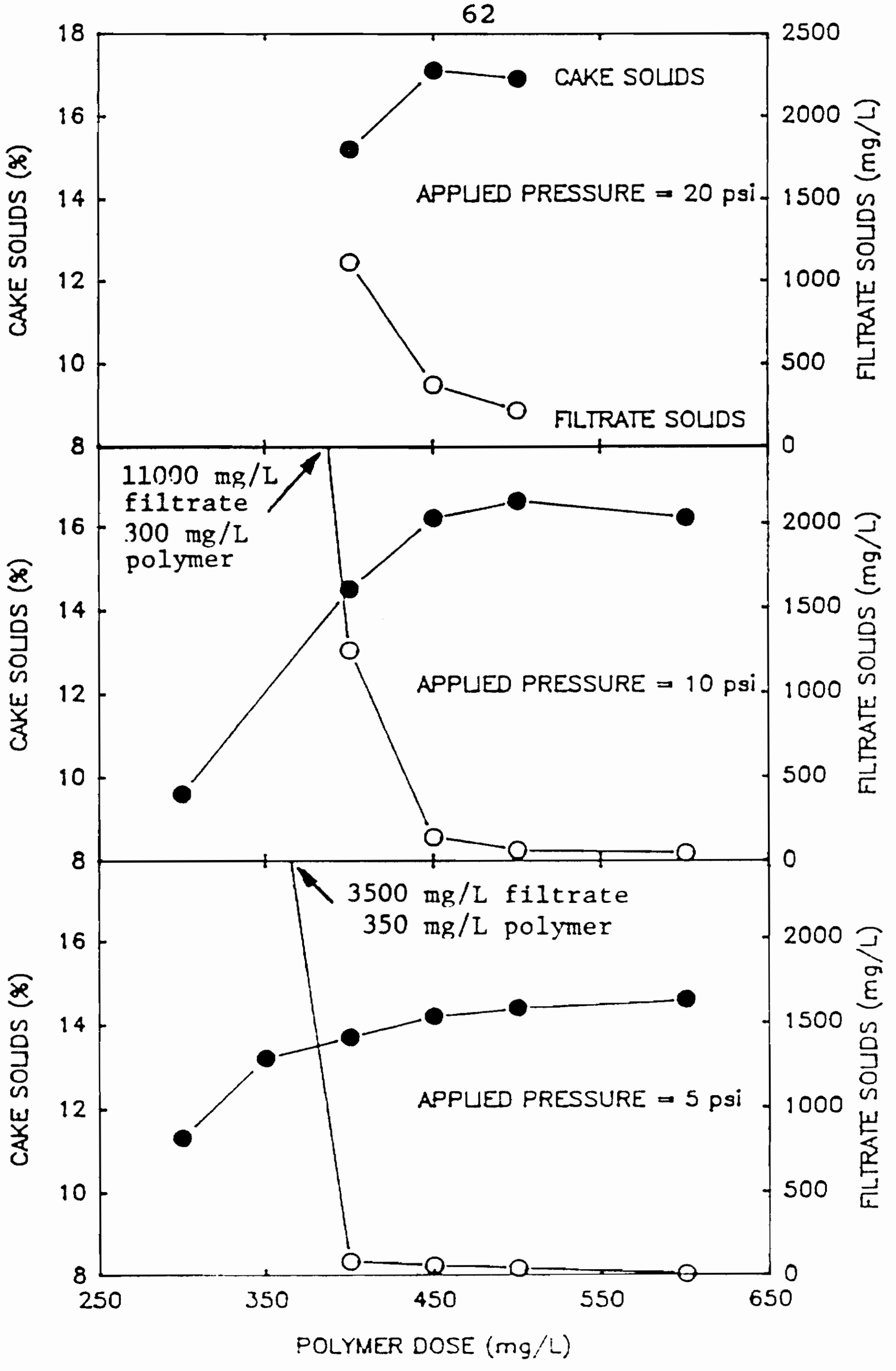

Figure 14. Cake solids and filtrate solids versus polymer dose for secondary sludge conditioned with Nalco 90WP030 polymer under three applied pressures.

test. Solids forced through the filter fabric at higher pressures accounted for this. Filtrate quality was shown to be pressure dependent, as seen with the other sludges tested.

Data related to filtrate production versus polymer dose for the three applied pressure tests are shown in Figure 15. Free drainage volume versus polymer dose responded very similarly to cake solids at each pressure. The optimum dose for free drainage volume was also 450 mg/L. The 3 minute discharge volume did not predict an optimum dose as clearly as the free drainage results.

The results from the applied pressure experiments with secondary sludge support the conclusions drawn from the identical experiments performed with anaerobically digested and alum sludges. Considering the differences in the nature and characteristics of these three sludges, it is significant that they all responded similarly. An overall summary of the optimum doses predicted for each sludge at each applied pressure is shown in Figure 16. The polymer dose required to optimize cake solids was independent of the applied pressure for each sludge tested. The polymer dose required to attain satisfactory filtrate quality was always greater for the 20 psi test than for the 5 psi test.

A general description of the conditioning requirements for sludge dewatering within the wedge zone of a belt filter

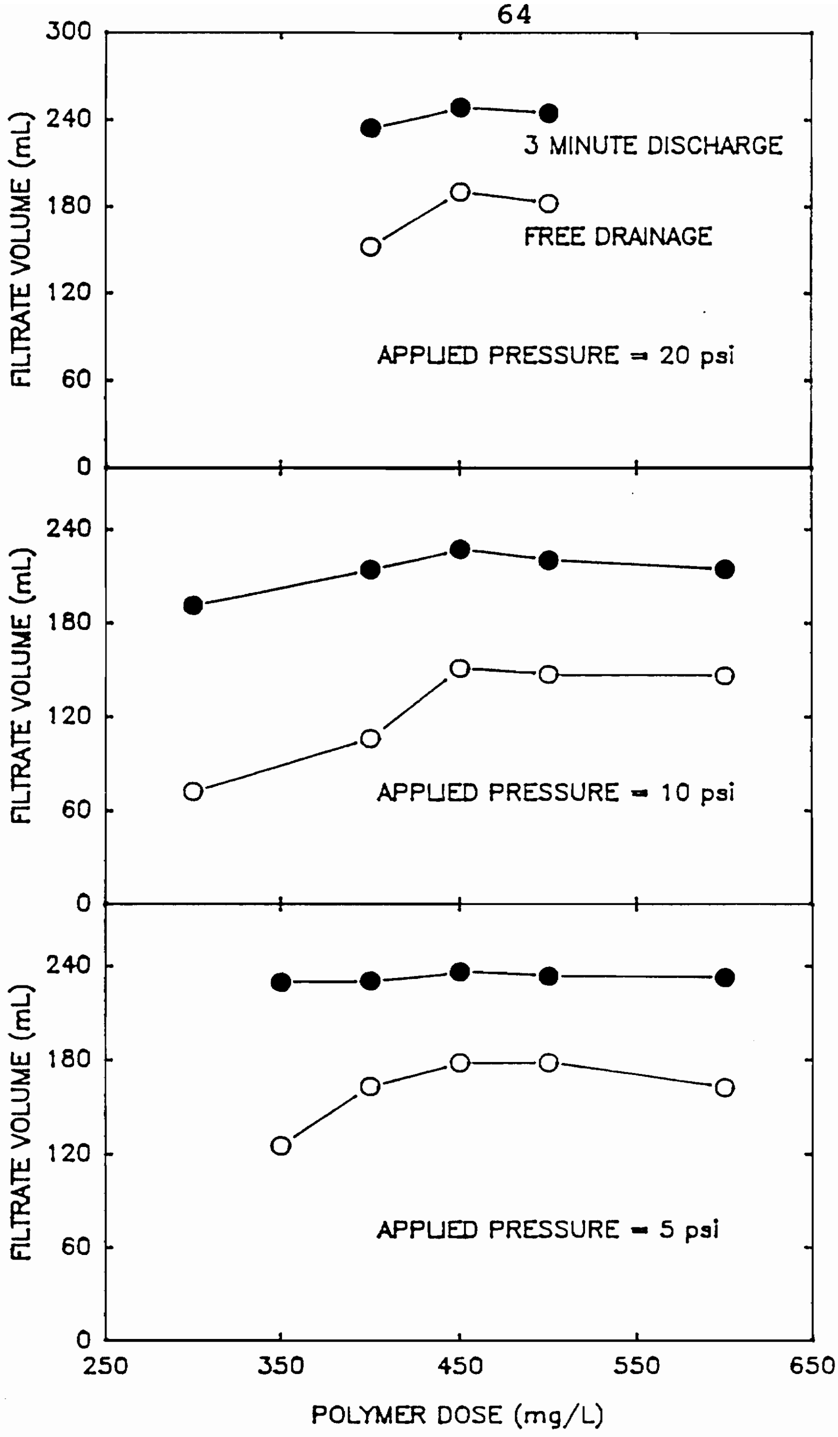

Figure 15. Three minute discharge volume and free drainage volume versus polymer dose for secondary sludge conditioned with Nalco 90WP030 polymer under three applied pressures.

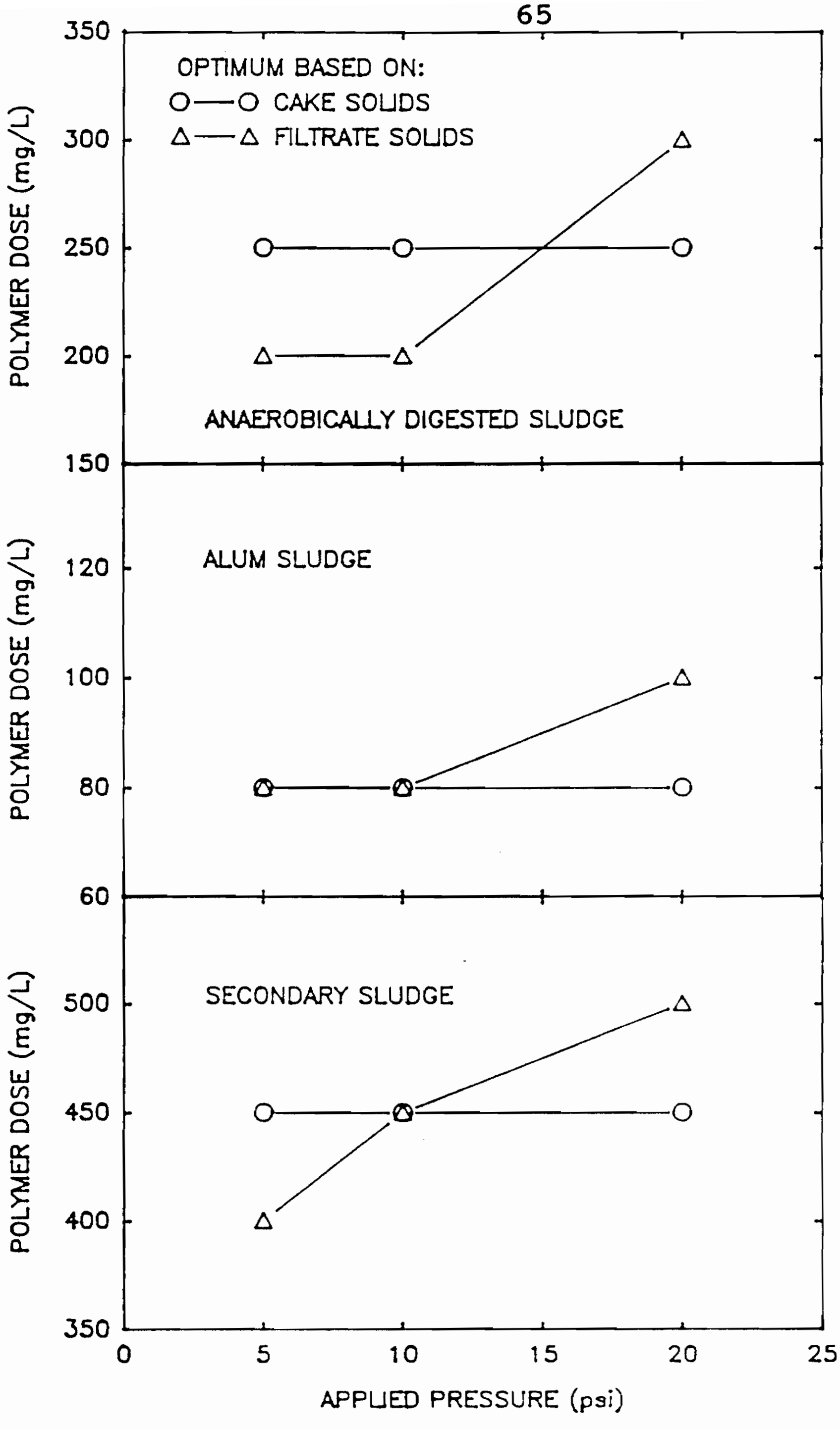

Figure 16. Optimum polymer dose versus applied pressure for anaerobically digested, alum, and secondary sludges.

press may be proposed from these results. The range of applied pressures used in this study did not exert a significant additional polymer demand for optimum conditioning. The free drainage volume was shown to be an excellent indicator for optimum dose selection. In fact, the optimum dose predicted by cake solids concentration was identical to the dose predicted by free drainage volume for each sludge tested. These two results imply that conditioning for the gravity drainage zone of a belt filter press may produce optimum results.

A second conclusion can be drawn from the fact that the optimum dose for cake solids and free drainage volume are very similar. The mixing energy input imparted during the conditioning step in a dewatering process may be significantly contributing to the polymer dose requirements. Superflocculation of the sludge prior to reaching the press is required to obtain good performance (1 - 3). The mixing energy which produces superflocculation is completely independent of the operating parameters of the press, excluding the polymer feed location. Therefore, optimizing polymer dose based on the Gt imparted during conditioning may optimize belt filter press performance.

The deterioration of filtrate quality as the applied pressure was increased cannot be easily explained by the previous conclusions. However, physically it is quite easy to explain. As the applied pressure was increased, sludge flocs were ruptured and accounted for the poorer filtrate quality. The fact that this occurred only at the higher pressures suggested that the range of pressures used in this study were near the threshold of where pressure effects would have a more significant impact. Finally, the physical nature of the sludge may limit the types of mechanical processes used for dewatering. Alum sludge displayed a fragile nature that may not dewater satisfactorily in high pressure equipment. The biological sludges did not seem to exhibit this limitation in the pressure range tested.

Mixing Intensity and Applied Pressure

The correlation of bench-scale mixing intensity experiments and wedge zone applied pressure tests will be analyzed in this section. Evaluation of Gt as a function of pressure will be investigated. A predicted Gt value of the wedge zone simulator will be proposed. Data collected from experiments with anaerobically digested, alum and secondary sludges will be reviewed.

Conditioning requirements predicted by the bench-scale mixing device and by the wedge zone simulator for anaerobically digested sludge are shown in Figure 17. Graphical interpretation of the data was used to estimate a Gt value of the wedge zone tester. The optimum polymer dose predicted from the applied pressure tests can be mapped into the optimum dose (CST value of 10 seconds) predicted from the mixing intensity experiments. The Gt value associated with this predicted dose can be used as the estimated Gt imparted by the wedge zone tester. These results would suggest that the Gt imparted by the wedge zone tester during the applied pressure tests was between 5,000 and 10,000.

Figure 18 is a compilation of the same results for alum sludge. The optimum polymer dose range for the wedge zone tester corresponded to a range of Gt values between 5,000 and 10,000.

A comparison of the effects of Gt and applied pressure on the conditioning requirements of secondary sludge is shown in Figure 19. A range of Gt values between 9,000 and 15,000 corresponded to the predicted polymer dose range for the wedge zone simulator. The higher predicted Gt value of the wedge zone from these experiments may have been due to the greater mixing energy input used during conditioning.

Evaluation of these three sets of data suggest that the Gt value imparted by the wedge zone simulator is roughly between 5,000 and 15,000, when operated in the range of applied pressures used in this study. This is a reasonable

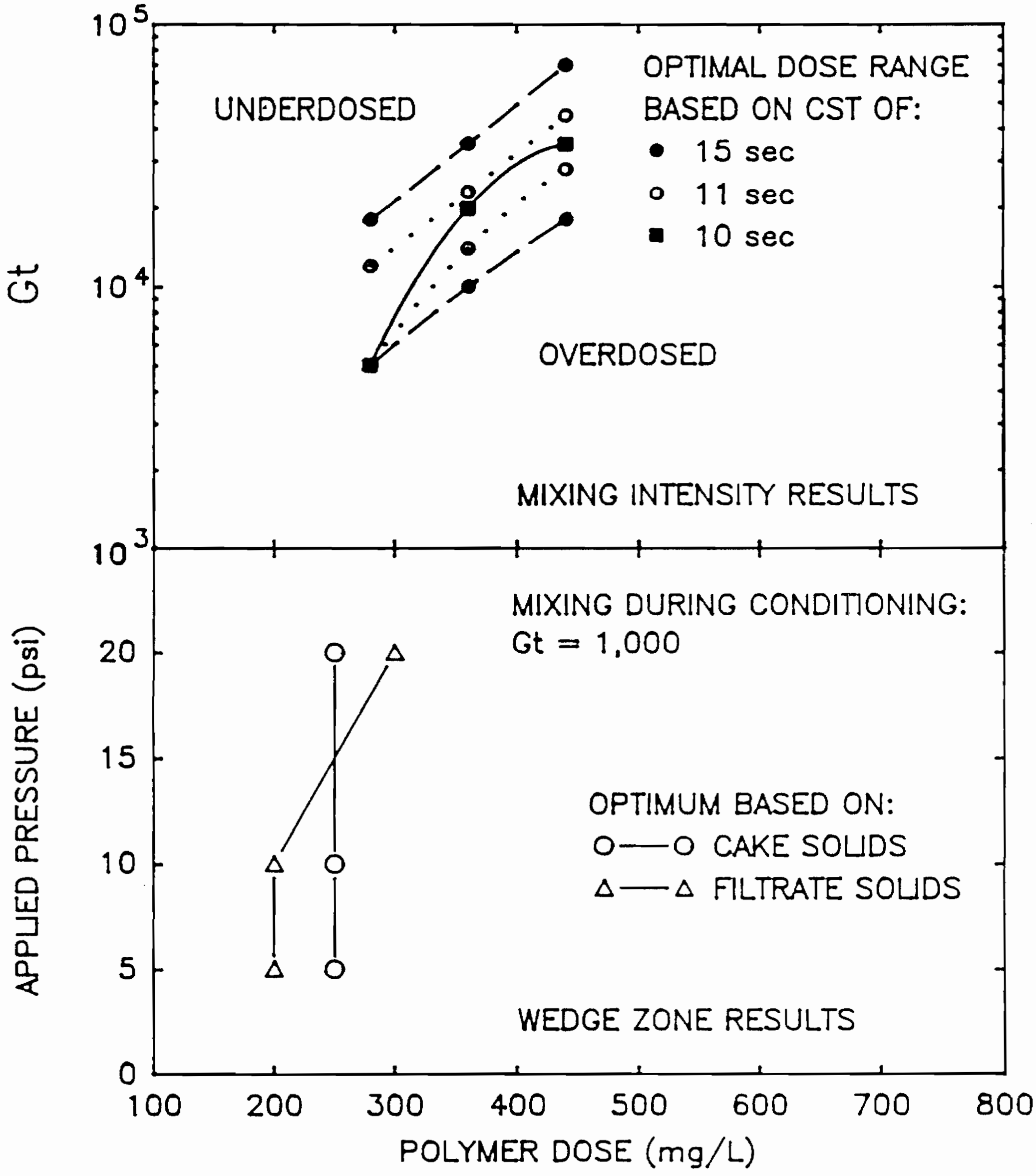

Figure 17. Effect of Gt and applied pressure on anaerobically digested sludge conditioned with Stockhausen D4160 polymer.

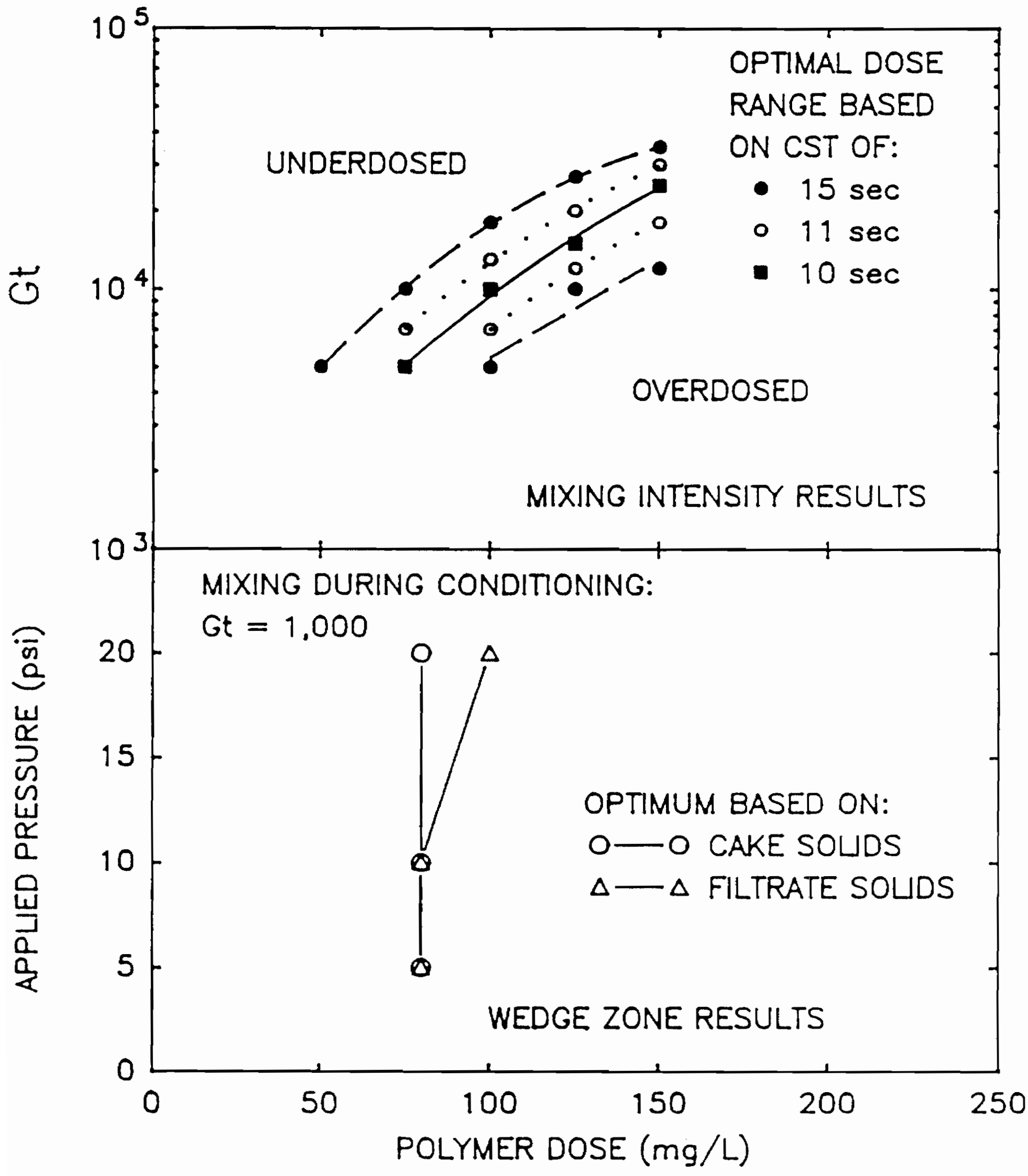

Figure 18. Effect of Gt and applied pressure on alum sludge conditioned with Betz 1120 polymer.

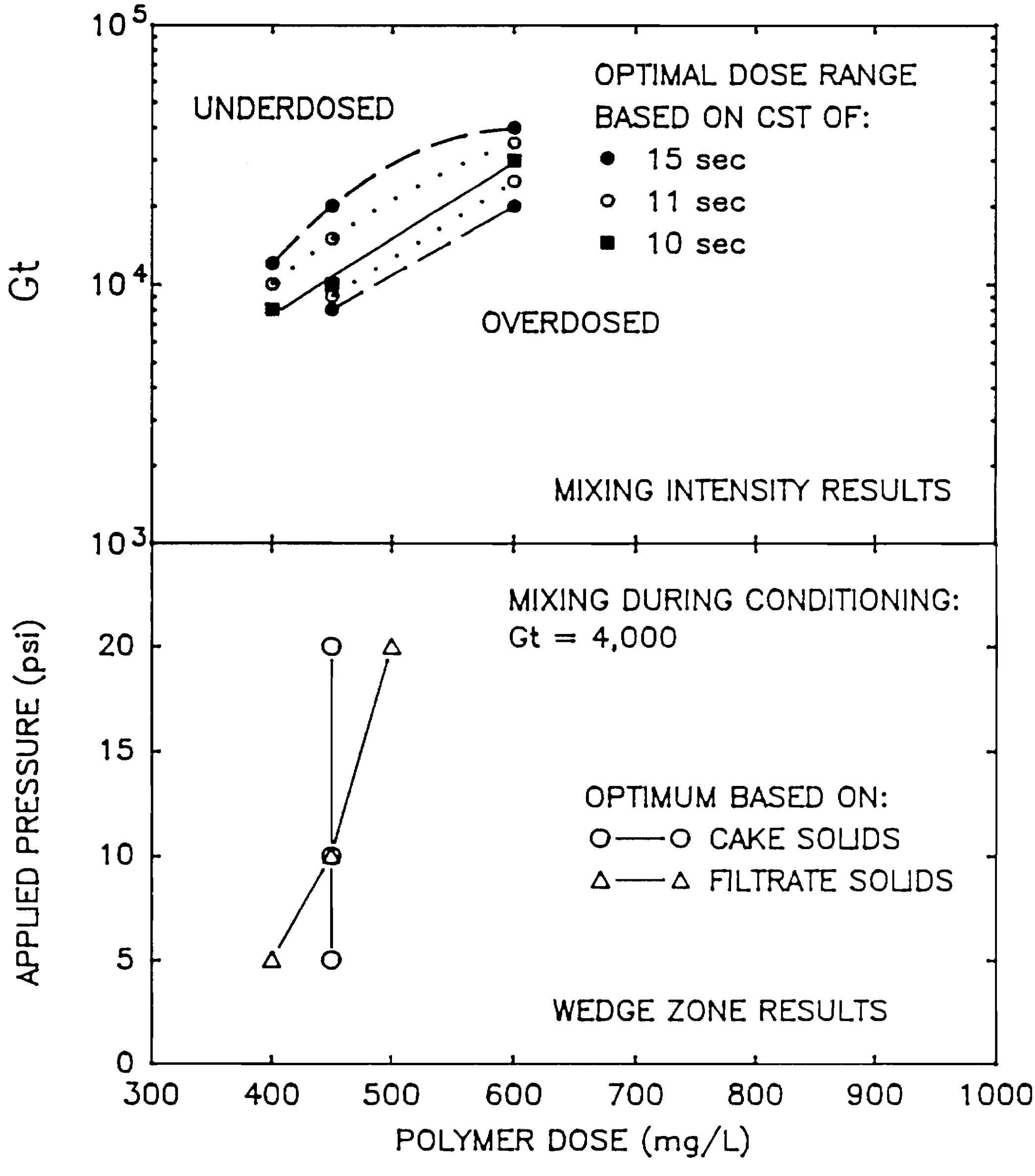

Figure 19. Effect of Gt and applied pressure on secondary sludge conditioned with Nalco 90WP030 polymer.

approximation when compared with the conclusion drawn by Schuler (22), who found that a Gt value of roughly 10,000 approximated a full-scale belt filter press.

Even though a unique range of Gt values was found for the wedge zone tester the relationship between applied pressure and Gt is still not clear. Research on mixing intensity effects have shown that as mixing energy increases, polymer requirements also increase (8 - 14). The polymer requirements within the wedge zone were virtually unchanged by the magnitude of the applied pressure. This would suggest that the corresponding mixing energies imparted by these pressures were nearly equal, regardless of the magnitude. This does not agree with the trend suggested by Novak and Lynch (11). However, their study did not allow free drainage to occur. Instead, they showed that filtrate drawn under applied vacuum pressure created shear through the sludge cake. This procedural difference may account for this apparent discrepancy.

The Gt imparted during conditioning may significantly contribute to the overall polymer demand exerted during dewatering. In fact, the Gt during conditioning may be a major factor controlling polymer performance. Experiments were performed to evaluate this hypothesis.

Mixing During Conditioning and Polymer Dose

A group of experiments were performed to evaluate the polymer requirements for the wedge zone with different mixing energy inputs imparted during conditioning. Alum sludge and Betz 1120 polymer were used in these experiments. The applied pressure within the wedge zone was held at 5 psi for every experiment. The G values of the bench-scale mixing device used were 50 sec^{-1} and 270 sec^{-1}. The mixing times imparted a mixing energy input, or conditioning energy (Gt), of 1,000, 5,000 or 15,000 during conditioning.

The first three experiments were performed with the mixer set at a G value of 50 sec^{-1}. Cake solids and filtrate solids data versus polymer dose for these three tests are shown in Figure 20. The combination of cake solids and filtrate solids versus polymer dose are displayed because these parameters were shown to mark the optimum dose most clearly. Both cake solids and filtrate solids approached a maximum and minimum, respectively. This response was expected from the other experimental data.

A comparison of the polymer demands at these three mixing conditions shows the clearest distinction between applied pressure effects and conditioning energy effects. The optimum dose for cake solids were 100 mg/L and 200 mg/L

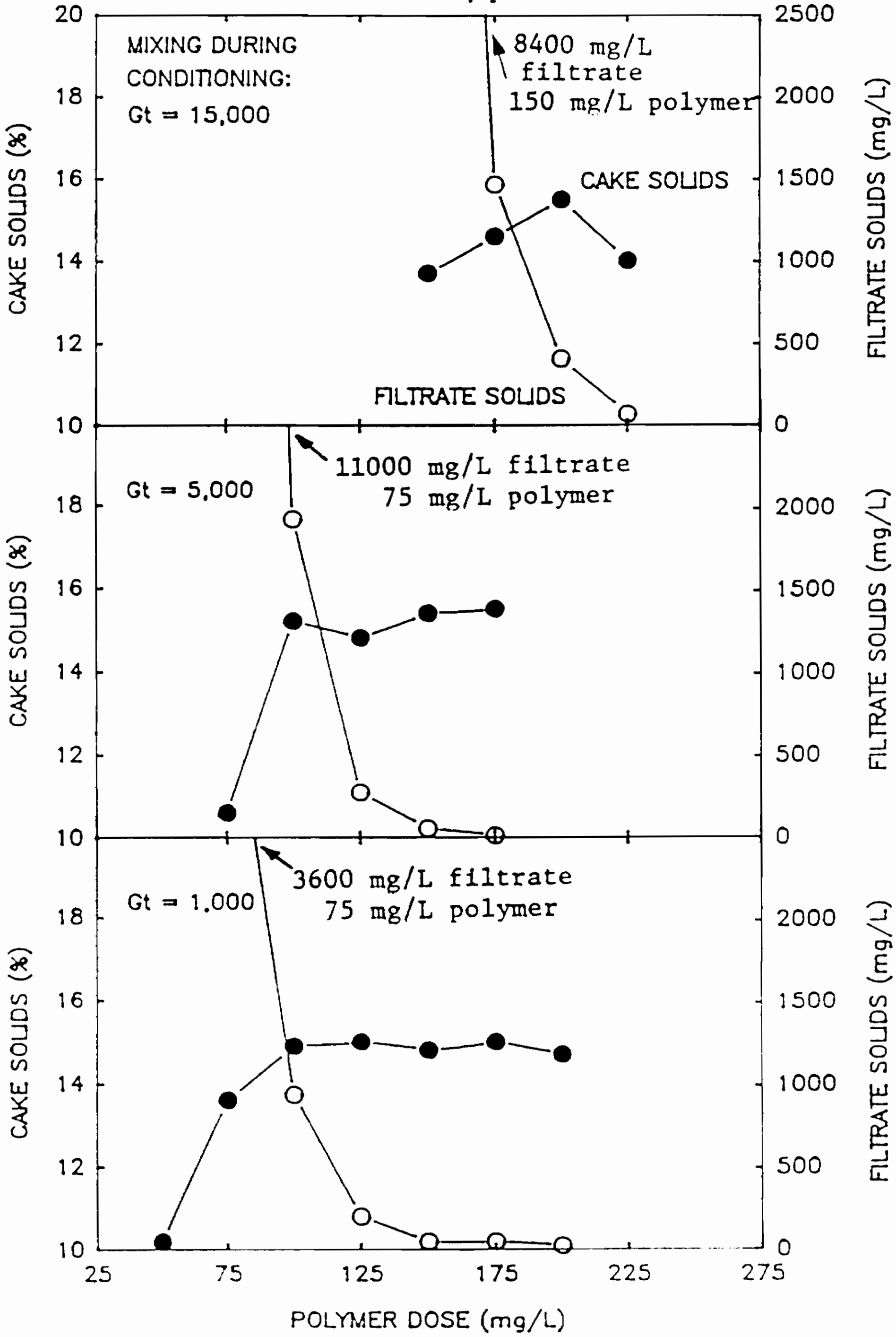

Figure 20. Cake solids and filtrate solids versus polymer dose for alum sludge conditioned with Betz 1120 polymer and mixed at G = 50 sec^{-1} for three mixing energy inputs.

for Gt = 1,000 and 5,000, and Gt = 15,000, respectively. For applied pressure tests, the optimum dose for cake solids was unchanged regardless of the magnitude of the pressure. This would suggest that this range of conditioning energies exerted a greater polymer demand than the range of applied pressures tested. This may also suggest that there was little shear (Gt) caused by the expression phase of dewatering.

This conclusion is illustrated by the data shown in Figure 21 regarding filtrate production versus time for the applied pressure tests and the conditioning energy tests. A polymer dose of 150 mg/L was shown to work well at any applied pressure and at the lower conditioning energy. However, when the conditioning energy was increased to Gt = 15,000 this dose was inadequate. It was suspected that overmixing ruptured the alum sludge flocs, which clogged the filter fabric and impeded filtrate production.

The next two experiments were performed with the mixer set at a G value of 270 sec^{-1}. Cake solids and filtrate solids versus polymer dose are shown in Figure 22. Characteristic shapes of these curves are seen again. The optimum dose for cake solids increased from 125 mg/L to 200 mg/L for Gt = 5,000 and Gt = 15,000, respectively. This large increase in polymer demand was never seen when the applied pressure was increased from 5 psi to 20 psi.

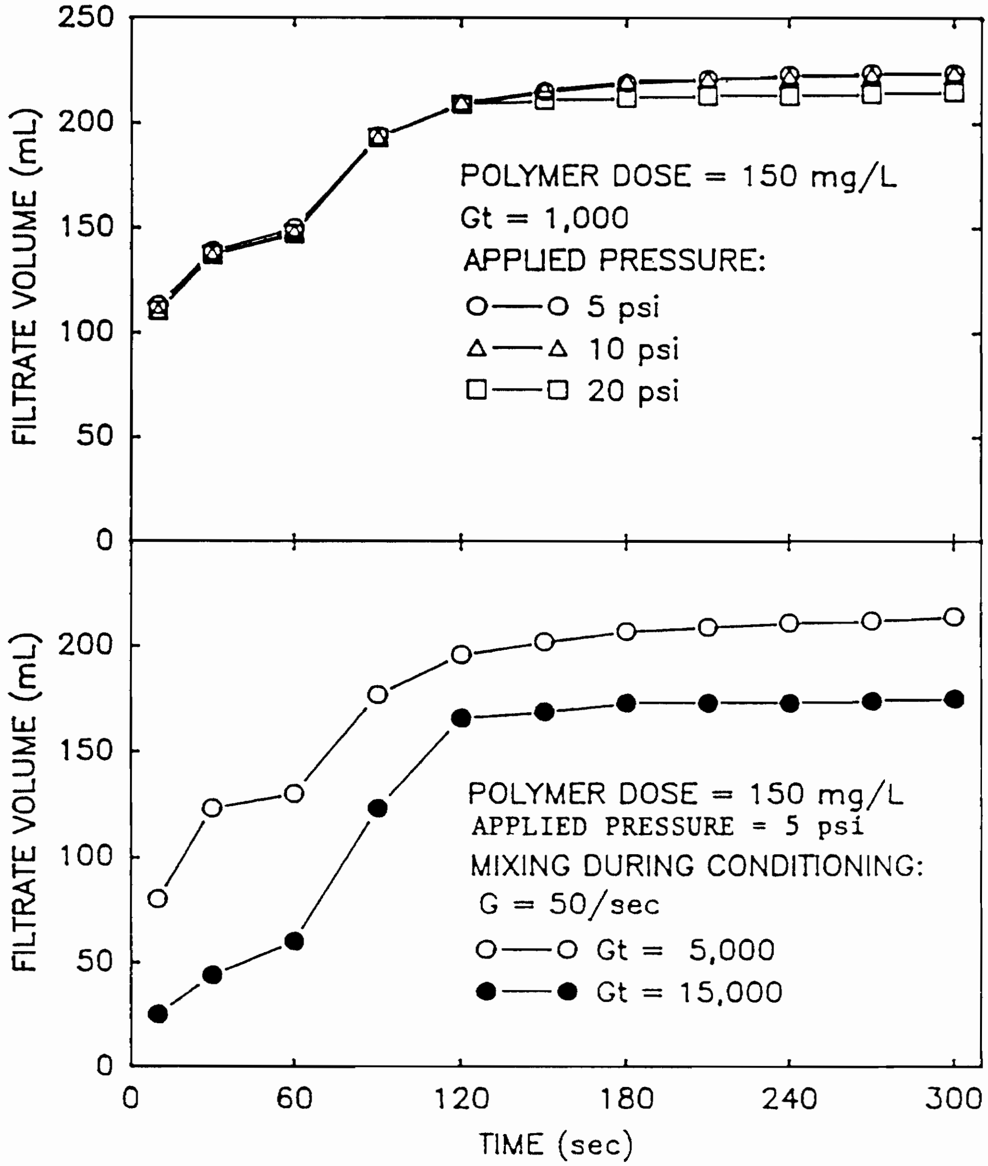

Figure 21. Effects of mixing during conditioning and applied pressure on alum sludge conditioned with Betz 1120 polymer.

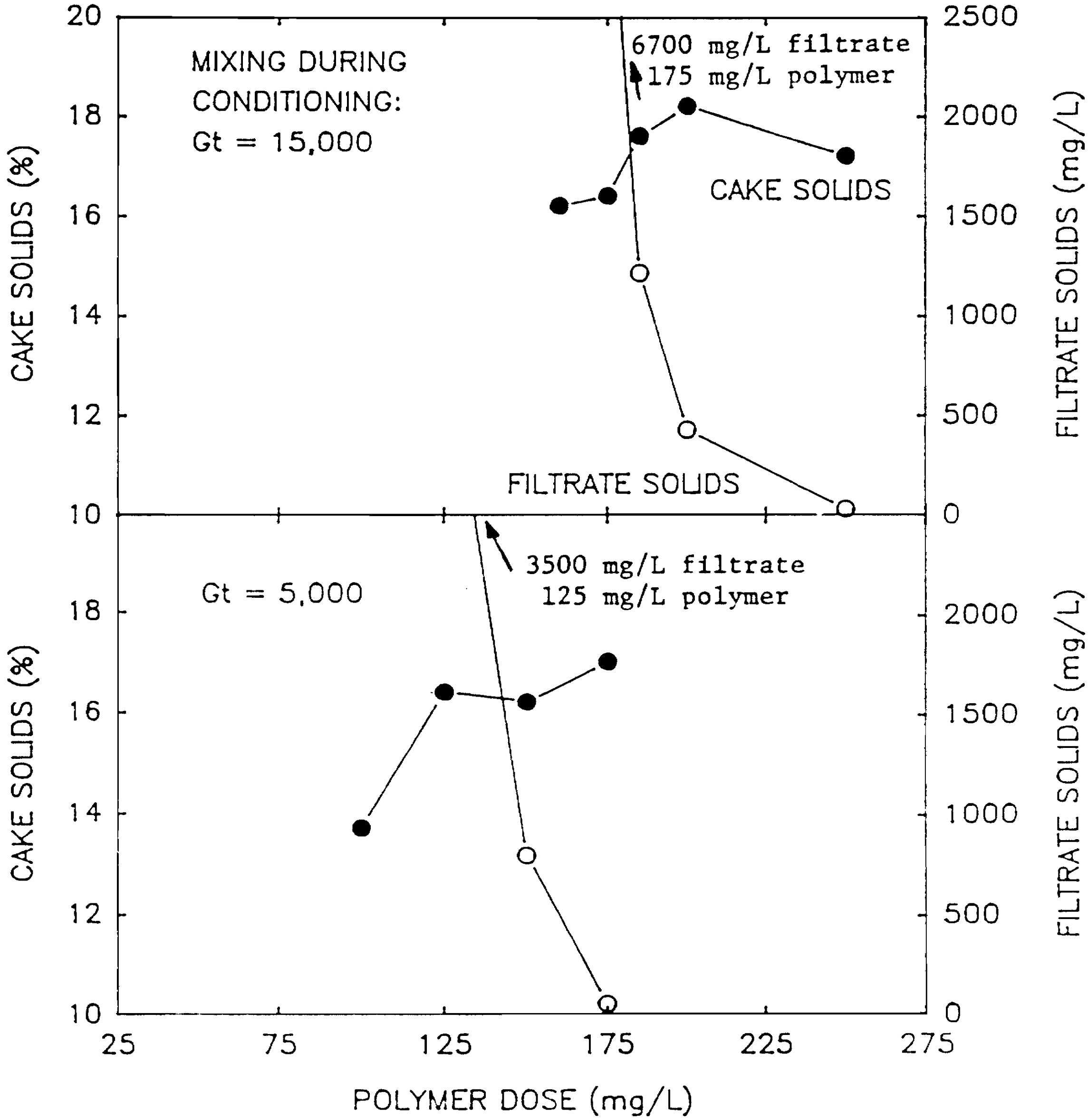

Figure 22. Cake solids and filtrate solids versus polymer dose for alum sludge conditioned with Betz 1120 polymer and mixed at G = 270 sec^{-1} for two mixing energy inputs.

Comparison of these two groups of data support the fact that the Gt during conditioning had a greater effect on polymer requirements than the range of applied pressures used in the wedge zone simulator during this study. This would suggest that the estimated Gt of the wedge zone tester was dependent on the Gt imparted during conditioning.

The work up to this point has focused on the evaluation of the wedge zone tester. Specifically, this apparatus was used to elucidate the effects of applied pressure on conditioning requirements. It was shown that the range of pressures used in this study, typical for the wedge zone of full-scale belt filter press (1), did not exert a significant additional polymer demand to maintain optimum dewatering conditions. Furthermore, the Gt imparted during conditioning was shown to a significant demand on polymer requirements.

A major goal of this research was to develop a bench-scale procedure to predict optimum conditioning requirements for a full-scale belt filter press. The remaining sections will focus on the evaluation of the wedge zone tester as a predictive tool for full-scale performance.

Full-Scale Experiments

Full-scale belt filter presses were studied at two locations to gauge the effects of machine and process variables on polymer performance. Stockhausen D4160 polymer was evaluated at the Peppers Ferry Regional Wastewater Treatment Plant (Peppers Ferry), Radford, VA, on February 26-27, 1990. Nalco 90WP030 was evaluated at the Ronile, Inc. textile plant, Rocky Mount, VA, on July 25, 1990.

Multi-variable experimental designs were performed at each facility. Belt speed, polymer dose and sludge throughput were the variables used for each test. Influent solids, gravity drainage solids, cake solids, and filtrate solids were the operational parameters measured to gauge polymer performance.

Peppers Ferry Results

Anaerobically digested sludge was conditioned with Stockhausen D4160 polymer during full-scale tests conducted at Peppers Ferry. Belt speed and polymer dose were varied at two fixed sludge throughputs. Belt speeds of 4.0 feet per minute (fpm), 4.4 fpm, and 4.8 fpm were used. Polymer doses ranged between 12 lb polymer/dry ton sludge and 18 lb/dry ton. Sludge throughputs of 63 gallons per minute (gpm) and 70 gpm were used. Dilution water was varied to bring the flowrate (gpm) onto the press up to the same value in both tests.

Cake solids and filtrate solids data versus polymer dose obtained at a sludge throughput of 63 gpm are shown in Figure 23 for the three belt speed settings. A few trends are evident from these data. First, cake solids generally increased with increased polymer dose. As the belt speed decreased, the maximum obtainable cake solids increased. This was due to the longer overall residence time in the press, including both drainage and expression stages. Finally, filtrate solids decreased with increased polymer dose. As the belt speed decreased, the amount of polymer required to attain a satisfactory filtrate quality decreased. This was apparently due to the longer time allowed within the drainage zone of the press.

Cake solids and filtrate solids data versus polymer dose obtained at a sludge throughput of 70 gpm are shown in Figure 24. Results obtained at this throughput displayed similar responses with those performed at the lower throughput operated at the lowest belt speed. As polymer dose increased, cake solids increased slightly and filtrate solids decreased. Higher cake solids were obtainable at the lowest belt speed. Filtrate solids were barely affected by

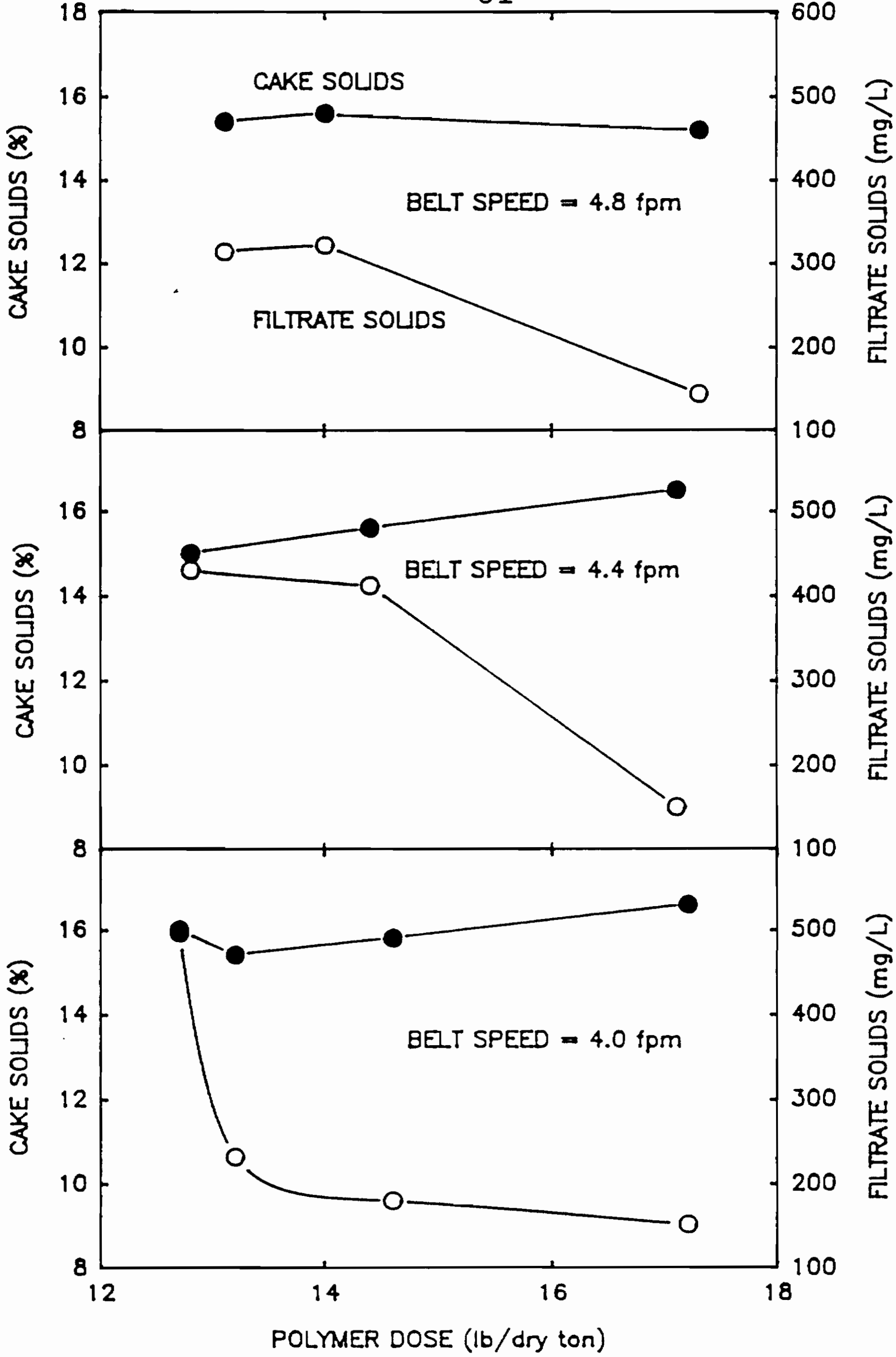

Figure 23. Cake solids and filtrate solids versus polymer dose for full-scale tests at Peppers Ferry operated at a sludge throughput of 63 gpm.

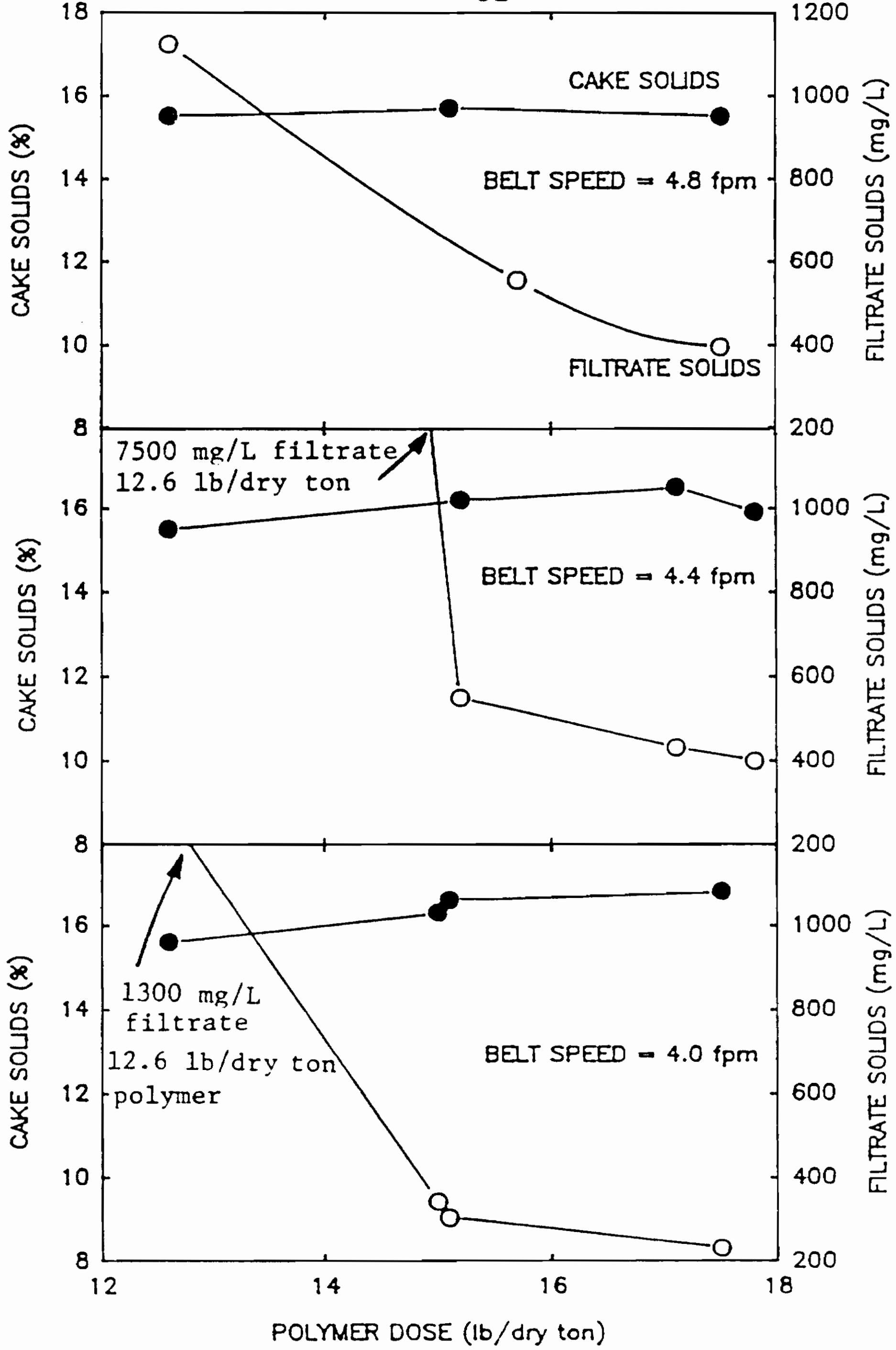

Figure 24. Cake solids and filtrate solids versus polymer dose for full-scale tests at Peppers Ferry operated at a sludge throughput of 70 gpm.

the belt speed at this throughput. Because of the higher mass loading onto the press during these tests, the range of belt speeds used apparently could not cause the effect seen at the lower throughput.

Selection of an optimum dose from these full-scale results was more difficult than with bench-scale results. For the range of polymer doses used, the response of cake solids was never dramatic enough to select a clear optimum. There are two similar explanations for this. One, the sludge was only slightly underdosed for the range of polymer doses used. Two, the press itself could compensate for slightly underdosed conditions within this dose range.

Analysis of the filtrate solids response supports the explanation that the range of polymer doses used in this study only slightly underdosed the sludge. Filtrate solids of roughly 500 mg/L were considered acceptable in the bench-scale wedge zone experiments. This measure of filtrate quality was seen for almost every testing condition, except at the higher throughput with low polymer doses.

Another presentation of full-scale results were the surface plots generated by Nalco representatives with the RS/Explore multi-variable software package. The effects of polymer dose and belt speed on cake solids, shown in Figure 25, was generated with the RS/Explore package. These data suggested that the optimum polymer dose was between 17

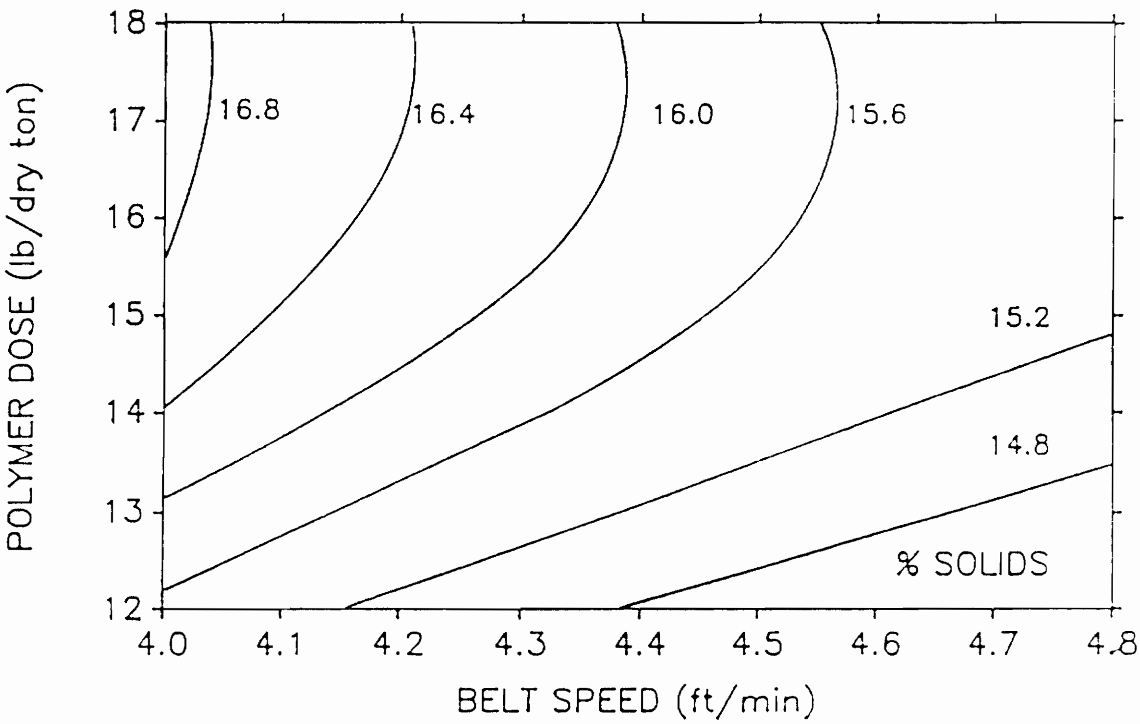

Figure 25. Effect of belt speed and polymer dose on cake solids at Peppers Ferry. From Schuler (22).

lb/dry ton and 18 lb/dry ton, and was virtually independent of belt speed. The highest cake solids obtainable occurred when the belt filter press was operated at the lowest belt speed.

Ronile, Inc. Results

Secondary sludge was conditioned with Nalco 90WP030 polymer during full-scale tests conducted at Ronile, Inc. Belt speed and polymer dose were varied at two fixed sludge throughputs. Belt speeds of 20 fpm, 40 fpm, and 60 fpm were used. Polymer doses ranged between 10 lb/dry ton and 45 lb/dry ton. Sludge throughputs of 7 gpm and 10 gpm were used.

Cake and drainage solids concentrations data versus polymer dose obtained at a sludge throughput of 7 gpm are shown in Figure 26 for the three belt speed settings. Filtrate solids were not shown because the belt wash water was included in the filtrate samples taken. This additional solids input would not reflect a polymer dose's performance with respect to filtrate quality. Cake solids and free drainage solids seemed to be virtually unchanged by polymer dose or belt speed.

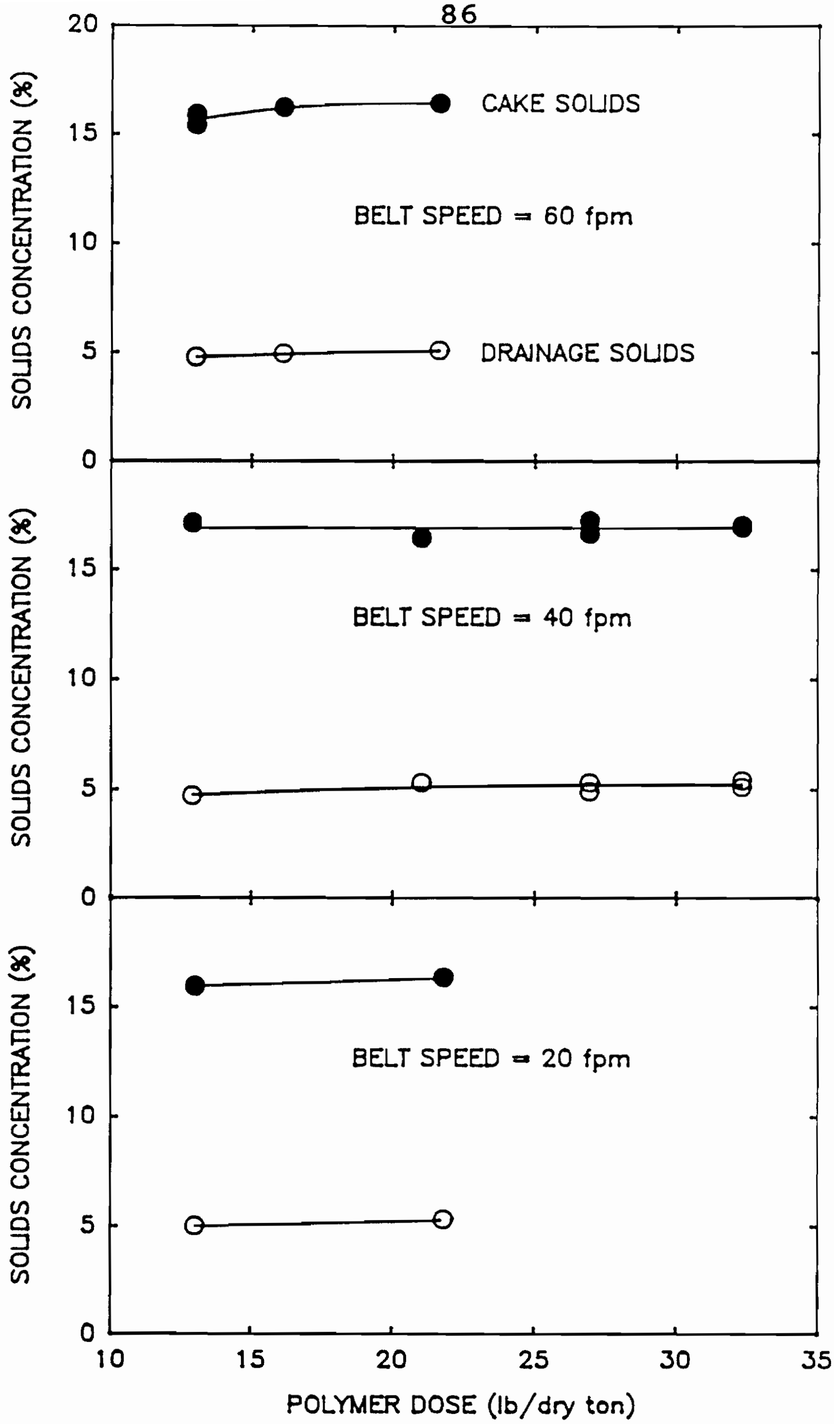

Figure 26. Cake solids and drainage solids versus polymer dose for full-scale tests at Ronile, Inc. operated at a sludge throughput of 7 gpm.

Figure 27 shows cake and drainage solids concentrations versus polymer dose at a sludge throughput of 10 gpm. As seen with the lower sludge throughput, cake solids and drainage solids were marginally affected by polymer dose or belt speed. Polymer conditioning seemed to have little effect on the solid concentrations obtained following gravity drainage and/or roller pressing.

However, the RS/Explore surface plots generated from the Ronile, Inc. data show clear effects of polymer dose on cake and drainage solids concentrations, as shown in Figure 28. Optimum cake solids occurred at a belt speed of 40 fpm with a polymer dose between 25 lb/dry ton and 30 lb/dry ton. The optimum dose for drainage solids was between 28 lb/dry ton and 32 lb/dry ton. Interpretation of these graphs would suggest that the optimum dose range was barely affected by belt speed.

Comparison of Full-Scale and Bench-Scale Performance

Full-scale and bench-scale experiments were performed with sludge obtained from the two wastewater treatment facilities. Bench-scale experiments with anaerobically digested sludge from Peppers Ferry, and Stockhausen D4160 polymer were conducted over a two day period in June, 1990.

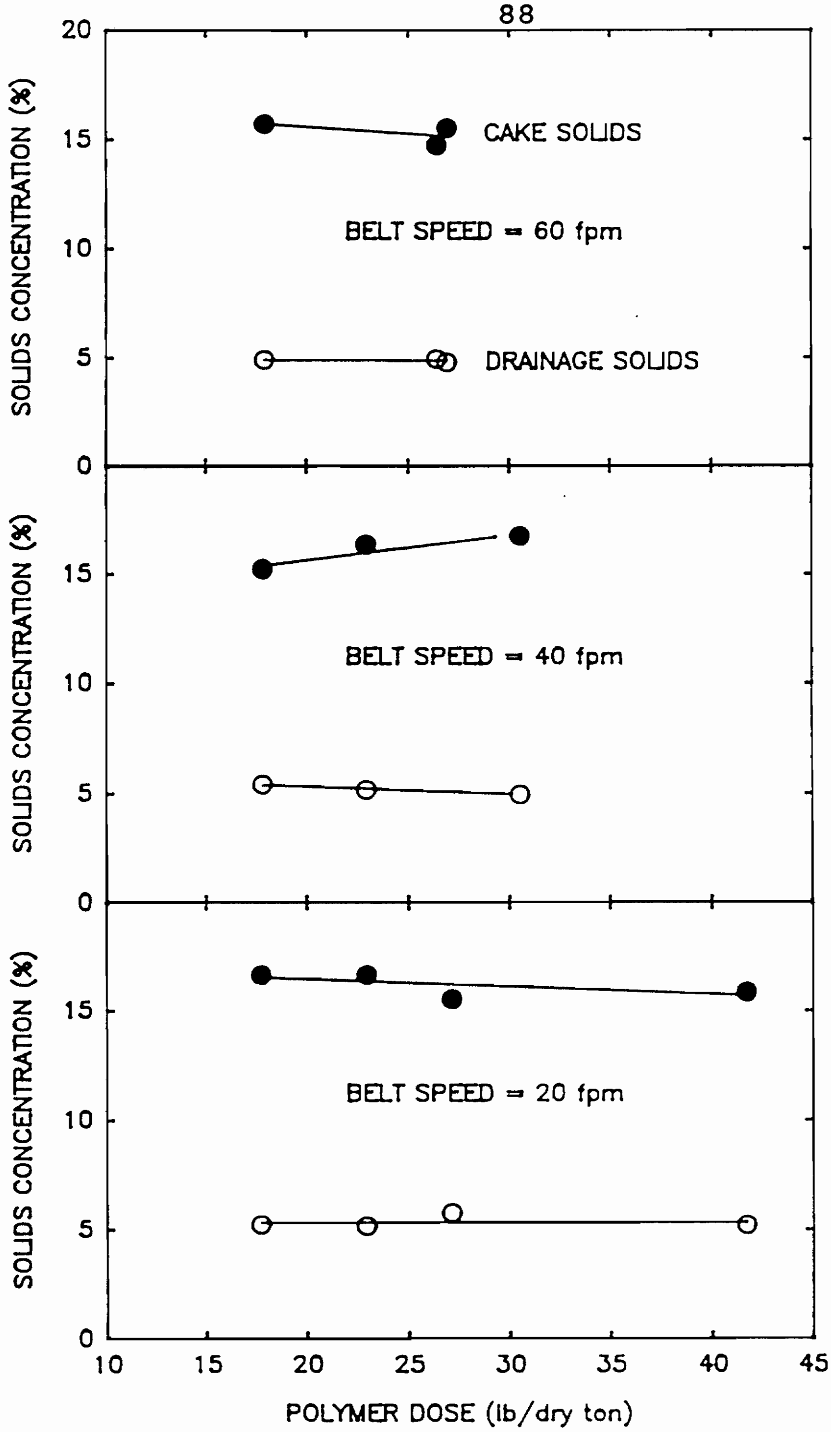

Figure 27. Cake solids and drainage solids versus polymer dose for full-scale tests at Ronile, Inc. operated at a sludge throughput of 10 gpm.

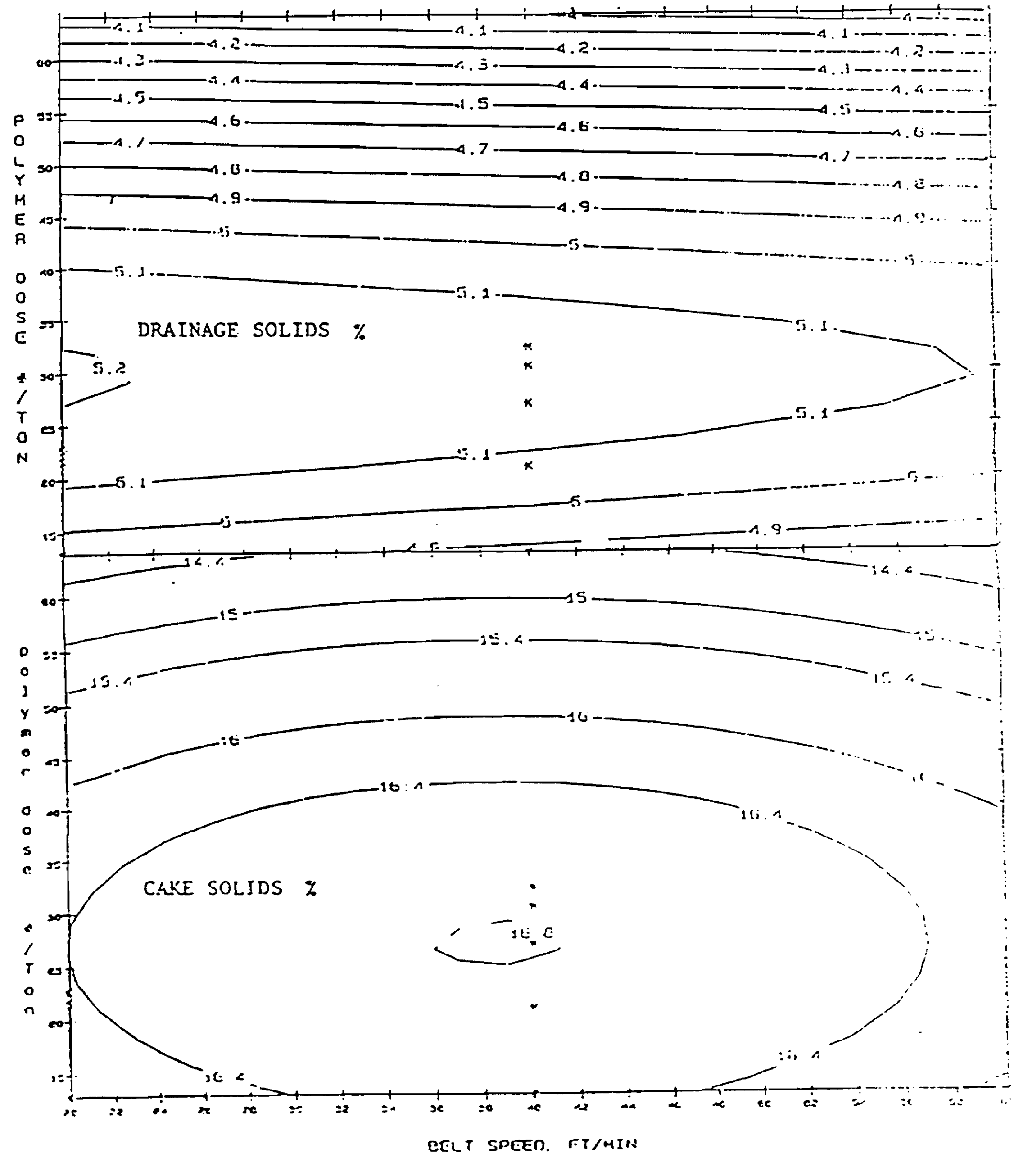

Figure 28. Effects of belt speed and polymer dose on cake solids and drainage solids at Ronile, Inc.

Full-scale experiments had been performed in February, 1990. While the sludge characteristics between February and June most likely changed, the general nature of the two batches was probably similar. The units for polymer dose used in the wedge zone experiments, mg/L, were converted to lb/dry ton to correspond with units used in the full-scale tests.

Cake solids and filtrate solids data versus polymer dose for one bench-scale test condition, and one full-scale test condition are shown in Figure 29. The top figure displayed typical results for the bench-scale wedge zone experiments. The lower figure displayed typical results for the full-scale experiments performed at the lowest belt speed. There are several important facts that can be drawn from this figure. First, the assumption that the small range of polymer dose used for the full-scale experiments barely included underdosed conditions is shown clearly. Second, the response of the cake solids and filtrate solids data versus polymer dose were very similar for both the bench-scale and full-scale tests. Finally, the optimum dose predicted by the wedge zone tester was very close to the optimum dose required for full-scale performance at the lowest belt speed.

Based on this comparison, the wedge zone tester could be used to accurately predict polymer conditioning requirements for dewatering anaerobically digested sludge

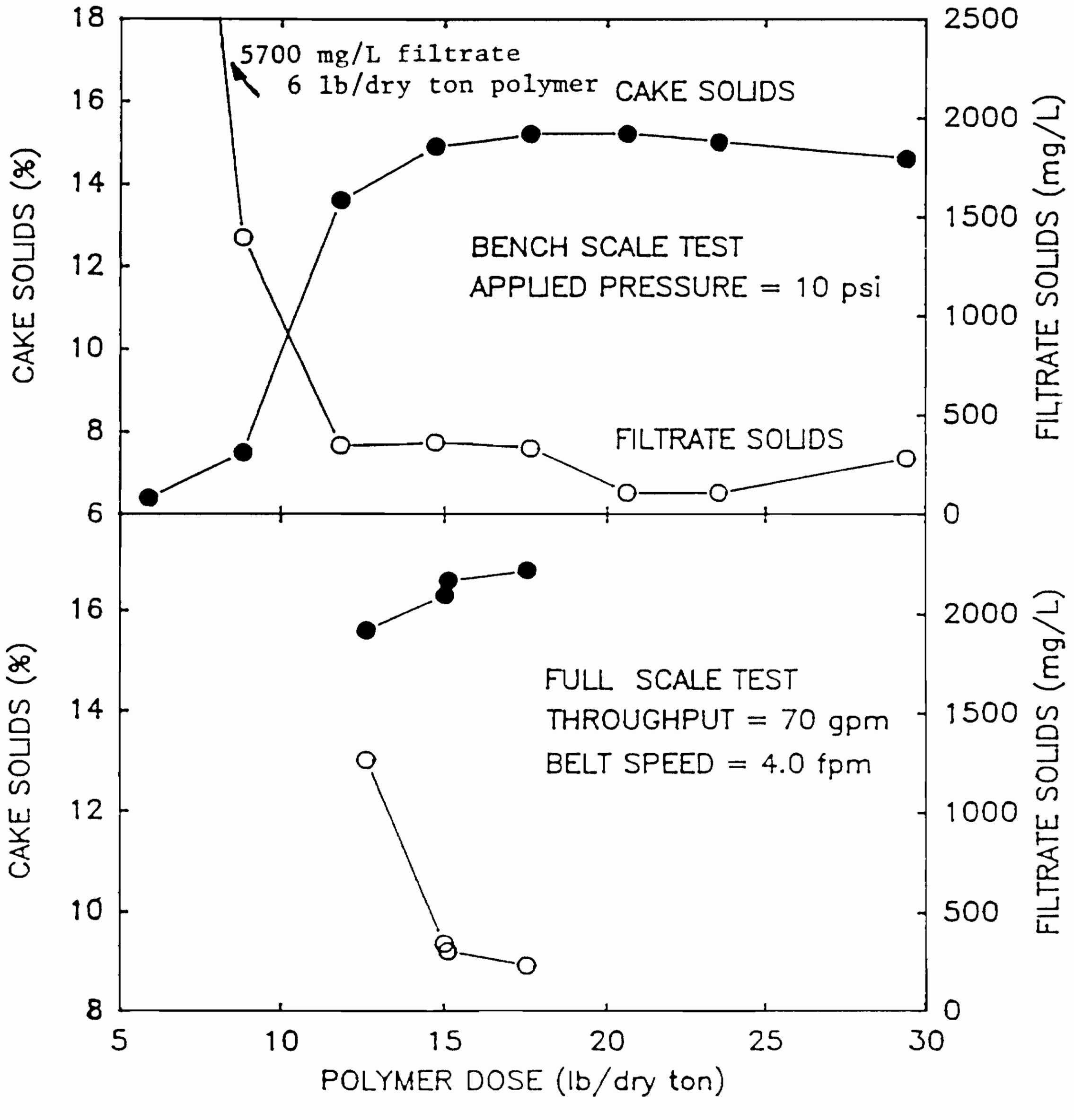

Figure 29. Comparison of bench-scale and full-scale results for anaerobically digested sludge conditioned with Stockhausen D4160 polymer.

with a belt filter press. An advantage of using a wedge zone tester would be the ability to gauge filtrate quality as a function of polymer dose. The deterioration of filtrate quality was the best indicator of further polymer demands exerted during expression.

Another approach to predicting full-scale polymer requirements from bench-scale tests would be to compare results from mixing intensity experiments with full-scale data. If a unique Gt value for the full-scale unit could be determined, simple mixing experiments performed at that Gt could predict optimum conditioning requirements. A comparison of the effects of Gt and the full-scale results predicted with the RS/Explore package is shown in Figure 30. Employing the previously described graphical interpretation of this data, the optimum conditioning requirements for the full-scale belt filter press at Peppers Ferry is roughly a Gt value of 8,000.

From this result, the bench-scale mixer could be used to predict polymer requirements for a full-scale belt filter press. The optimum dose predicted for a mixing energy input of roughly Gt = 8,000 would be adequate for full-scale polymer performance. This Gt value agrees with the estimated range of Gt values for the wedge zone tester.

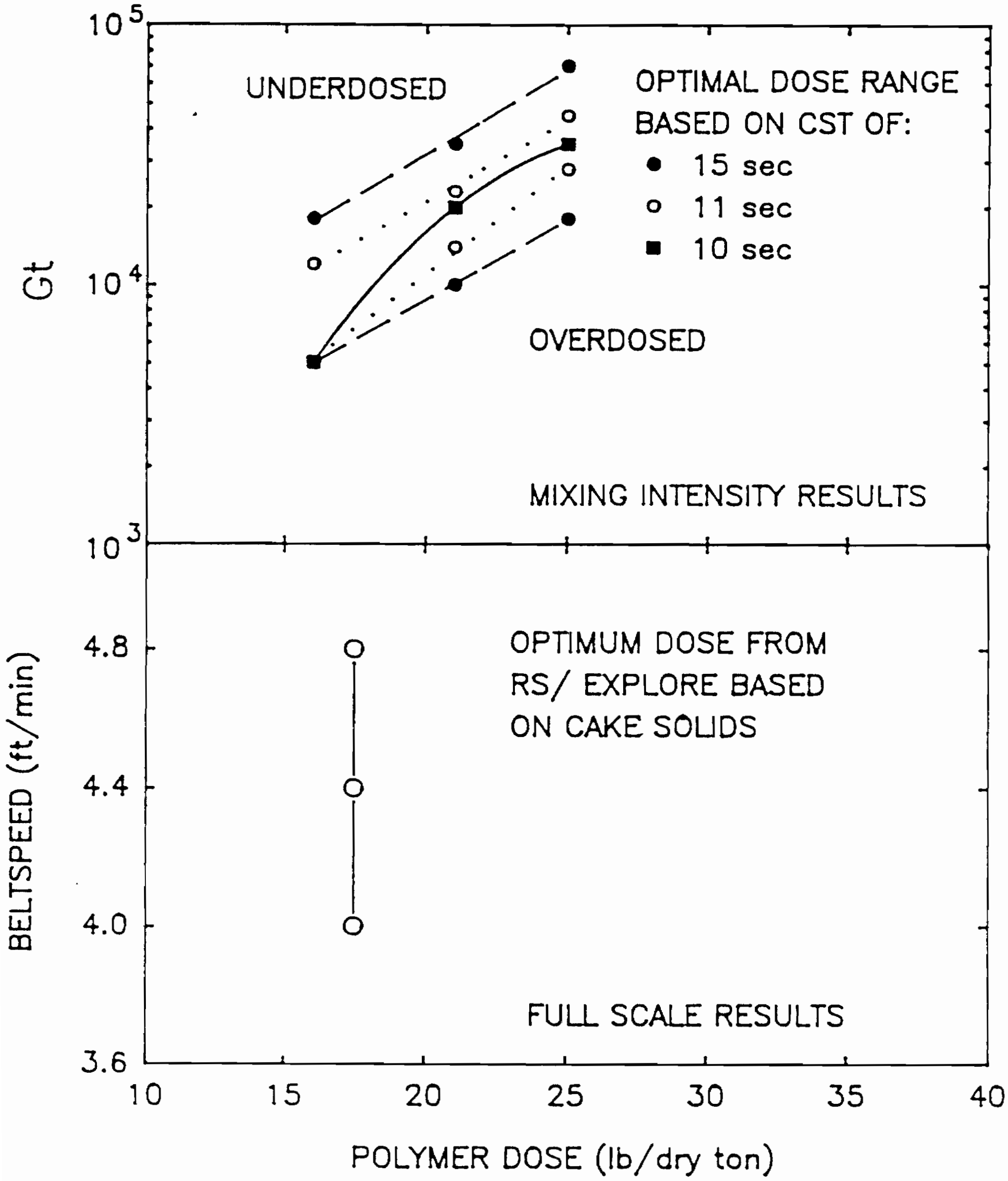

Figure 30. Comparison of bench-scale mixing intensity and full-scale belt speed effects on anaerobically digested sludge conditioned with Stockhausen D4160 polymer.

Bench-scale and full-scale results were performed simultaneously at Ronile, Inc. on July 25, 1990. Cake and filtrate solids for one bench-scale condition, and cake solids versus polymer dose for one full-scale test condition are shown in Figure 31. Both test conditions displayed typical results for their respective group of experiments. A comparison of these responses showed that a closer examination of cake solids would have revealed the effects of polymer dose displayed in the RS/Explore surface plot of these data. The response of cake solids was similar for both bench-scale and full-scale tests. From this comparison, the bench-scale wedge zone tester could be used to predict polymer requirements for optimum full-scale performance.

A comparison of the mixing intensity results, and full-scale results predicted with the RS/Explore software is shown in Figure 32. Graphical interpretation of this data would suggest that the belt filter press at Ronile, Inc. was between a Gt value of 10,000 and 15,000. Based on this information, a bench-scale mixer imparting a Gt in this range could be used to predict the polymer requirements for a full-scale belt filter press.

The wedge zone tester corresponded to a Gt value between 5,000 and 12,000. The optimum polymer dose range predicted by the RS/Explore package for full-scale results

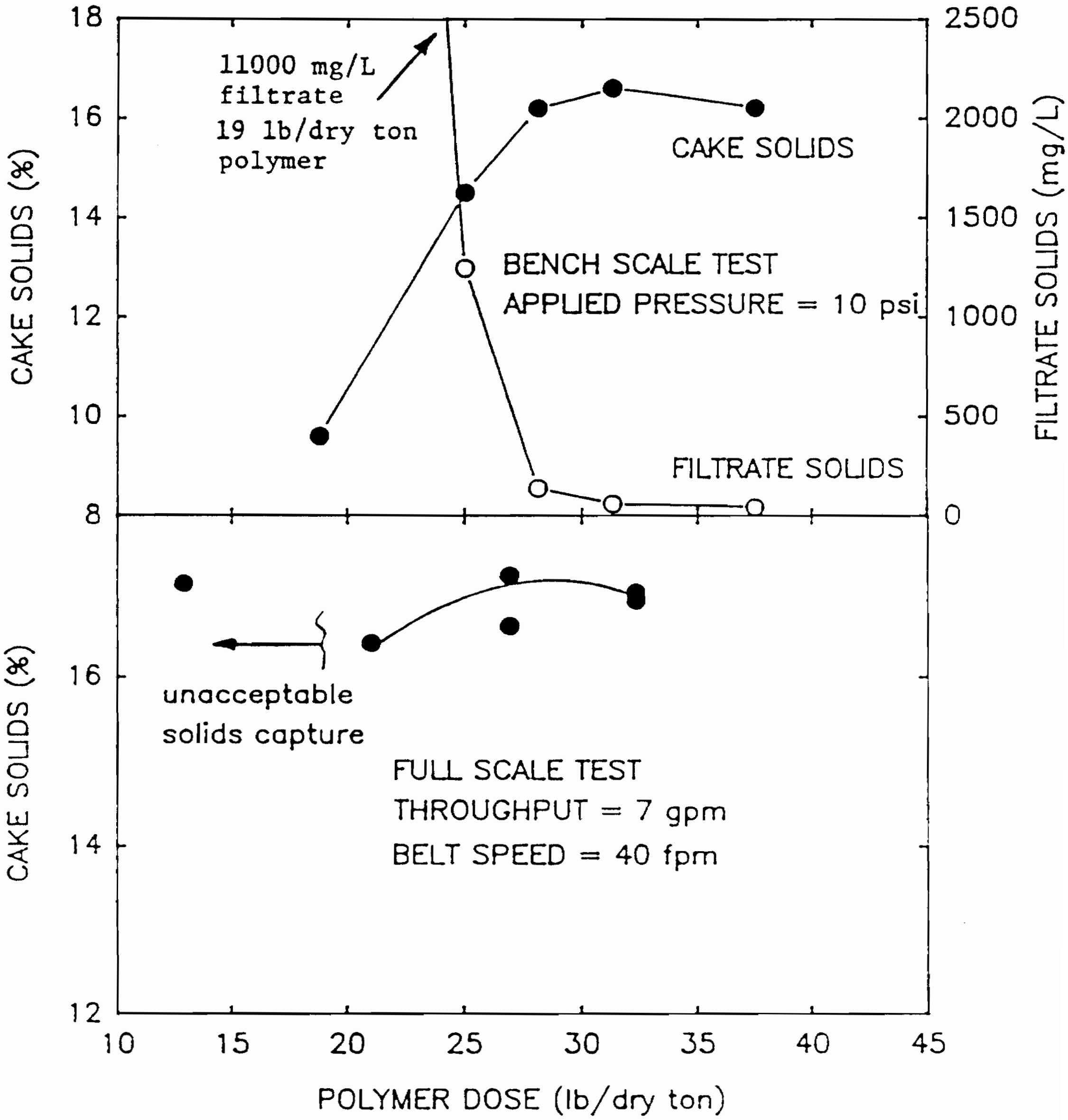

Figure 31. Comparison of bench-scale and full-scale results for secondary sludge conditioned with Nalco 90WP030 polymer.

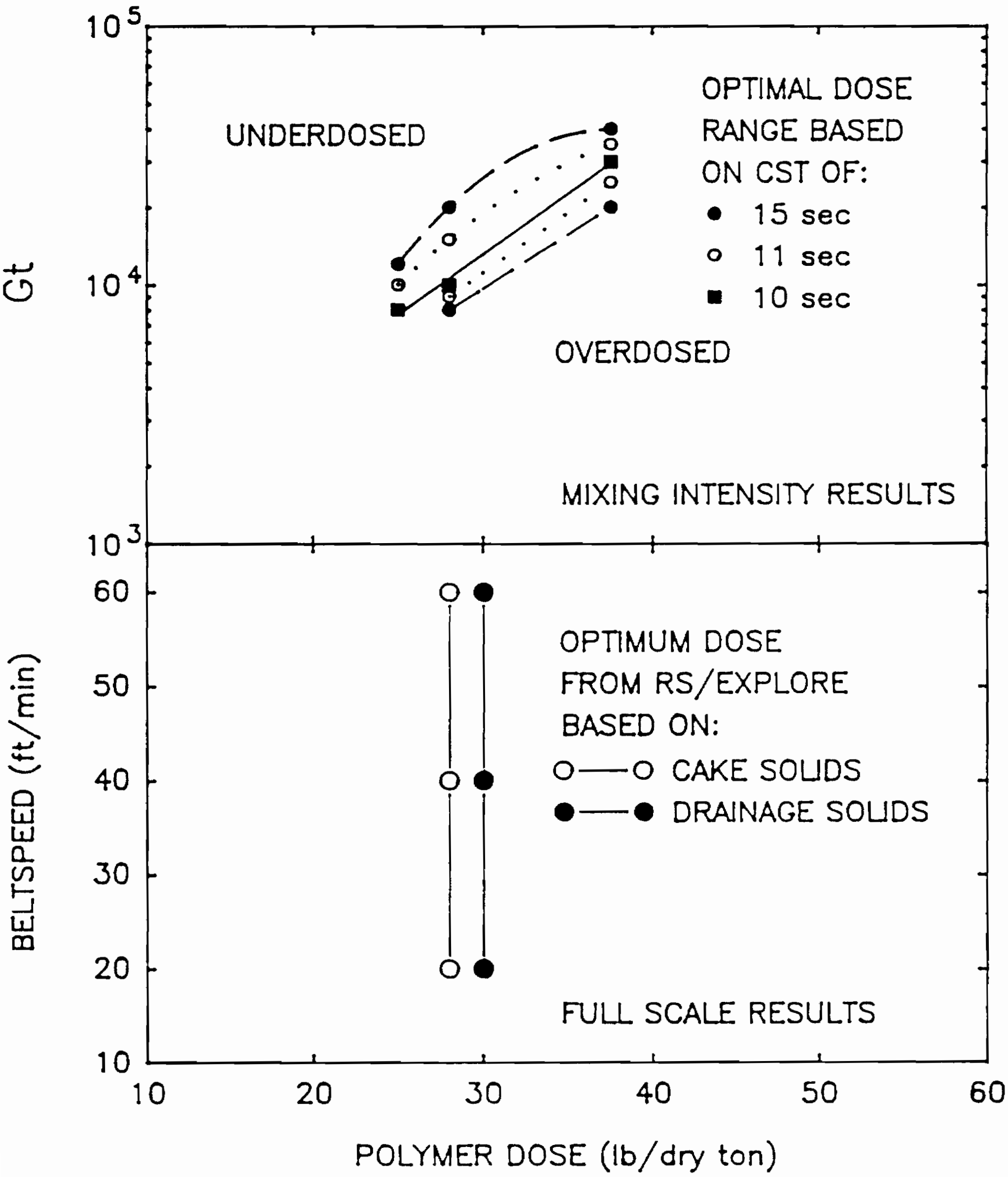

Figure 32. Comparison of bench-scale mixing intensity experiments and full-scale belt speed effects on secondary sludge conditioned with Nalco 90WP030 polymer.

tester and the bench-scale mixing device can be used to adequately predict full-scale polymer requirements, and that the Gt imparted by the wedge zone tester is approximately equal to the Gt imparted by a full-scale belt filter press.

SUMMARY AND CONCLUSIONS

The purposes of this study were to develop a laboratory procedure to predict polymer requirements for optimum full-scale belt filter press performance, and to elucidate the conditioning requirements exerted by applied pressure. Mechanical dewatering equipment is known to impart enough shear to rupture conditioned sludges, which deteriorate dewatering properties. Researchers have proposed that the shear encountered during dewatering can be simulated with a high energy mixer. Bench-scale mixing intensity experiments were performed to evaluate the effects of the mixing energy input (Gt) and polymer dose. Polymer requirements increased as Gt increased, which was expected from previous research.

A bench-scale high energy mixing device was shown to adequately predict polymer conditioning requirements for a belt filter press. A Gt value between 8,000 and 12,000 was shown to simulate the shear encountered in the conditioning and dewatering stages within a full-scale belt filter press. If the mixing device is operated in a G range of 300 sec^{-1} to 600 sec^{-1} and used to impart a Gt value in this range, then the optimum dose for that mixing condition should optimize full-scale performance.

Bench-scale wedge zone experiments were performed to evaluate the effect of applied pressure on conditioning requirements. The primary advantage of this device was that it clearly showed the polymer demand exerted at high pressures to maintain an acceptable filtrate quality. Pressure and Gt were believed to exert a similar demand on polymer requirements. Results revealed that the pressure range used in this study (5 psi to 20 psi) did not exert a significant additional polymer demand for optimum conditioning.

Experiments were also performed at two wastewater treatment facilities to correlate bench-scale experiments with full-scale results. Both the wedge zone tester and the bench-scale mixing device were shown to be able to predict full-scale polymer requirements.

Based on the results of this study the following conclusions were made:

1. The wedge zone tester can be used to adequately predict polymer conditioning requirements for full-scale belt filter presses.
2. A bench-scale mixing device used to impart a Gt between 8,000 and 12,000 can adequately predict polymer conditioning requirements for full-scale belt filter presses.
3. Mixing during conditioning can exert a greater polymer demand than the expression phase of the wedge zone tester.
4. The range of applied pressures used to simulate the expression phase of a belt filter press did not exert a significant additional polymer demand for optimum conditioning. This would suggest that conditioning for the gravity drainage phase will optimize belt filter press performance.

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VITA

William David Burgos was born January 26, 1966 in lovely Trenton, NJ. He grew up as a sheltered suburban youth in Yardley, PA and for a few years in Clifton Park, NY. He attended public schools in both of these communities, graduating from Pennsbury High School in June, 1984. In September, 1984 he enrolled at Virginia Polytechnic Institute & State University, Blacksburg, VA. While continuing his undergraduate education he worked for General Electric Astro Space Division in Princeton, NJ. Finally, after five long years he received a B.S. in Mechanical Engineering from VPI&SU. Unable to leave Blacksburg and unenthused about a lifelong career in mechanical engineering, he enrolled in the Environmental Engineering graduate program at VPI&SU in August, 1989. In December, 1990 he completed his final degree requirements for a M.S. in Environmental Engineering.