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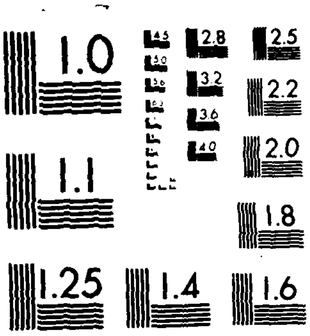

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EFFECTS OF HIGH-STRESS POLYMER CONDITIONING ON THE FILTERABILITY OF WATER AND WASTEWATER SLUDGES

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Tests were conducted on samples of alum, activated, and primary sludges obtained from water and wastewater treatment plants in southwest Virginia. The purpose of the testing was to determine if the sludges could be conditioned with polymers and still provide good filterability. Tests were conducted using a variable speed mixer with mixing intensities ranging from 246 to 2030 sec^{-1}. Both anionic and cationic high molecular weight polymers were used during conditioning. The capillary suction time (CST) was used to measure relative changes in filterability. Results indicated that alum, activated, and primary sludges can be condi-

tioned to dewater readily during high-stress processes. In this regard, the tandard jar test device was found to be inadequate in predicting polymer dose equirements in cases where high-stress dewatering processes are to be used. The most significant parameters governing high-stress conditioning were found to be polymer dose and total mixing energy input (Gt). It was discovered that once an optimum Gt had been established for a given polymer dose, any combination of G and t within the ideal range of G to t ratios could be used with no appreciable loss in filtering performance.

EFFECTS OF HIGH-STRESS POLYMER CONDITIONING ON THE FILTERABILITY OF WATER AND WASTEWATER SLUDGES

by

Christopher Paul Werle

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
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I. INTRODUCTION

An area of growing concern in environmental management is the treatment and disposal of sludges that are formed during water and wastewater treatment. These sludges consist of varying amounts of organic and inorganic materials, particulates, microorganisms, and other precipitates. The actual content and volume of sludges differ greatly from one treatment system to another, and are generally classified as either chemical, biological, or primary in nature.

Variations in physical and chemical characteristics have fostered problems in preparing these sludges for disposal. One of th most significant problems involves the difficulty in achieving effect and efficient dewatering of these slurries. Since sludges contain large percentages of water (usually from 90 to 99 percent), the advantages of dewatering prior to disposal become readily apparent. The total volume of sludge can be greatly reduced, and a more solid state makes for easier handling.

Sludge dewatering processes vary in scope and effectiveness. Technological improvements and the desire to conserve land area have resulted in a movement away from the time and space consuming lagoon or drying bed applications toward more efficient mechanical methods. This movement has generated yet another area of concern: the need for adequate sludge conditioning prior to dewatering.

Treatment facilities often achieve less than desirable results with these processes. The problem seems to arise from the very nature of mechanical dewatering. Typical devices such as the centrifuge or filter press subject sludges to extreme stress and shear forces during operation. Unfortunately, sludge flocs are generally very weak and cannot withstand this turbulence without shearing. This reaction is counter-productive, since the floc become smaller and more compacted, thereby reducing the amount of void space between particles and increasing frictional resistance. This in turn tends to retain water within the sludge by reducing available outlets in the sludge mass.

Researchers have found that conditioning sludges with polymers can greatly improve their filtering rate. Parameters which have been suggested to most significantly affect filtering rates include the polymer dose, mixing time (t), and mixing energy (commonly called the velocity gradient G). To date, most research dealing with mixing has used a low G mixing apparatus, such as the Phipps and Bird jar test device, for conditioning sludges. While these devices certainly have some valid applications, it is unlikely that the relatively low turbulence conditions generated adequately simulate the high stresses inherent with mechanical dewatering processes. As a result, it is possible that many treatment plants are not conditioning sludges to optimum levels prior to dewatering. Accordingly, the need to develop additional data dealing specifically with high-stress polymer conditioning was the focus of this research.

The assumptions underlying this research were: (1) that sludges exhibiting good filterability after high-stress polymer conditioning will also dewater readily during high-stress mechanical dewatering processes; (2) that optimum polymer dose requirements determined during low-stress testing may prove to be inadequate under subsequent high-stress testing; and (3) that some critical relationship may exist between optimum polymer dose and mixing input.

Recognizing that there are many different types of sludges, each having unique chemical and physical properties, and each reacting differently to stress, research was conducted to include sludges from the chemical, biological, and primary categories. This was done in order to facilitate the application of results to a more complete range of sludge dewatering techniques.

With these facts in mind, the specific objectives of this research were to:

(1) Determine the effects of polymer dose, mixing time (t), and mixing energy (G) on the relative filterability of water and wastewater sludges.

(2) Simulate the high-stress conditions expected in modern dewatering processes.

(3) Determine if jar test systems adequately predict optimal polymer dose requirements when conditioned sludges will be subjected to high-stress dewatering processes.

(4) Determine the relationship between optimum polymer dose and mixing energy input (Gt).

II. LITERATURE REVIEW

A complete understanding of the mechanisms involved in sludge conditioning requires that many varied topics be investigated. Summaries of the most pertinent publications addressing these areas are included in this chapter.

1. Sludge Characteristics Affecting Dewaterability

Sludges generated by the various types of treatment plants differ in moisture content, amount of degradeable organics, chemical composition, and microbial activity. In general, they can be classified as either raw/primary, activated, or chemical in nature. Primary sludges are the water-carried solids that settle to the bottom of primary clarifiers during wastewater treatment. These sludges usually contain between two and five percent solids, have a very objectionable odor, and may be contaminated with large amounts of pathogenic organisms. Activated sludges result from the biological degradation of organic material. Activated sludge floc are typically very weak and will contain up to 98.5 percent moisture. The solids are generally of low density which makes concentration by conventional dewatering methods troublesome. Chemical sludges are generated from water treatment and will normally contain from 90 to 95 percent water, depending on what types of chemical coagulants have been used. The most common coagulants are aluminum sulfate (alum) and ferric chloride (WPCF, 1972).

Vesilind (1980) stated that these basic parameters can only be of limited value to researchers, and therefore a knowledge of detailed operational characteristics is essential to gain an understanding of sludge response. Specifically, one must consider how sludges are affected by (1) particle size, (2) particle charge, (3) compressibility, (4) temperature, (5) solids content and (6) pH.

Particle size has already been suggested as a most critical characteristic in sludge dewatering. Indeed, as particle size decreases, the total surface area within the sludge mass will increase proportionally. Three probable adverse effects of this action have been postulated (EPA, 1972). These are: (1) greater electrical repulsion between particles resulting from a larger area of negatively charged surface, (2) increased frictional resistance to the movement of water and (3) more attraction of water to particle surfaces due to an increase in the number of adsorption sites. These conclusions are in agreement with generally accepted theory.

Vesilind (1980) citing Karr (1976) described experiments involving fractionated colloidal particles and their relative effects on sludge specific resistance to filtration. It was determined that the smallest particles had the greatest inhibitory effect on filterability. This was attributed primarily to the tendency of the particles to form blockages within the sludge cake. Later research by Knocke et al. (1980) suggested that specific surface area was the most likely cause of these variations. They concluded that sludge floc size had the greatest effect on the rate at which metal hydroxide sludges dewater.

Particle charge was only lightly addressed above. Since most sludge particles are negatively charged, these electrical forces result in the tendency toward repulsion. Repulsion will become more pronounced as particles are forced more closely together, inhibiting the formation of large floc and thereby reducing filterability (Edzwald _et al_., 1974).

Compressibility is yet another important variable, referring to the tendency of particles to deform. This is particularly troublesome when high-stress dewatering processes are used. During deformation, the amount of void space between particles is greatly reduced. This in turn restricts the flow of water from the sludge mass. Novak and O'Brien (1975) observed that chemical sludges exhibit varying degrees of compressibility. They also noted that polymer conditioning will in some instances increase the coefficient of compressibility. While this may sound detrimental, it was discovered that there was little change in resulting filter cake solids concentration after conditioning. Apparently, a more porous matrix was formed that allowed the rapid draining of water.

Temperature changes may also affect dewaterability. As with most liquids, the viscosity of sludges will tend to decrease as temperature rises. Viscosity refers to the amount of resistance within a fluid to shearing forces. Thus less viscous sludges may be more susceptible to particle breakup and compression. On the other extreme, more viscous sludges can also present a problem. Stokes law states that particle settling velocities during centrifugal acceleration will vary according to an inverse linear relationship with viscosity. Thus as viscosity increases, the efficiency of centrifuges may be reduced (EPA, 1982).

Solids concentration will often have markedly pronounced effects. Novak and Calkins (1975) investigated the variations in chemical sludge physical characteristics as a function of solids concentration. It was concluded that the rheological characteristics of sludges are closely related to solids content. As the solids concentration increases, so does the internal friction within the sludge. This would, of course, have a direct impact on the resulting viscosity. In a similar study of the factors affecting the drainability of activated sludges, Randall _et al_. (1971) determined that solids concentration was the single most important cause for water retention. It was noted that total drainage and drainage rates decreased rapidly as solids levels approached 2.5 percent, although there was little added effect as the level rose beyond that point. Bugg _et al_. (1970) concluded that solids content affected polymer dose requirements for alum sludge conditioning.

The final parameter to be discussed is sludge pH. It has been determined that adjustments to pH through chemical addition can affect the surface charge on sludge particles. This can be of particular importance in the selection of polymers that might be used during conditioning. Generally, anionic polymers work best at a high pH, while cationic polymers are more suited to values near the neutral range. Novak and O'Brien (1975) tested three sludges with different polymers and at varying pH levels. They concluded that pH will not only influence polymer selection, but polymer dose requirements as well.

In some cases, relatively small changes in pH necessitated doubling the polymer dose to maintain desirable performance levels of dewaterability.

2. Sludge Dewatering Processes

Numerous techniques have been developed over the years for the removal of water from sludges. Some are more effective than others, and their use is normally dependent on the type of sludge being treated, its characteristics, available land area, and other economic considerations. Generally, they are classified as either evaporative/percolative or mechanical in nature. Some of the more interesting and/or widely used processes are discussed in this section. They include (1) lagoons, (2) drying beds, (3) vacuum filters, (4) pressure filters, (5) centrifuges and (6) freezing.

Lagoons are nothing more than earthen basins and may be used for sludge storage or drying. When used as a storage lagoon, they are constructed at varying depths, with five feet being about average. Normally, sludge will be held only until it can be pumped out and processed through more expedient methods. The drying lagoon may be used as a sole dewatering process. Here the depth is reduced to about two feet, with the total depth of sludge normally not exceeding 15 inches. Sludge is pumped in and allowed to dry through a combination of percolation and evaporation. Frequently it is necessary to remove standing supernatant from the surface for recycle back through the treatment plant. Lagoons are relatively inexpensive to construct and maintain, but they often will require large land area, making them unsuitable for most urban applications. Additionally, problems may develop with groundwater pollution, insect breeding, and severe odor levels (WPCF, 1969). The major inadequacy with this type of dewatering process is that the sludges are normally not sufficiently concentrated to allow removal for subsequent landfilling. A detailed study of lagoons at the Monroe County Water Authority, Shoremont Plant, New York State, indicated that even after three years of settling, the highest solids concentration found anywhere in the lagoon was only about 10 percent (Neubauer, 1968). It is possible that the efficiency of lagoons might be improved with the installation of some sort of underdrain system.

Drying beds originally consisted of the sand bed type and are one of the oldest systems known. They essentially operate like a sand filter in trapping solids. Loss of water is also through evaporation and percolation mechanisms. Roughly 21 percent of sludge weight is lost through drainage (WPCF, 1969). Beds are normally constructed in partitioned fashion with sand and gravel layers overlaying a tile drain system. Sludges can be conditioned prior to application to improve performance. After sludge cakes have dried sufficiently, they are removed manually for further disposal.

While they are more efficient than the lagoon, drying beds still may require extended periods to produce desirable results. In recent years, more efficient versions such as the paved, wedgewire, and vacuum assisted types have seen increasing use. Paved beds were developed to protect the underdrain system during sludge removal. These beds slope gently toward the center drain and are overlayed with asphalt or concrete. Wedgewire beds employ a wedge-shaped panel fitted over a concrete basin. The panel serves as a false bottom, and the area beneath serves as the collector for water which percolates down through the sludge. It is possible to dewater some sludges to 20 percent solids content in 24 hours utilizing these beds. Vacuum assisted beds employ gravity drainage until maximum sludge depth is reached. At this point a vacuum pump draws through a sump, forcing the sludge against a porous filter media plate. The vacuum is ceased when the filter cake cracks. Here again, solids content between 16 and 20 percent is possible.

Vacuum filters have been in use for over 50 years and have been one of the most common types available. Sludge is normally conditioned prior to being applied. The most familiar variety is the rotary filter, consisting of a cylindrical drum which rotates partially submerged in a trough of sludge. Usually 25 percent of the filter will be under the sludge at any one time. The drum itself is normally divided into compartments and is covered with a filter medium. Vacuum is applied between the drum and filter, drawing filtrate inside the drum and leaving a sludge cake to form on the filter surface. Early models utilized scraper mechanisms to remove sludge from the drum. More modern versions incorporate string, belt, or coil type filters that automatically separate from the drum at the appropriate time. Vacuum filters tend to produce a very high solids content within the filter cake, a relatively clear filtrate, and good filter yield (Vesilind, 1980).

Pressure filters, or filter presses, have also seen widespread use. Normally they will consist of a series of chambers formed either by a group of flush plates and distance frames spaced alternately, or by a series of recessed plates. A filter medium is either hung or fitted over each plate. The plate assembly is then closed either hydraulically or with screws. Applied pressure must be intense enough to withstand the forces generated during the filtering process. Sludge is then fed up through feed openings in the plates under pressures of up to 225 pounds per square inch. Solids are retained within the chambers between the filters. After pressure is applied for the required time (from one-half to 24 hours dependong on sludge type) the plates are opened and the sludge cake falls into a mechanical hopper that usually loads it directly onto waiting trucks for land disposal. As with the vacuum filter, results are usually good if the sludge has been properly conditioned. Solids content will average 20 percent or better (Thomas, 1971).

Centrifuges represent another significant development in dewatering methods. They make use of centrifugal force to separate solids from the sludge. Three basic types in use today are the solid bowl, disk, and basket models. The solid bowl centrifuge consists of a tapered, imperforate, cylindrical bowl and a rotating screw-type conveyor. Sludge enters through a fixed feed pipe extending well into the bowl. As the sludge flows through the system, particles adhere to the wall of the rotating bowl. The conveyor then transports them toward the tapered end for discharge. Free water normally drains out the opposite end. Bowl centrifuges are available in varying length-to-diameter ratios and speeds. The more powerful versions work best with sludges that will pack easily into a cake. Basket centrifuges utilize a perforated bowl where solids are retained and water passes out through the sludge cake and bowl wall. Problems will sometimes develop when small particles clog the holes. This will tend to make the effluent very dirty and requires shutdown for cleanup. In general, centrifuges will produce cakes with solids contents ranging from 20-35 percent (Keith and Little, 1969).

The final method of sludge dewatering to be addressed is known as freezing. Developed in England in the early 1950's, the method has not seen widespread use in the United States. Sludges are first prethickened to reduce volume and ultimate cost. The ensuing freezing process appears to remove water of hydration from sludges formed by hydroxide coagulant conditioning. On thawing, the sludge takes on seemingly new characteristics. The end result is a clear water with small, granular-like particles that dewater readily. Volume reduction is to about one-sixth of the original (Krasauskas, 1969). Research was conducted by Farrell _et al_. (1970) to determine the effectiveness of natural freezing on the dewatering of alum sludge. It was concluded that sludge dewaterability and solids content can be improved dramatically by slow freezing and thawing, provided freezing is complete. Thirty fold reductions in specific resistance were noted after using this method.

Of the processes discussed in this section, vacuum filtration, centrifuging, sand bed drying, and filter pressing seem to be the best available. These methods require minimal time and each can produce sludge cakes at about 20 percent solids. Of course the ultimate choice should be based on careful lab and plant testing for the sludge to be handled. The method chosen should offer the greatest volume reduction at least cost, while giving an acceptable sludge form for disposal.

3. Coagulation and Flocculation Theory

Most of the particulate impurities in wastewaters range in size from several hundred microns for suspended materials, to as low as just a few Angstroms for soluble substances. A large portion of these impurities can therefore be removed through simple sedimentation processes. In the case of those substances too small to be removed by gravity settling, however, it is necessary to impart some sort of action designed to form larger, readily settleable aggregates (Weber, 1972).

In order to accomplish this task, we must first consider some basic facts about colloidal particles. Of primary importance is the realization that they carry an electrical charge. It has already been mentioned that most sludge particles are negatively charged. Since the net charge of the solution is always neutral, it follows that the charges on the particles must be balanced somehow in solution. The generally accepted theory of this phenomenon is the electric double layer concept. The Guoy-Stern colloidal model (Steel and McGhee, 1979) describes this effect. An electric double layer consists of the negatively charged particles and a bound layer of water in which oppositely charged ions are drawn from within the bulk solution.

Particles thus tend to become stabilized. That is to say, when similar particles approach each other, they will tend to be repelled by electrostatic forces. Thus it is obvious that the particles will first have to be destabilized before they can be agglomerated for sedimentation.

The destabilization of particles is normally accomplished through the addition of chemical coagulants, such as aluminum or iron salts, and more recently, synthetic organic polymers. This process of chemically altering colloids so that they will be able to approach each other is called coagulation (Cornwell and Bishop, 1981). Four distinct methods of particle destabilization mechanisms have been advanced. They include (1) compression of the double layer, (2) adsorption to produce charge neutralization, (3) enmeshment in a precipitate and (4) adsorption with interparticle bridging. Double layer compression involves the addition of high concentrations of counter-ions to solution. This causes a decrease in zeta potential (the magnitude of charge at the surface of shear within the double layer), which in turn reduces the range of the electrostatic repulsive forces. Adsorption with subsequent charge neutralization is similar, except that counter-ions are adsorbed onto the surface of the colloid, thereby neutralizing it. Enmeshment in a precipitate is one of the most common methods in use. In this process salts such as aluminum sulfate or ferric chloride are added which form hydroxide flocs. As the floc falls or moves through solution, colloidal particles are entrapped by the precipitate. Adsorption with the interparticle bridging refers to the use of long-chained polyelectolytes to adsorb particles onto the polymer chain. A more detailed description of this process is presented later in this chapter.

Once particles have been destabilized, action must be taken to increase their frequency of contact or collision in order for agglomeration to occur. Collisions in water normally occur by either Brownian diffusion, fluid shear, or differential settling (O'Melia, 1978). The quickest and perhaps easiest way to increase contacts is by utilizing the fluid shear concept. In other words, some sort of mixing or stirring action is imparted to the fluid. This process is known as flocculation.

Basic theory of orthokinetic flocculation was first proposed by M. Von Smoluchowski in 1918, and was later introduced into the literature by Camp and Stein in 1943 (Harris et al., 1968). Orthokinetic refers to an increase in particle contact due to fluid motion. Camp (1955) described the basic mechanism by stating that "the rate of flocculation caused by the motion of the fluid (at a point in the fluid) is directly proportional to the absolute velocity graient or space rate of change of velocity at that point, and is directly proportional to the concentration of flocculable particles at that point." It has been shown by Camp and others (Cornwell and Bishop, 1981; Lawler et al., 1980; Argaman, 1968; Harris et al., 1966) that the rate of floc formation is directly proportional to the velocity gradient (G). The value of the velocity gradient is found by using the formula

$$G = \sqrt{W/u} \qquad (1)$$

where u is the absolute viscosity of the fluid, and W is known as the dissipation function given by

$$W = 2\pi\ sT/V \tag{2}$$

where s is the measured rotor speed in rps, T is the measured torque input, and V is the volume of the sample (Camp, 1968). Units for G are in $\sec^{-1}$ (or a numerical value per second).

According to theory, the higher the velocity gradient, the more turbulent the mixing action, and the more frequent the number of collisions between particles. The more frequent the collisions, the more rapid the rate of flocculation. While this concept follows readily, it has also been determined that there is a limit for most particles regarding how high a velocity gradient may be. As the G value increases, so does the magnitude of shearing forces within the fluid. Since floc particles become weaker as they grow larger, the point will eventually be reached when the shear force in the fluid exceeds the shear strength of the floc. The result will be the breakup of the floc and a counterproductive effect.

A great deal has been written concerning the effects of turbulence during the flocculation process. Argaman and Kaufman (1970) suggested that the primary mode of floc breakup is surface erosion of floc through turbulent drag forces. They determined that particles are stripped from the floc at a rate proportional to the surface area and shearing stress applied to the surface. Thomas (1964) had postulated earlier that breakup resulted from dynamic pressure differentials on opposing sides of the floc. Deformations developing after this action thus caused the floc to shear apart. Parker *et al*. (1972) seem to agree with the former, concluding that the shearing of primary particles is promoted through the action of fluid motion on the floc. They further demonstrated in lab testing of inorganic and biological floc that there is a maximum stable floc size for the amount of stress (G value) applied. Floc larger than this will become unstable, and will then begin to erode at the surface as the shear strength of the interparticle bonds are exceeded. This explanation seems to be the most plausible.

Mixing or flocculation can be accomplished by several means. Baffled mixing chambers were the earliest devices used for this purpose. They are simply tanks with baffle plates spaced so that the influent is forced either over and under or around the end of the plates. This method is the least effective of all since the degree of mixing action is generally small, and is dependent on the rate of discharge of influent. This makes it very difficult if not impossible for operators to control the intensity of mixing. More modern methods include mechanical devices that can be controlled variably and at will. Common types are the paddle and walking beam flocculators.

4. Polyelectrolytes as Sludge Conditioners

The practice of conditioning sludges is not new. On the contrary, the French were known to have used chemicals in sludge treatment as early as 1740. Since then, various products such as iron, lime, sulfuric acid, sulfur dioxide, aluminum sulfate, and ferric chloride have been used for this purpose. Today, the most frequently used chemical is ferric chloride alone or in conjunction with lime (WPCF, 1969).

The advent of polyelectrolytes or polymers as sludge conditioners has been more recent. Bargman et al. (1958) provided the first report of large scale testing in both the laboratory and field. From the results obtained in this study it was found that many of the polymers evaluated were only effective in coagulating wastewaters, but that others used together with ferric chloride greatly improved filterability as well.

Goodman and Witcher (1965) undertook studies to determine if polymers could be used to aid sludge elutriation and filtration processes. Elutriation facilities constructed at Ann Arbor, Michigan during the 1950's were performing poorly. Specifically, operators noted high losses of sludge solids in spent wastewater. Attempts were made to adjust operational parameters, but no improvement resulted. Conventional chemical conditioning was also found to be non-productive and extremely expensive. Eventually, the basins were converted to sludge holding facilities. Goodman and Witcher procurred washwater samples and tested the effects of polymer conditioning. They used three liter samples in glass battery jars, added varying amounts of polymer, and then mixed them thoroughly for about five minutes. The actual mixing intensity used is not known. They then plotted percent recovery of washwater against time, concluding that polymer could be used to greatly improve the settling characteristics of sludge. This in turn resulted in the more efficient operation of elutriation units. Additional testing was done with well-digested primary and trickling filter sludge to see how polymer might affect the operation of vacuum filters. Working with sludges containing from two to five percent solids, they used

Purifloc 601 and ferric chloride to condition them prior to filtration. Results were very favorable during plant-scale testing with rotary filters. This was one of the first instances where polymers offered good results at very economic cost.

Morris (1965) investigated the use of polymers in conditioning digested primary and waste activated sludges at Atlanta's water pollution control plant. Original designs for the facility called for ferric sulfate and lime conditioning prior to vacuum filtration. He compared the effects of polymer conditioning to conventional methods over the normal seasonal range. Trial lab runs were made with Buchner funnels being used to measure filterability. It was noted that sludge characteristics changed periodically, and optimum dose levels varied between six and 20 pounds per ton. Overall results were excellent, often reaching 24 percent solids in the sludge cake. Morris drew the following conclusions from his work: (1) lab studies are a good indicator of coagulant efficiency during plant operations, (2) polymers required less capital expenditure in vacuum filtration than many other chemicals in use, (3) polymers give exceptional production rates with little loss in sludge drying efficiency, (4) feed sludge percent solids and alkalinity strongly affect polymer performance and (5) filtrate clarity from polymer conditioning is at least equal to that of other processes.

Sharon (1967) conducted studies of polymer conditioning at a plant in Hamilton, Ontario. His objective was to compare polymers to conventional inorganic conditioners with respect to cost, production rates, filtrate solids content, handling characteristics, and response to seasonal variations. He utilized Reten 210, a high molecular weight cationic polymer. The plant's 300 gallon tanks normally used for ferric chloride addition were used to prepare the polymer solutions. No other alterations to plant operations were made. Polymer was added in place of ferric chloride during distinct seasonal operating periods, with each test period lasting about four weeks. During the first period (June-July), chemical costs were lower and filtrate quality was better, although the production rate was slightly lower. Increased operator experience produced better results during the second period (July-August). While polymer production rates were still lower than simultaneous ferric chloride performance, both were higher than those obtained the previous year. By the end of the third and fourth periods (September-November), higher production rates were observed with polymer at only a slight increase in operating cost. In the final period (December), chemical costs for polymer were less than for ferric chloride and production rates were identical. Sharon concluded that with increased operator experience, both lower chemical costs and higher production rates were obtainable with polymers. He also noted greater solids content of the sludge cake and its improved handling characteristics.

While good results were being obtained with polymers, little was known at the time about how they functioned. Goodman (1966) first suggested that the mechanism of polymers was charge neutralization, which in turn allowed coagulation to occur. He likened the action to the attraction of flies to flypaper, with the coagulated system bearing a good deal of resemblance to a bucket of flypapers all enmeshed with their trapped flies. While this may have been a somewhat simplified explanation, it does parallel modern theory.

Today there are two accepted concepts of polymer flocculation mechanisms. One concerns the idea of interparticle bridging, and the other follows the notion of charge neutralization. Combined effects have also been postulated.

Stumm and O'Melia (1968) felt that the only way to explain the destabilization of colloids in solution was through chemical bridging theory. La Mer (1964) had already proposed a mathematical model of such a theory to explain destabilization of colloidal dispersions. Bugg et al. (1970) conducted extensive research into the mechanisms of polyelectrolyte conditioning of alum sludges. They concluded that molecular bridging theory offered the most satisfactory explanation of the conditioning process.

Chemical bridging theory states that coagulation of particles can occur by either the bridging of two or more particles by one polymer molecule, or by the joining of polymer chains that had been adsorbed onto different particles (Sato and Ruch, 1980). These actions result from the makeup of polymers used in conditioning. Generally speaking, they are long-chain organic molecules of high molecular weight, containing numerous functional groups along the branches of the molecule. Upon dissolution, some of these functional groups will ionize. Thus polymers are classified as either anionic, cationic, or non-ionic, depending on the charge they assume in solution. Anionic polymers are negatively charged. This makes them particularly effective for binding up positively charged particles. As mentioned earlier, most sludge particles are also negatively charged. Thus anionic polymers are normally used for sludge conditioning in conjunction with other chemical agents that help in coagulation. Cationic polymers carry a positive charge. These are most effective in binding up negatively charged particles. Non-ionic polymers do not ionize in solution. However, they do provide long, fibrous molecules with numerous active surface sites which will allow for the bridging of sludge particles into aggregates. They too are normally used together with other chemical conditioners (WPCF, 1969).

Basic theory of charge neutralization follows intuitively from the foregoing discussion. The stability of sludge particles has already been addressed, being attributed to the double-layer theory. When an oppositely charged polymer is added to the solution, ions will be immediately adsorbed onto the particle through electrostatic attraction. This results in neutralization of the negative charge on the particle, with a resultant lowering of repulsive forces. The particles are then free to coagulate for more efficient settling. While it is logical to assume that high molecular weight polymers probably utilize both neutralization and bridging to effect coagulation, it has been suggested that low molecular weight polymers rely more on charge neutralization to destabilize particles.

A considerable amount of work has been done in past years in attempts to evaluate the effectiveness of polymers in conditioning sludges and strengthening floc. Hannah et al. (1967) stated that the purpose of conditioning is not only to produce a quickly settling floc, but also one that is resistant to the shearing forces generated by hydraulic velocity gradients. They felt this was particularly important during filtration, since fragmented floc could be carried through the filtering media and into the finished water. During their research, they estimated floc strength by measuring changes in particle size distribution in a turbid wastewater. Samples were mixed in a Covette jar test apparatus and subjected to a constant velocity gradient. A six channel particle counter was used to determine particle size distributions within the floc. During testing, alum-conditioned samples were subjected to G values of 29 sec^{-1} for mixing times up to 3,720 seconds. Analysis of resulting particle counts showed that low intensity mixing (Gt = 41,000) yielded a readily settleable floc, while high intensity mixing (Gt = 108,000) caused floc breakup and high residual turbidity in the water. Similar tests were run to evaluate the effectiveness of polymer in strengthening floc. Polymer doses (Purifloc N-17) were varied between 0.5 and 2.5 mg/l, and were added prior to the alum. They noted that as the polymer dosage increased, particle size distributions shifted toward the larger end, indicating increased floc strength.

Additional work was done by Birkner and Morgan (1967) in examining polymer flocculation kinetics. They investigated the effects of mixing intensity, mixing time, and cationic polymer dose on the flocculation phase of the destabilization process. Reactions were conducted using a variable speed stirrer for mixing, and a particle counter for particle size distribution measurement. Prepared latex suspensions were used as the wastewater source. Polymer doses were varied between 50 and 12,500 μg/l. G values ranged between zero and

120 sec^{-1}, while mix times fell between six and 424 minutes. Particle counts were taken frequently to record changes in size distributions. They determined that an optimum dose exists for maximum flocculation efficiency for a given mixing intensity (Gt). This followed from the tendency for very small and very large doses to exhibit high particle size stability. They also showed that increased mixing intensity will tend to deflocculate or fragment polymer destabilized suspensions. This finding was important in substantiating previous beliefs that mixing intensity is a significant factor in the breakup of large particle aggregates.

In 1970, Bugg et al. conducted extensive research into polymer conditioning of alum sludges. They utilized a conventional jar test apparatus as the mixing device to treat one liter sludge samples. They then applied varying polymer doses up to 100 mg/l at a speed of 100 rpm. Mix time was also varied. After mixing, samples were allowed to settle for 15 minutes, supernatant was withdrawn, and the filterability of the remaining sludge was determined using the standard specific resistance test. Specific variables investigated by the research were pH, solids content, mix time, and polymer dose. Cationic, anionic, and non-ionic polymers were utilized. Results obtained serve to reinforce previous work. They concluded that (1) an increase in mixing time in general led to a deterioration in the specific resistance of the sludge cake. This was due to the breakup of floc caused by increased energy input to the system; (2) the specific resistance of the sludge decreased with increasing polymer dose. Overdosing was not observed within the range of polymer doses used; and

(3) polymer effectiveness is influenced by pH. Cationic polymers were only effective at low pHs, while anionic and non-ionic polymers gave good results between pH values of 6 and 10. These results were later reproduced by O'Brien and Novak (1977). Additionally, they noted that as the solids content increased, so did the mixing time required for optimal performance.

Research described thus far has revealed much about the nature and effectiveness of polymers in the coagulation and flocculation processes. It has also been shown that they can be of great value in improving the filterability of sludges. There is, however, one drawback that reduces the applicability of the data. As yet, the effects of high-intensity mixing on polymer performance has not been investigated. The standard jar test apparatus has been the only type used thus far. The problem with this is that jar testers operating at 100 rpm can only generate G values between 100 and 150 sec^{-1}. It is suspected that high-stress dewatering processes, such as the centrifuge or filter press, generate G values in the hundreds or even thousands. In order to predict polymer performance in these situations, it is necessary to simulate high-stress conditions.

Perhaps the earliest work done in the area of high-intensity mixing was by Letterman _et al_. (1973). This study was designed to determine the effects of rapid mix intensity, rapid mix time, coagulant dose, and initial turbidity level on the subsequent clarification of wastewaters. While polymers were not used, results obtained were nonetheless pertinent to this discussion. A special mixing unit was devised utilizing a variable speed motor, shaft-mounted torquemeter, and baffled mixing chamber. The ability to read torque measurements allowed precise determination of velocity gradients using equations discussed earlier. Mixing energies between 100 and 1000 sec^{-1} were obtained. One liter wastewater samples were synthesized by adding powdered carbon to water in doses ranging from 50 to 1000 mg/l. Coagulant doses (alum) were varied between 10 and 125 mg/l. A Hach model 1860 turbidimeter was used for turbidity measurements. In a typical experiment (of which there were 300), a sample would be dosed with alum and subjected to a rapid mix period of specific length and intensity. This would be followed by a slow mix period of specified length and 30 minutes of settling. Residual turbidity was then measured using samples of the supernatant. Most significant among the conclusions drawn were that (1) residual turbidity was a function of rapid mix time; (2) for the lowest turbidity level achievable with each wastewater sample, there was an associated optimum mix time, mixing intensity, and alum dose and (3) the required Gt, normally used to represent total mixing energy input, was only a function of alum dose for a given optimum level of turbidity removal.

Stump and Novak (1979) evaluated the performance of cationic polymers in direct filtration applications. A standard jar tester and a special high-intensity mixer similar to that used by Letterman _et_ _al_. were utilized. With this mixer, velocity gradients ranging from 100 to 900 sec^{-1} were possible. For their experiments, synthetic wastewaters were prepared using Kaolin powder. Parameters measured to judge polymer effectiveness were headloss generated in a direct filtration apparatus and residual turbidity of the supernatant remaining after a

30 minute settling period. Varying polymer doses were added to the samples and mixed at several G settings for different mix times. Results of jar testing and high-stress mixing were compared. One of the most important conclusions they were able to draw was that jar testing results were not necessarily good indicators of polymer suitability for filtration. In one instance, jar testing at G = 100 sec^{-1} showed that a certain polymer (A) gave better results in coagulation than another polymer (B). Later, when mixing energy was increased to the 200-350 sec^{-1} range, polymer B proved to be superior to polymer A in improving filtration. In general, they determined that high molecular weight polymers (100,000 or above) performed best with intense mixing at G = 600-1000 sec^{-1}, while low molecular weight polymers (10,000-50,000) did better at G = 300 sec^{-1}. Overall, the best filtering runs came at G = 300 sec^{-1}, t = 20 minutes or more, and polymer molecular weight = 50,000. It was further noted that flocculation almost always improved polymer performance. Rapid mixing was found to be critical in determining optimal polymer usage.

Of the remaining literature describing high-stress polymer conditioning, perhaps the most significant experimentation was done by Novak and Piroozford (1981). Their work was directed at the use of polymers in conditioning water plant (chemical) sludges prior to dewatering. Specifically, they investigated the effects of mixing and dosing on polymer performance. Both the standard jar tester and the "standard stirring device" were used so that jar test results could be compared to high-intensity mixing. Polymers used included a high molecular weight anionic (Betz 1120), a low molecular weight cationic

(Betz 1190) and a high molecular weight cationic (Betz 1160). Both alum and lime sludges were tested at various polymer doses, mixing intensities, and mixing times. Parameters measured to judge relative effectiveness of polymers were particle size distribution, electrophoretic mobility, specific resistance, and capillary suction time (CST). From data obtained, the following conclusions were drawn (1) optimal polymer dose selection using low mixing energies does not adequately predict polymer requirements when mixing is more intense; (2) optimal conditioning at low mixing energies produces a sludge that is unstable to high-stress mixing or additional polymer dosing; (3) for alum sludge, a readily dewaterable sludge can be obtained through intense mixing and large polymer dosing; (4) for alum sludge, polymer requirements for optimal conditioning increase as mixing energy increases; (5) for lime sludge, polymer dose will also increase with mixing intensity and (6) for lime sludge, too much mixing will result in a reduction of sludge dewaterability which cannot be corrected with additional polymer input.

These findings are very significant in that they clearly show the inadequacy of jar testing for predicting polymer conditioning requirements when sludges are to be subjected to high stress. A verification of these results and an expansion to include activated and primary sludges is needed to provide a more solid base for general applicability.

5. Filterability Measurement

The final topic to be addressed in this chapter is methods used to measure the relative filterability of sludges. The literature has already shown that monitoring this parameter is one of the most practical ways to evaluate the effectiveness of polymers and their reactions to such things as mixing intensity and mixing time.

It is generally acknowledged that the two most effective means currently in use for measuring sludge filterability are the specific resistance test and the capillary suction time (CST) (Haugan and Mininni, 1980). Specific resistance is defined as the resistance to filtration offered by a weight of sludge per unit area of filter. It is usually calculated from the equation (Glenn et al., 1973)

$$r = 2PA^2b/uc \qquad (3)$$

where r = specific resistance, m/kg; P = applied filtration pressure or vacuum, dynes/cm^2; A = filter area, cm^2; u = filtrate viscosity, g/cm-sec; c = suspended solids concentration, g/ml; and b = slope of a plot of the ratio of time to filtrate volume vs filtrate volume, s/ml^2.

The apparatus most frequently used for specific resistance is the Buchner funnel. The test is conducted by pouring a constant volume of sludge into a funnel lined with filter paper. Vacuum is applied and the amount of filtrate is recorded over time. Filtrate viscosity and suspended solids concentration are determined by using standard methods. Test results indicate the percent of total moisture recovered or percent solids in the filter cake produced (WPCF, 1969). Relative filterability can be estimated from the amount of time required to obtain a given volume of filtrate, or the time required for the filter cake to crack.

While this method is clearly effective, it does have some drawbacks. It is fairly complex, requires expensive equipment, such as a vacuum pump, and, more importantly, takes a great deal of time to perform. In recent years, a much more efficient method has been developed for achieving the same results. It involves a very simple instrument known as the capillary suction time (CST).

The apparatus consists of two basic parts - a filtering component and an automatic digital timer (Figure 1). The filtering component consists of a plexiglass base which holds a 7 by 9 cm piece of filter paper. A second plexiglass plate with a circular hole in the center is placed on top, being held level by three metal pins. A steel cylinder is fitted into the hole against the filter paper. Also fitted into the top piece are two electrical contacts, aligned with two circular scribes. Connections are made to these contacts through screws that lead to the terminal box. The contacts are spaced exactly one centimeter apart.

During operation, the sludge sample is poured into the metal cylinder just flush with the top. The fluid spreads through the filter paper, eventually reaching the first electrical contact. This starts the digital counter. After travelling one centimeter through the paper, the fluid triggers the second contact, stopping the digital counter. Thus it measures the time needed for the fluid to travel one centimeter through the filter paper. The lower the capillary suction time, the more readily dewaterable the sludge.

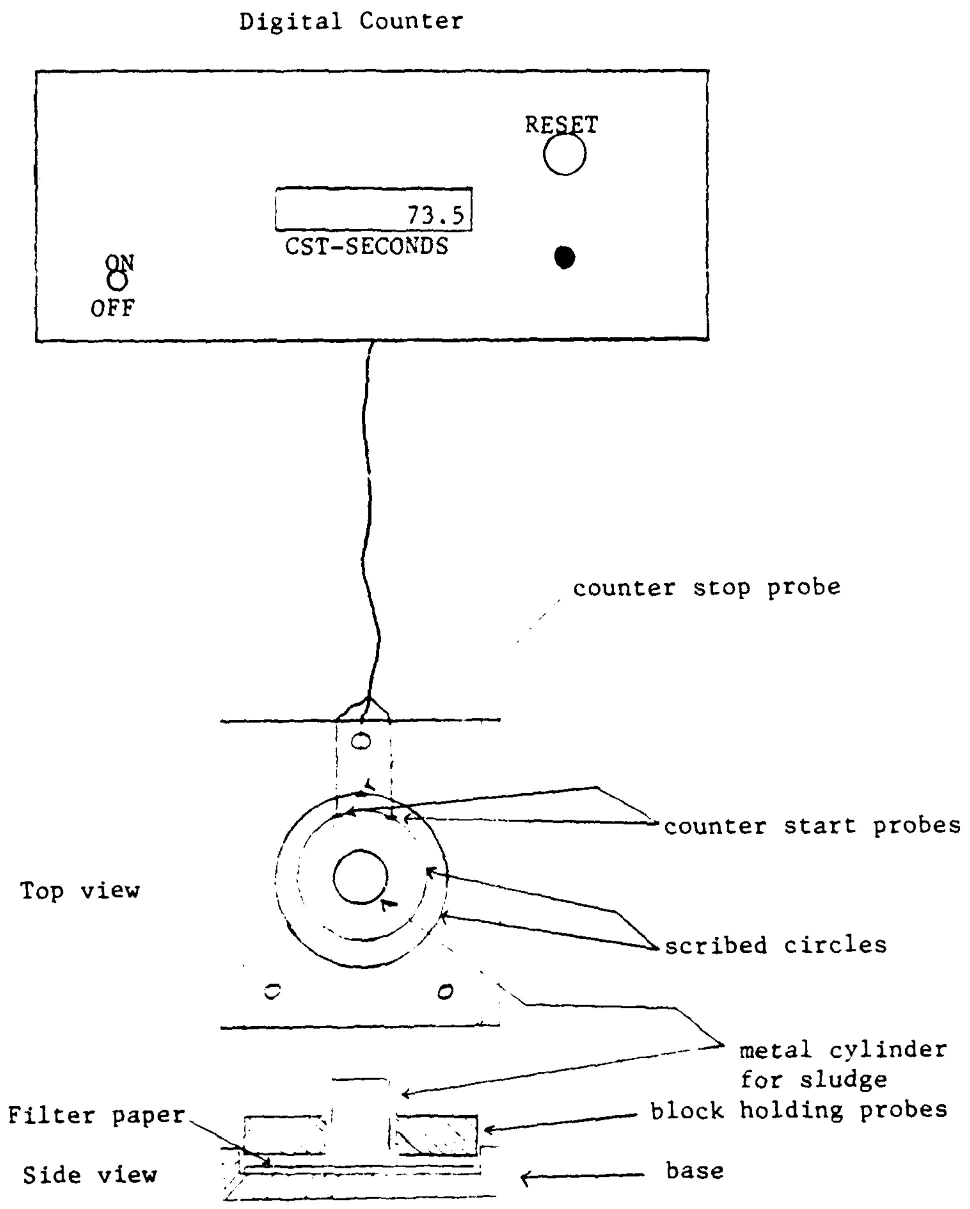

Figure 1. Diagram of CST apparatus

Baskerville and Gale (1968) have conducted extensive testing of this device. They found that readings are affected by filtrate surface tension, temperature, and suspended solids concentration. This is to be expected. After measuring CSTs for numerous sludge samples, they concluded that the instrument offers a fast, simple, reliable method for determining the relative filterability of any aqueous solid-liquid mixture.

While the CST has seen widespread use, there are many who feel results are meaningful only if first correlated with specific resistance (EPA, 1979). This is apparently because of its extreme sensitivity to solids content. It has also been noted that there is considerable data scattering with the instrument. While this may be true, the CST still gives good indication of relative filterability of sludges, and, more importantly, changes thereto resulting from variations in conditioning parameters. Consequently, as long as the solids content of samples remain constant, such correlation should not be necessary.

6. Summary

From the literature review it can be seen that considerable research has been done in the areas of dewatering process evaluation and applicability, sludge dewatering characteristics, coagulation and flocculation kinetics, and the use of polyelectrolytes as sludge conditioners. This information is very valuable to plant operators, since the nature of the sludge being dewatered will dictate the type and degree of conditioning required for the dewatering process being utilized. While variations in polymer effectiveness resulting from changes in mixing energy and mixing time have also been examined, additional work is needed in these areas. The standard jar test apparatus has been shown to be unreliable in predicting polymer requirements for sludges subjected to high stress. Most of the high-intensity mixing research has been restricted to synthetic wastewaters or chemical sludges. Studies determining the response of biological and primary sludges to high-intensity mixing and polymer dosing are also needed to extend the range of applicability of this work.

III. MATERIALS AND METHODS

This chapter details the materials and experimental procedures used in determining the effects of polymer dose, mixing time, and mixing intensity on the relative filterability of typical water and wastewater sludges. Care was taken to insure the reproducibility of the experiments, and, at the same time, to adequately simulate a high-stress conditioning environment. The tests performed during this research should be applicable to virtually any type of sludge conditioning analysis.

1. Sludge Sampling, Characterization, and Preparation

The sludges used in this research were obtained from water and wastewater treatment plants in southwest Virginia. Alum sludge was procurred from the water treatment facility at the Radford Army Ammunition Plant, Radford, Virginia. Primary and activated sludge (#1) samples were provided by the Blacksburg-VPI wastewater treatment plant, Blacksburg, Virginia, and additional activated sludge (#2) was furnished by the wastewater treatment plant in Christiansburg, Virginia. Characteristics of these sludges are as indicated in Table I. Total solids concentrations were determined using procedures outlined by Vesilind (1980). Readings for pH were taken with a Fisher Acumet Model 610A pH meter, while viscosity measurements were made with a Brookfield Model LVT viscometer.

Alum sludge provided by the ammunition plant was very unique. Under current operational procedures, it is suctioned from the bottom

Table I. Sludge characterizations.

Type	Total Solids Conc (%)	pH	Base CST (sec)*	Kinematic Viscosity $\left(\frac{in^2}{sec}\right)$
Alum	1.44	7.5	81.4	5.68×10^{-3}
Activated #1	0.76	6.6	17.1	**
Activated #2	0.92	7.1	74.1	**
Primary	0.75	7.2	37.9	**

*Base value for unconditioned sludge.

**Values assumed to be equal to that for alum. See text for explanation.

NOTE: All samples were tested at room temperature.

of large flocculation basins on a bi-weekly basis and held in metal storage tanks for periods of up to one month. From there it is pumped to a filter press for dewatering. The sludge was brownish-green in color, extremely concentrated (i.e. thick), and had a disagreeable odor. Since the water source was the New River, the odor was probably caused by the decay of organic material. Samples were obtained directly from an interception valve in the main sludge pipeline, and came entirely from the bottom of the tank. They were stored in five gallon carboys prior to conditioning. In its pure state, the alum sludge dewatered so poorly that it was not feasible to use. Capillary suction times for these unconditioned samples were in excess of 300 seconds. To reduce these times to a manageable range, the sludge was diluted with two parts distilled water. This reduced the CST to about 80 seconds. Samples were not diluted until just before conditioning.

Activated sludge (#1) obtained from the Blacksburg-VPI plant also displayed interesting characteristics. Samples were procurred by holding a bucket under the overflow weir of the aeration basin. Sludge was then poured into three, five-gallon carboys and allowed to settle for about ten minutes. Supernatant was then poured off, and the three containers condensed into one. Capillary suction times for these unconditioned samples were only 17 seconds, indicating a readily dewaterable sludge. This led to the procurement of activated sludge (#2) from the Christiansburg plant. This second activated sludge came directly from a process return line and was much more concentrated. Capillary suction times for this unconditioned sludge were about

75 seconds. Both activated sludges were light brown in color and essentially odorless.

Primary sludge samples were drawn into a five-gallon carboy through a return line from the bottom of the clarifier. The sludge was light brown in color, contained large suspended particles, such as string and corn kernels, and had a putrid odor. The solids concentration was much below the normally expected five percent. This resulted from a sudden interruption in flow during sampling which allowed process water to mix with the sludge. Actually, this was desirable, since it eliminated the need to further dilute the samples.

Prior to conditioning, all sludge samples were prepared in the same basic manner. Each carboy was tipped back and forth for about 3 minutes to insure that all settled particles were resuspended. Samples were then measured out in a graduated beaker and poured into the mixing apparatus. In the case of alum sludge, samples were diluted with two parts distilled water and shaken for one minute in a sealed bottle before being poured into the mixing chamber. All sludge samples were maintained and conditioned at room temperature.

2. Polymer Preparation and Descriptive Data

Two polymers were used in conditioning experiments. Betz 1120, which had previously been found effective with chemical sludges (Novak and O'Brien, 1975), was applied to the alum samples. It is a high molecular weight (15-20 million) anionic polymer that hydrolizes about 25 percent in solution. Betz 1195 was used in conditioning the activated and primary sludges. This is a high molecular weight

(2-3 million), high charge density, cationic polymer. Because the effectiveness of these polymers was already known, no other types or brands were utilized in the research.

Solutions of Betz 1120 were prepared from granulated product samples obtained at 0.5 percent concentration. One gram of polymer was placed in the bottom of a graduated flask to which distilled water was added to the one liter mark. The flask was then placed on a magnetic stirrer for 24 hours to insure complete dissolution. Solutions were then refrigerated to prevent deterioration, but were allowed to return to room temperature before use.

Betz 1195 solutions were prepared in a similar manner from 0.5 percent liquid product samples. One gram of polymer was placed in the bottom of a graduated beaker and distilled water added as before. The solution was then stirred with a glass stirring rod until all polymer had dissolved (about five minutes). Solutions were then poured into a flask and refrigerated for 24 hours. As with Betz 1120, they were allowed to reach room temperature prior to use.

3. Description and Calibration of Mixing Apparatus

A high-intensity mixer was developed similar to that used by Letterman *et al*. (1973). It was comprised of two basic parts (1) a baffled mixing chamber, and (2) a stirring mechanism that fit over the top of the chamber to form a self-supporting unit. The stirring mechanism consisted of an Eastern Model 3 1800 rpm variable speed motor connected directly to a Power Instruments Model 783 ounce-inch torquemeter. An intermediate coupling connected the torquemeter to the paddle assembly. A small magnet was imbedded in this coupling so that it rotated opposite a Hall Effect device, or magnetic sensor. Each time the magnet passed the sensor, an electric impulse was transmitted to a Hewlett-Packard Model 3734A electronic counter. Gate time on the counter was set at one second, allowing determination of revolutions per second, and thus revolutions per minute. The speed of the stirring mechanism was controlled by a Model 116B Powerstat Variable Autotransformer, allowing output voltage adjustments from 0 to 140 volts. The aforementioned part of the apparatus was designed as an integral unit, allowing easy, one-step removal from and reinstallation on the mixing chamber. The base and supports for each component were made of Plexiglass, and the base contained a small hole which allowed for easy polymer addition.

The Plexiglass mixing chamber was cylindrical and measured 4.6 cm in diameter by 21.6 cm high. Baffles 1.2 cm wide and running its entire height were spaced at 90 degree increments around the circumference. When the mixing device was installed, the paddle was 0.6 cm above the bottom of the chamber. The paddle itself measured 1.2 by 5 cm.

Before using the mixing apparatus, it was necessary to calibrate it so that revolutions per minute readings could be translated directly into velocity gradients, or G values. To do this, sludge characteristics were applied to equation used by Stump and Novak (1979):

$$G = \sqrt{2\pi gNT/60\ Vvp} \tag{4}$$

where g = acceleration due to gravity, in/sec; N = paddle rotational speed, rpm; T = net torque on paddle, oz-in; V = sample volume, in^3; v = sample kinematic viscosity, in^2/sec; and p = density of water, oz/in^3.

Torque readings were taken with the aid of a Strobotach strobe light unit. This was needed to "freeze" the scale on the torquemeter at high rpms. Readings were first taken in air, then in sludge. The difference gave the net torque. Sample volumes were constant at 0.5 liters. Kinematic viscosity was measured for alum sludge by using a Brookfield Model LVT viscometer. A homogeneous ten ml sample was placed in the test cylinder and readings taken at viscometer settings of six through 80 rpm. A significant problem developed during this process when the gage kept getting snagged on particles in the sludge. Each time this happened, the needle would jump completely off the scale. After about 90 minutes of testing at every possible speed, the most consistent reading was selected as the true value. This of course could only be considered a good estimate. Given the problems in taking accurate viscometer readings, the value obtained for alum sludge was used throughout all experiments. This was done since it was felt that the even larger particle sizes in primary and activated sludges would make viscosity measurements more difficult, if not impossible. Since these readings are generally on the order of 10^{-3} - 10^{-4} in^2/sec, it was felt that using the same value for all sludges would not adversely affect experimental results. Thus the calibration curve for alum sludge was used for all experiments.

Given the above considerations, equation (4) was reduced to:

$$G = 20.10\sqrt{NT} \qquad (5)$$

At this point the mixer was set at readings of 300, 600, 720, 960, 1200, and 1500 rpm. Corresponding velocity gradients were then computed using net torque readings and equation (5). G values of 246, 623, 800, 1214, 1734, and 2030 sec^{-1} respectively were obtained. (It should be realized, of course, that given fluctuations in rpm and torque readings during operation, actual G values could possibly vary by ± 15 sec^{-1} at any given time.) The numbers used in these computations are shown in Table 2. These results were then plotted on log-log paper for rpm vs. G value. This gave a straight-line plot with a slope of 1.43 (Figure 2). According to accepted theory (Argaman, 1968), the slope should have been about 1.50 for a correctly calibrated system. Thus the apparatus was considered ready for sludge testing.

4. Filterability Measurements

All filterability measurements were made using a Triton Type 165 capillary suction time apparatus and standard Triton CST filter papers. In all tests, the steel cylinder having an inside diameter of 1.0 cm was utilized as the sludge receptacle (there are two different sizes provided with the set). Sufficient sludge was added to fill the cylinder completely to the top. The only problems noted with the CST apparatus were that (1) on occasion it would fail to reset itself, even though the reset light indicated it was ready. This probably resulted from failing to dry the contacts completely between experiments; (2) the initial amount of time required for cleanup and replacement of filter paper after each run was excessive (2-3 minutes). With experience, cleanup time was later reduced to about one minute.

Table II. Equipment calibration data.

RPM	Torque (air)	Torque (sludge)	Torque (net)	G (sec^{-1})
300	0.8	1.3	0.5	246
600	0.8	2.4	1.6	623
720	0.8	3.0	2.2	800
960	0.8	4.6	3.8	1214
1200	1.0	7.2	6.2	1734
1500	1.2	8.0	6.8	2030

NOTE: All torque readings in ounce-inches.

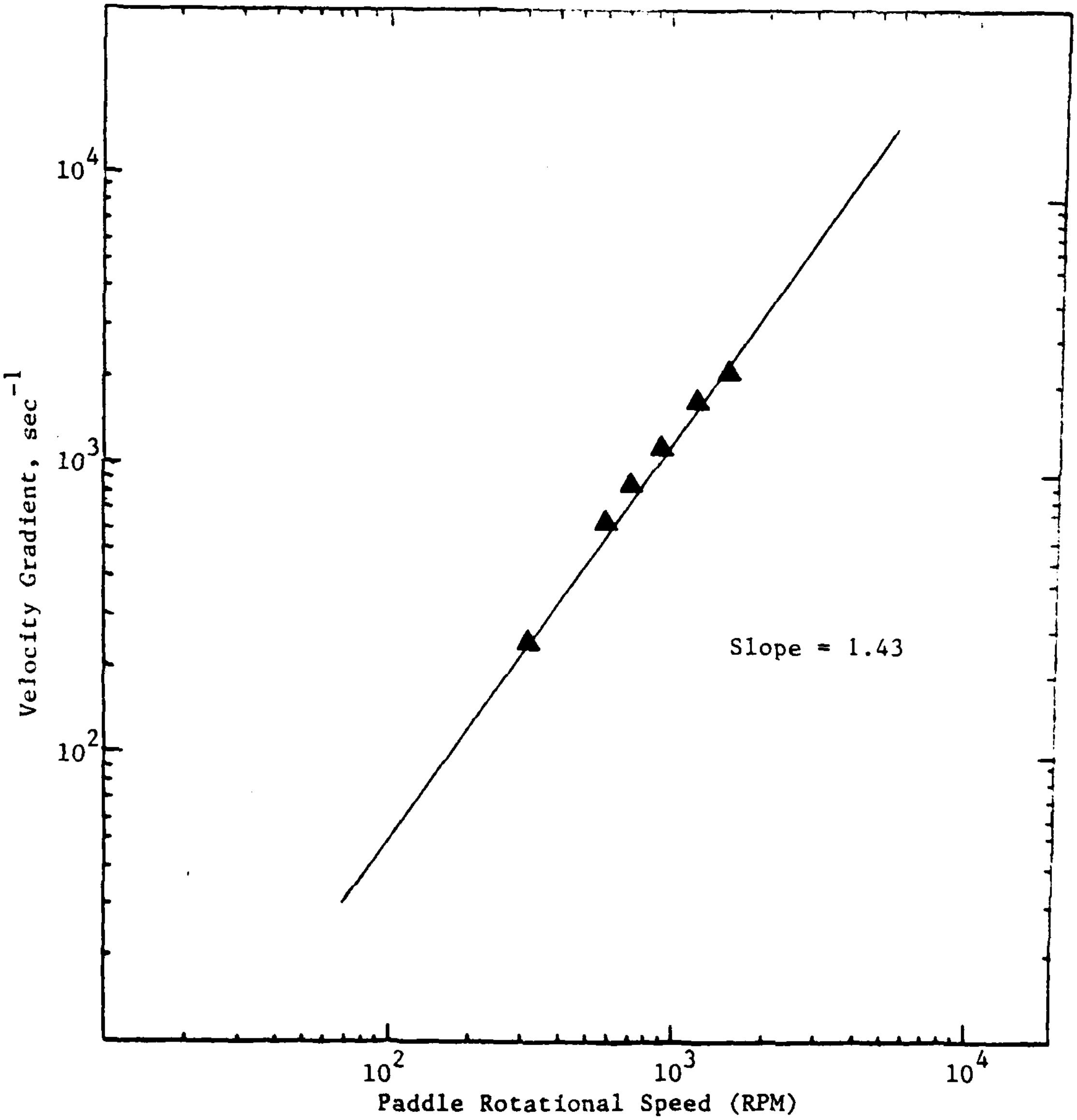

Figure 2. Calibration curve for mixing device.

5. Sample Testing Procedure

Half-liter sludge samples were prepared as described earlier and poured into the mixing chamber. Polymer was added through the hole in the base of the stirrer by using a standard pipette with suction bulb, or a graduated cylinder in the case of large doses. Since 0.5 liter samples of sludge were used, each milliliter of polymer solution added represented a dose of 2 mg/l. After polymer addition, the mixer was set to the specified G value and run for the desired mix time. The mixer was then stopped and a sample withdrawn using a pipette from which the pointed end had been removed. Samples were immediately analyzed using the CST apparatus and the observed readings recorded. Polymer doses, mixing times, and mixing energies applied to alum sludge samples are indicated in Table III. It should be noted that all mix times were cumulative. In other words, the mixer was stopped at each successive sample point, a sample withdrawn, the mixer restarted, and then the sample tested. The mixer was stopped and restarted in this manner until the desired total mixing time was achieved. To illustrate this, series one alum sludge samples were dosed and mixed for a total of 12 minutes, with samples being withdrawn and tested at the 15 second, 30 second, 1 minute, 3 minute, 6 minute, 9 minute, and 12 minute time points. This process was conducted separately for each of the doses and G values specified. Fresh sludge samples were prepared for each polymer dose and G value change.

CST readings for series one alum sludge indicated that either the polymer doses were too small, the mixing times and G values too great, or both. Consequently, dosage was increased and mix time decreased

Table III. Alum sludge conditioning data using Betz 1120 polymer.

Series	Dose (mg/l)	G Values Applied (sec^{-1})	Total Mix Time at Each G (min)	Series Sampling Points
1	0	246, 623, 1214, 2030	12	15 sec, 30 sec, 1 min,
	1	246, 623, 1214, 2030	12	3 min, 6 min, 9 min,
	2	246, 623, 1214, 2030	12	12 min
	3	246, 623, 1214, 2030	12	
	4	246, 623, 1214, 2030	12	
	5	246, 623, 1214, 2030	12	
2	0	246, 623, 1214, 2030	4	15 sec, 30 sec, 1 min,
	10	246, 623, 1214, 2030	4	2 min, 3 min, 4 min
	15	246, 623, 1214	4	
	20	246, 623, 1214, 2030	4	
	30	246, 623, 1214, 2030	4	
	40	2030	4	
3	0	246, 623, 1214, 1734	30	15 sec, 30 sec, 1 min,
	50	246, 623, 1214, 1734	30	3 min, 5 min, 10 min,
	75	246, 623, 1214, 1734	30	15 min, 20 min, 25 min,
	100	246, 623, 1214, 1734	30	30 min
	125	246, 623, 1214, 1734	30	

during series two testing. Series three samples received large polymer doses. This was done to observe the effects of possible overdosing on filterability, and to see if additional mixing energy input had any influence if overdosing occurred. It should be noted that data obtained in series three at G value 1734 sec^{-1} had to be discarded. For the polymer doses used, the intensity of mixing action was so great that substantial quantities of solids were thrown out of solution and deposited on the walls of the mixing chamber. This in turn reduced the solids concentration of the samples tested, giving artificially low CST readings. This problem was not observed at polymer doses below 50 mg/l.

After all tests were made on alum sludge, similar procedures were employed with the two activated and one primary sludge. Conditioning data for these sludges are shown in Table IV. Note that the total number of experimental trials made was considerably less than that for alum. Experience gained during alum sludge conditioning reduced guesswork, making dose and mixing energy input determination easier to predict. Additionally, only that amount of data which would facilitate comparison to alum sludge response was desired.

Data obtained during the experiments described were then plotted to illustrate the following effects:

(1) polymer dose on CST at various mixing intensities (G) and mixing times

(2) mixing intensity on CST at various polymer doses and mixing times

Table IV. Activated and primary sludge conditioning data using Betz 1195 polymer.

Dose (mg/l)	G Values Applied (sec^{-1})	Total Mix Time at Each G (min)	Sampling Points
0	246, 623, 1214	5	15 sec, 30 sec, 1 min, 3 min, 5 min
5	246, 623, 1214	5	
15	246, 623, 1214	5	
50	246, 623, 1214	5	
100	246, 623, 1214	5	
125	246, 623, 1214	5	

(3) mixing time on CST at various polymer doses and mixing intensities

(4) mixing time and mixing intensity on optimum polymer dose

(5) Gt on CST at various polymer doses

(6) various Gt product combinations on CST reproducibility

IV. RESULTS AND DISCUSSION

Data obtained during this research were significant in that it clearly indicates the effects of polymer dose, mixing time, and mixing intensity on the filterability of water and wastewater sludges. More importantly, the data reflects the inadequacy of standard jar testing in predicting conditioning requirements, and suggests that a critical relationship exists between optimum polymer dose and total mixing energy input (Gt). In this chapter, data will be presented and discussed in the order obtained during experimentation. The intent is to provide detailed explanation of the effects noted during testing, so that a proper foundation is laid for substantiating the conclusions which will follow.

1. Series 1 Alum Sludge Conditioning

The results of series 1 alum sludge testing are shown in Figures 3-9. Conditioning data relative to these tests are given in Table III. This series was used as a starting point to determine what range of polymer doses, mixing times, and mixing intensities might best illustrate their corresponding effects on filterability. It can be seen in Figure 3 that even small amounts of polymer (1 mg/l of Betz 1120) improved the filtering rate over that of the unconditioned sludge. With low intensity mixing ($G = 246 \text{ sec}^{-1}$) for periods up to one minute, performance improved steadily as the dose was increased to the maximum of 5 mg/l for the series. Within the dose range, 5 mg/l appeared to be optimum. Note, however, that as mixing time increased beyond one

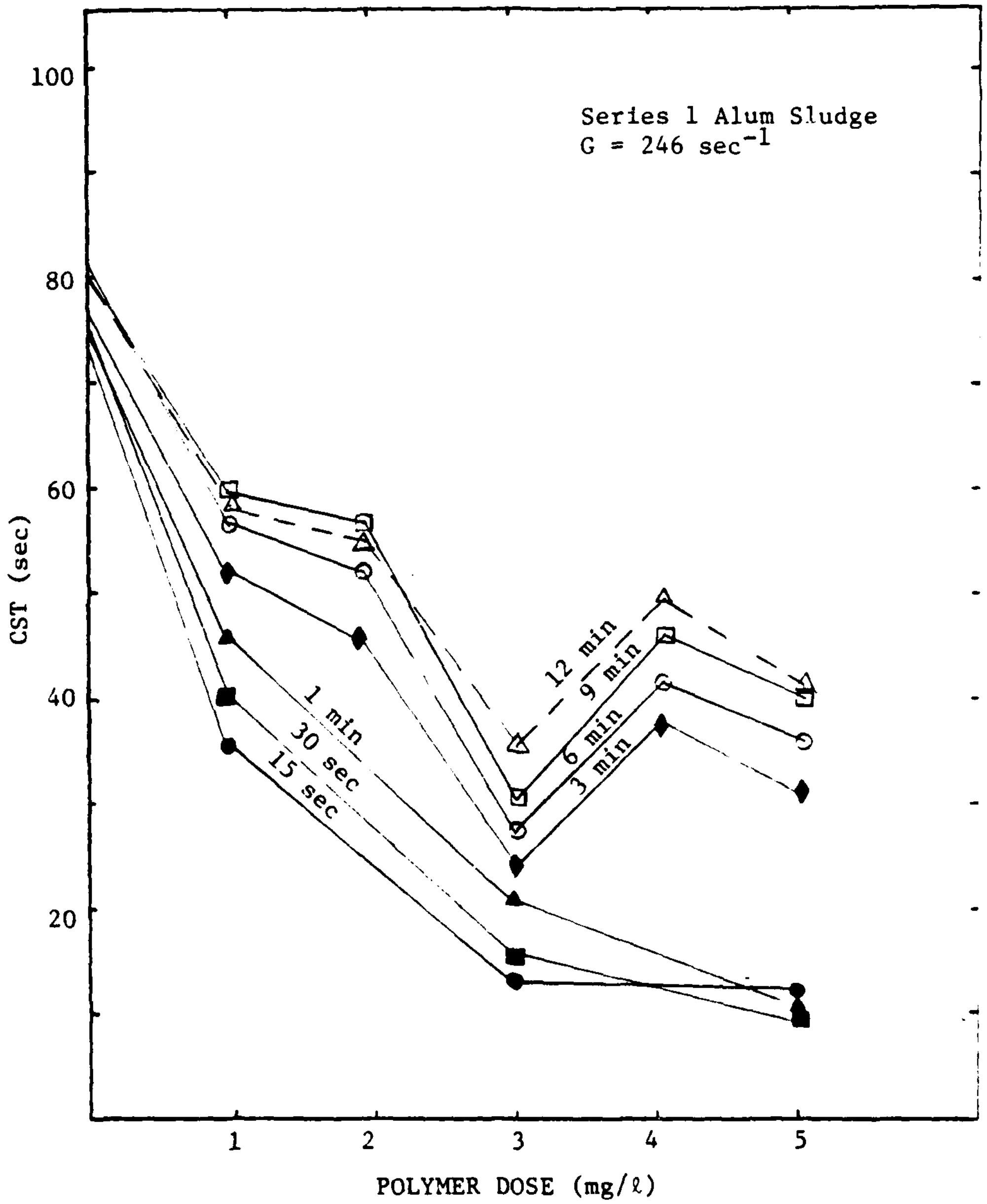

Figure 3. Effect of polymer dose and mix time on alum sludge filterability (G = 246 sec^{-1}).

minute, deterioration in filterability began, becoming more pronounced as the mix time was lengthened. It is generally accpted that the polymer acted to increase the particle size. Apparently the effect of extended mixing was the gradual breakup and restabilization of particles.

Figures 4 and 5 illustrate what happened when the mixing intensity was increased with all other variables being held constant. Once again significant deterioration occurred as mixing intensity rose. Here deterioration was much more extensive, especially at the highest G value (1214 sec^{-1}). Apparently the higher shear forces acted to break up the floc more quickly and completely. The combined effects of mixing time and mixing intensity can be seen clearly in Figures 6-9. In each case, filterability deteriorated as G increased, becoming more pronounced as the mixing time was lengthened. These facts led to an increase in polymer dosing and reduction in mixing times during series 2 testing.

2. Series 2 Alum Sludge Conditioning

Conditioning data for series 2 testing are also shown in Table III. The effects of increased polymer dosage and reduced mixing time were very significant. Figure 10 shows that with low intensity mixing, the 10 mg/l dose provided excellent filterability at all mixing times within the range utilized. Note, however, that as dose increased, extensive deterioration resulted at the 15 and 30 second mix times. Also note that this deterioration diminished as mixing time was increased. It appeared that polymer concentrations of 15 mg/l

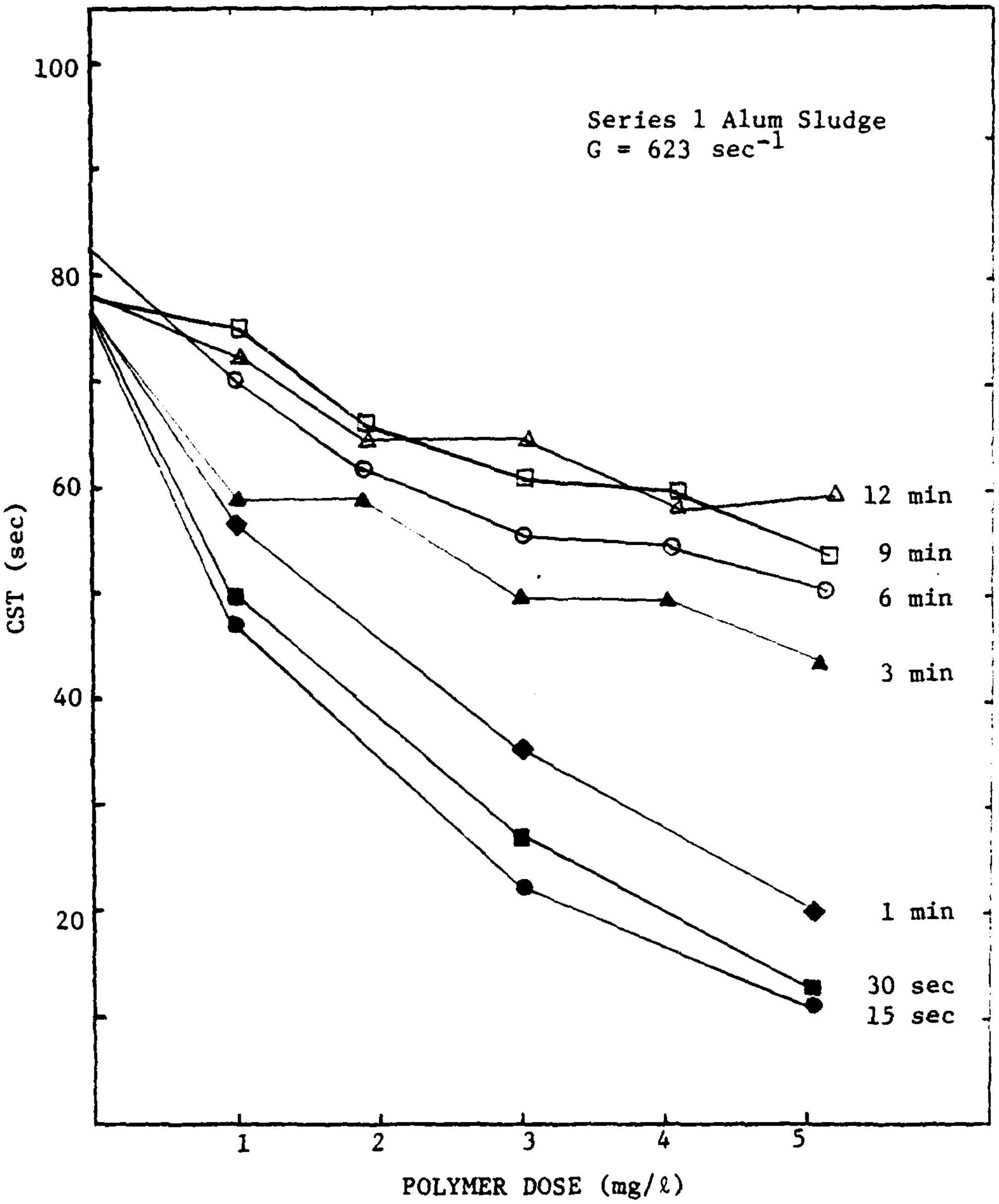

Figure 4. Effect of polymer dose and mix time on alum sludge filterability (G = 623 sec^{-1}).

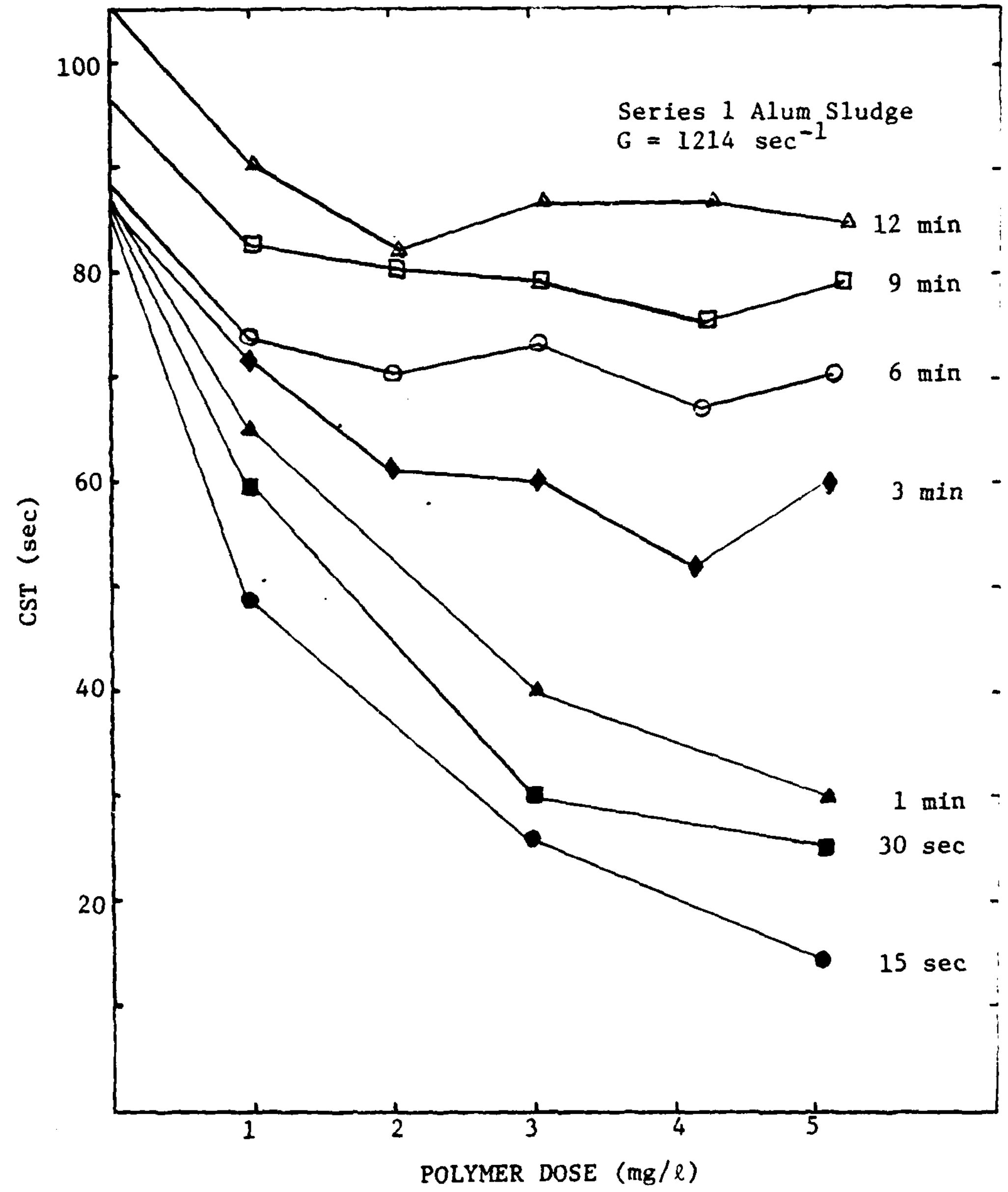

Figure 5. Effect of polymer dose and mix time on alum sludge filterability (G = 1214 sec^{-1}).

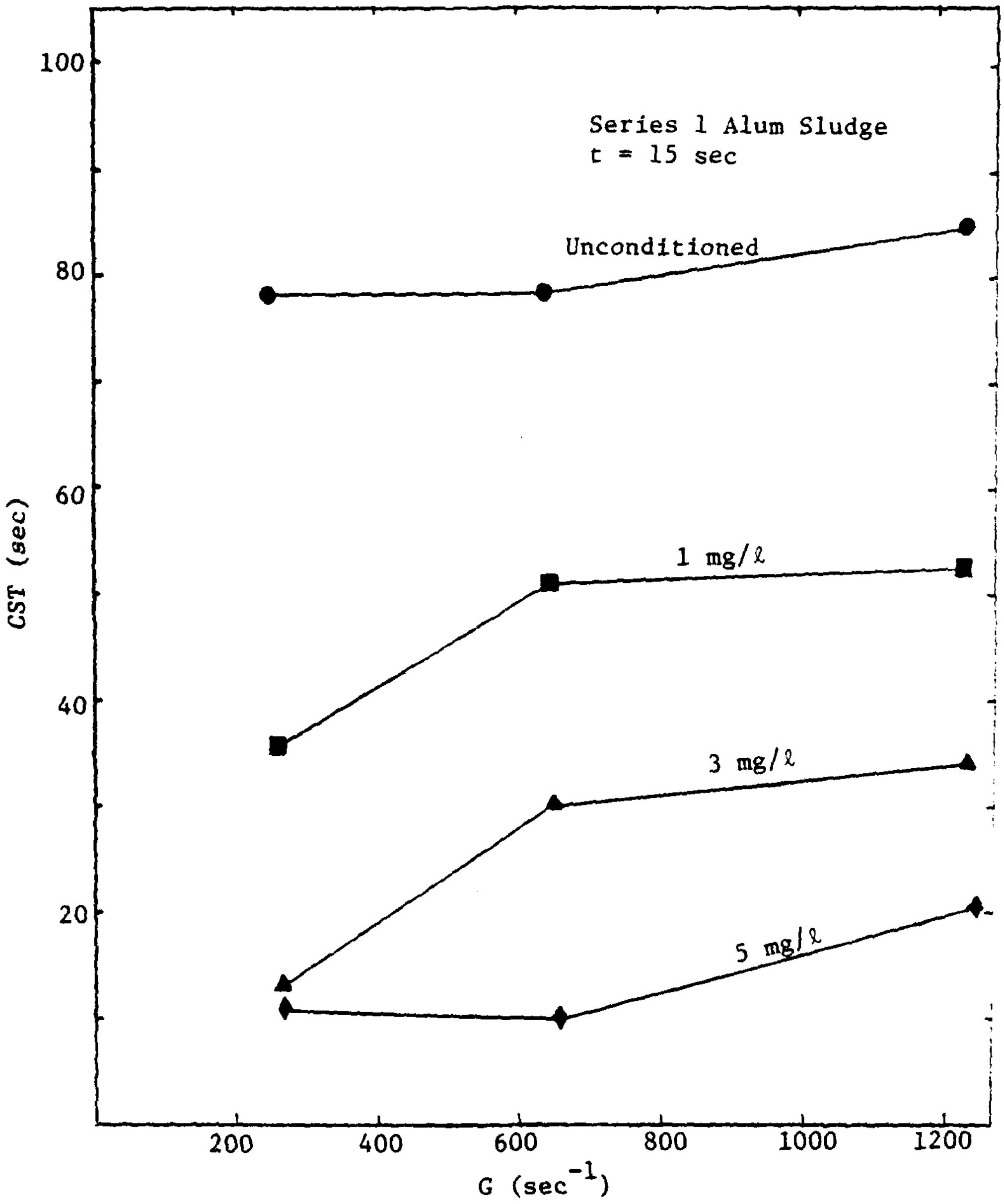

Figure 6. Effect of G value and polymer dose on alum sludge filterability (t = 15 sec).

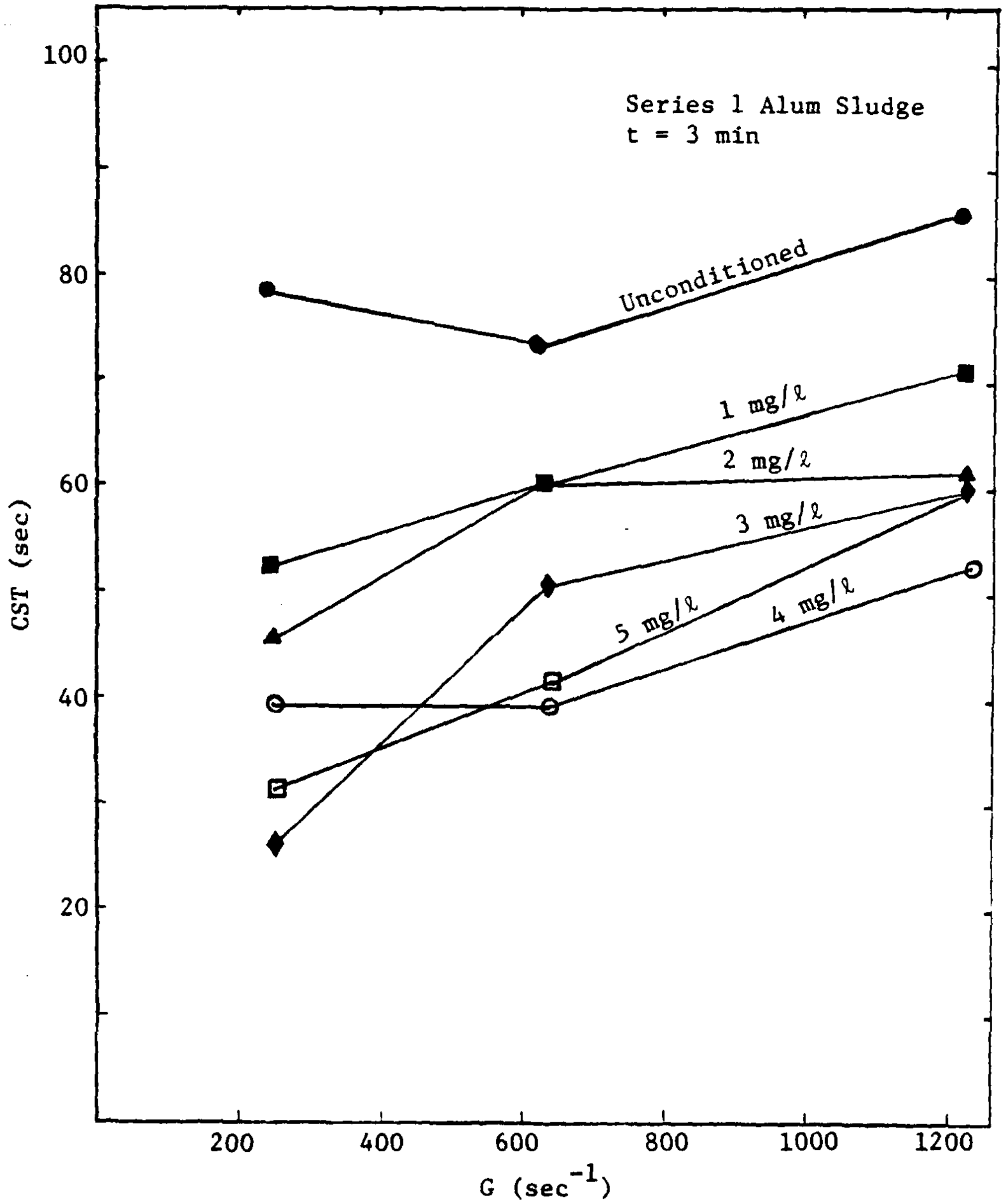

Figure 7. Effect of G value and polymer dose on alum sludge filterability (t = 3 min).

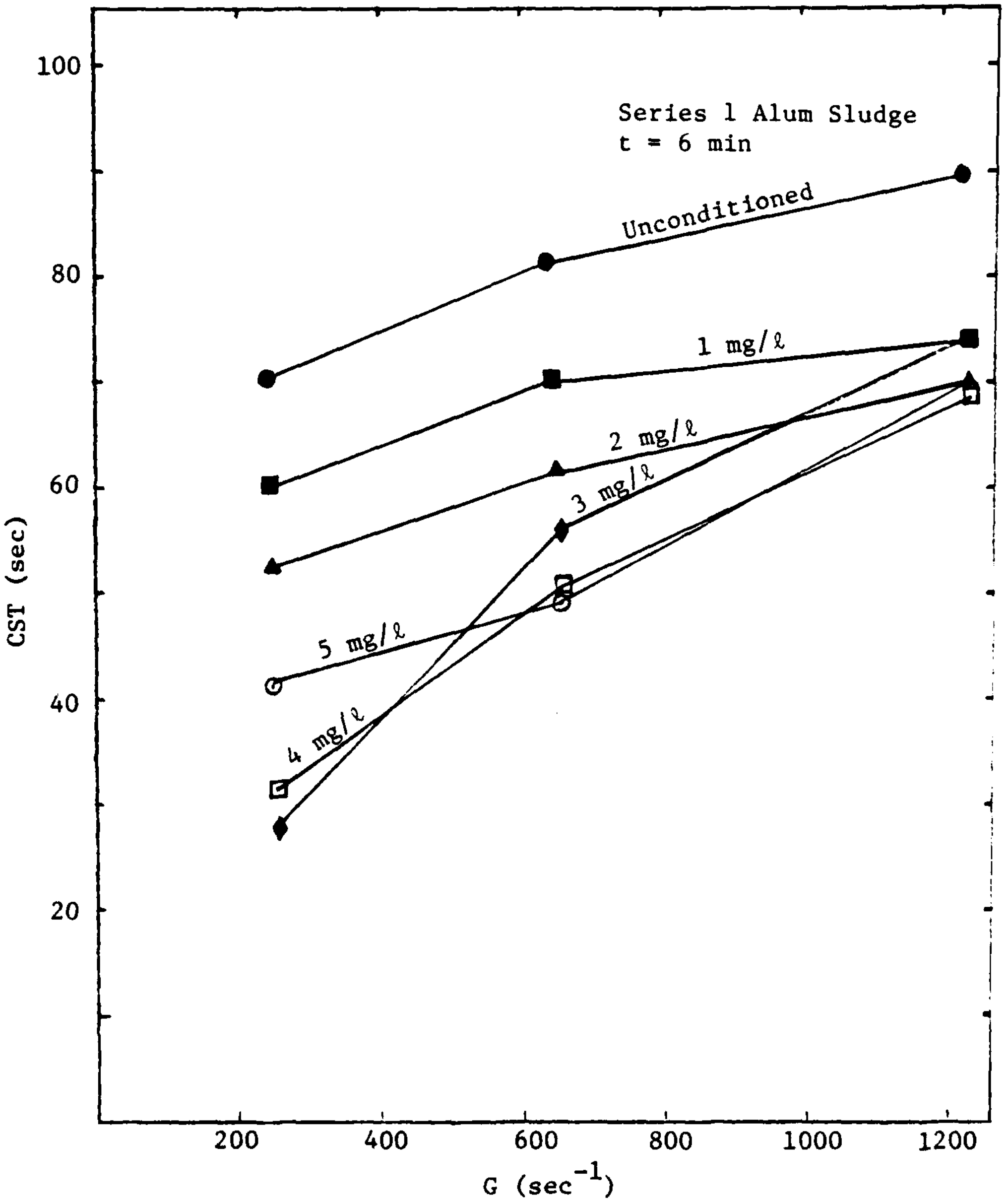

Figure 8. Effect of G value and polymer dose on alum sludge filterability (t = 6 min).

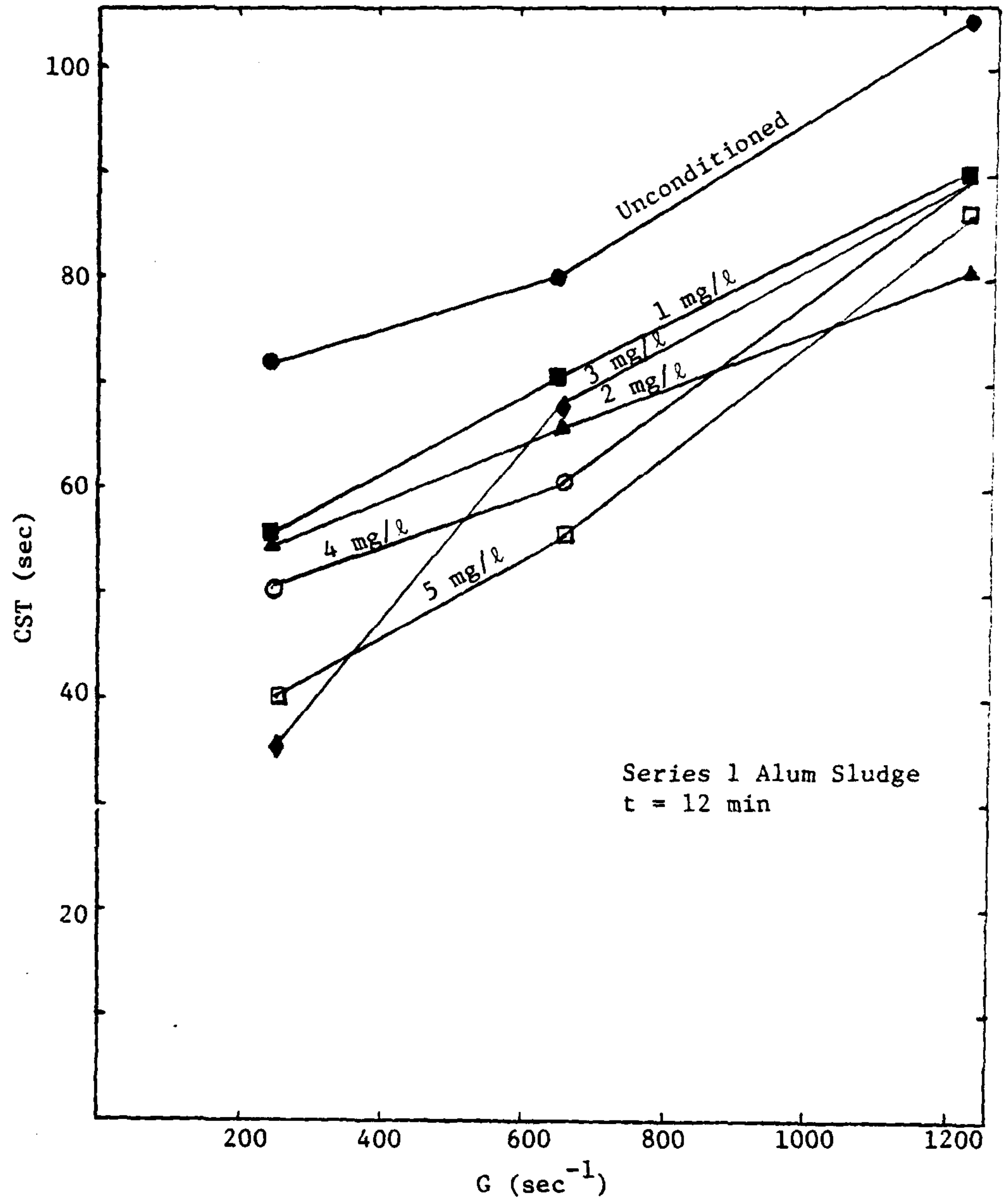

Figure 9. Effect of G value and polymer dose on alum sludge filterability (t = 12 min).

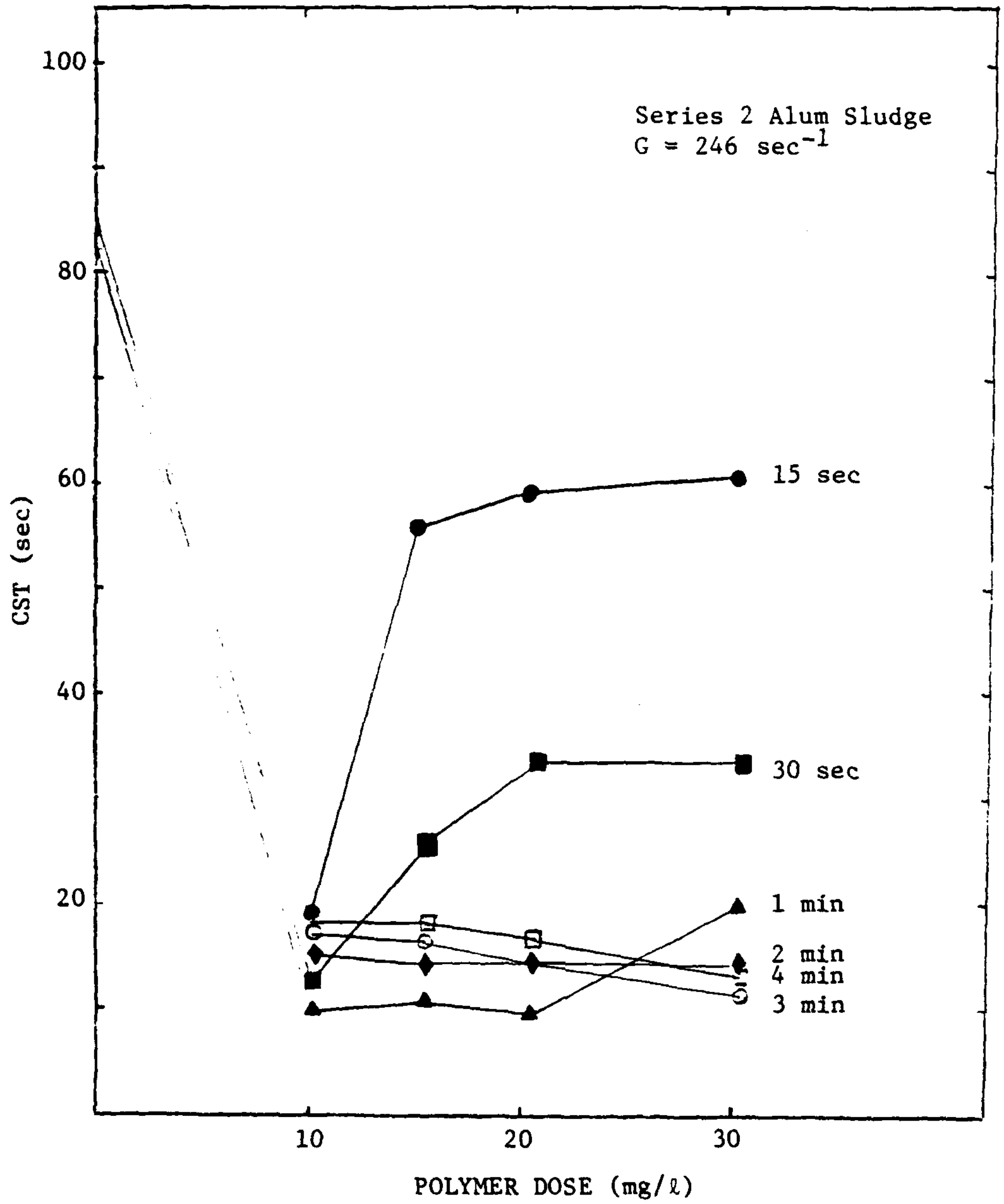

Figure 10. Effect of polymer dose and mix time on alum sludge filterability (G = 246 sec^{-1}).

constituted overdoses at the short mix times, but that continued mixing had the effect of improving performance. The exact reason for the overdosed condition is not known, but it is possible that attachment sites on the sludge particles became saturated with excess polymer, thereby preventing bridging from occurring. This overdosing mechanism has been described by O'Melia (1977) for coagulation using high molecular weight anionic polymers. It also appears that excess polymer may form additional colloids such that overdosed sludges dewater more slowly than unconditioned sludges.

Figures 11-13 show the effects of increased mixing intensity with all other variables being held constant as before. The effect of overdosing appeared to be less pronounced as G increased, with the 15 and 30 second mix times actually becoming optimum at doses of 35 mg/l and G values of 2030 sec^{-1} (Figure 13). Also note that longer mixing times compounded deterioration of performance as G increased to the maximum value. This was exactly the opposite of filterability performance with low intensity mixing (G = 246 sec^{-1}).

Figure 14 provides a better picture of mixing time effects. As before, the larger polymer concentrations constituted an overdose at short mixing times, but performance improved as mixing times were lengthened. Figures 15-17 illustrate the added effect of an increase in mixing intensity. As the G value rose, the degree of initial overdosing was lessened, until at a G of 2030 sec^{-1}, no overdosing was observed. Again, it was seen that as mixing time increased, deterioration began and became more extensive as mixing continued.

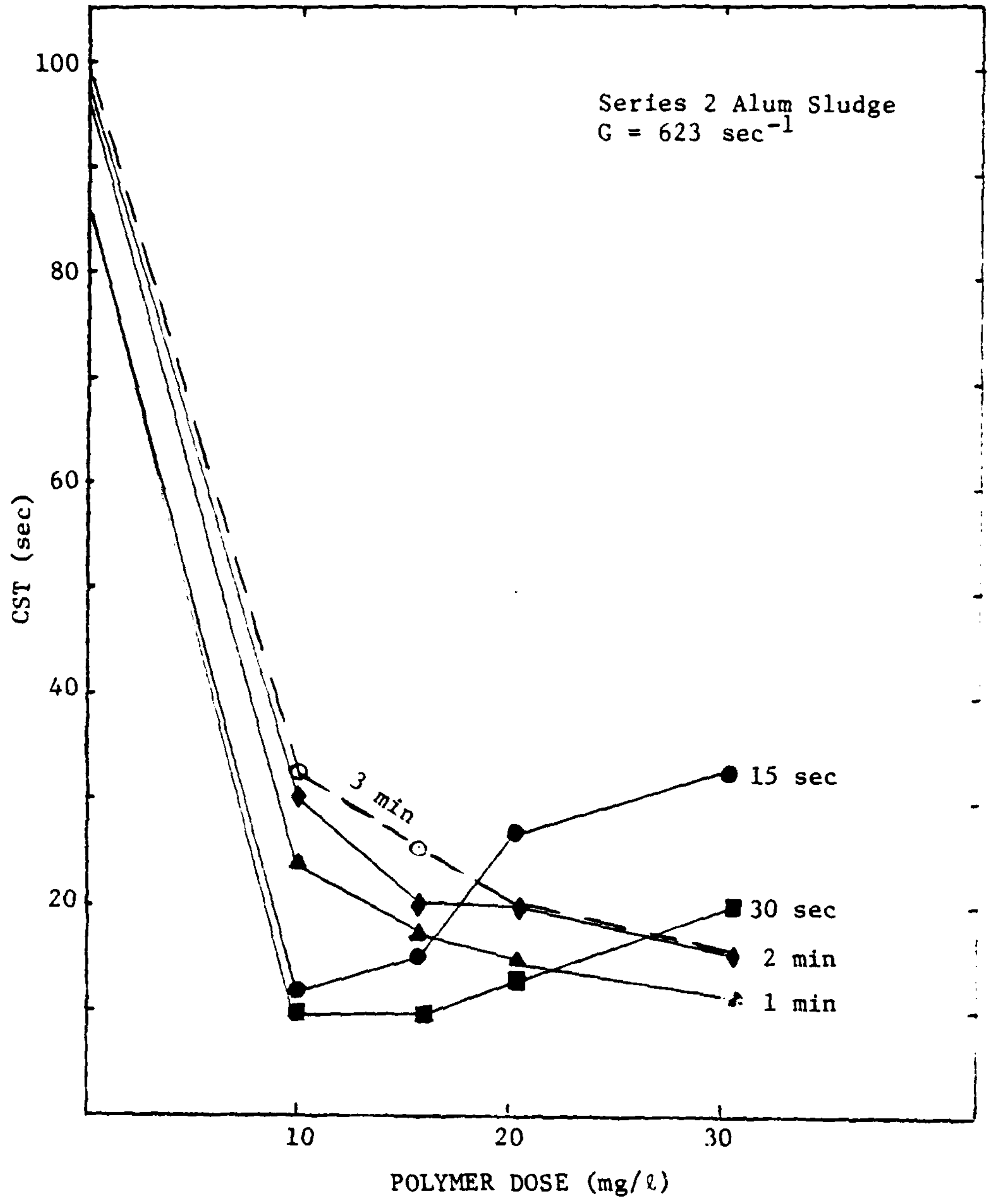

Figure 11. Effect of polymer dose and mix time on alum sludge filterability (G = 623 sec^{-1}).

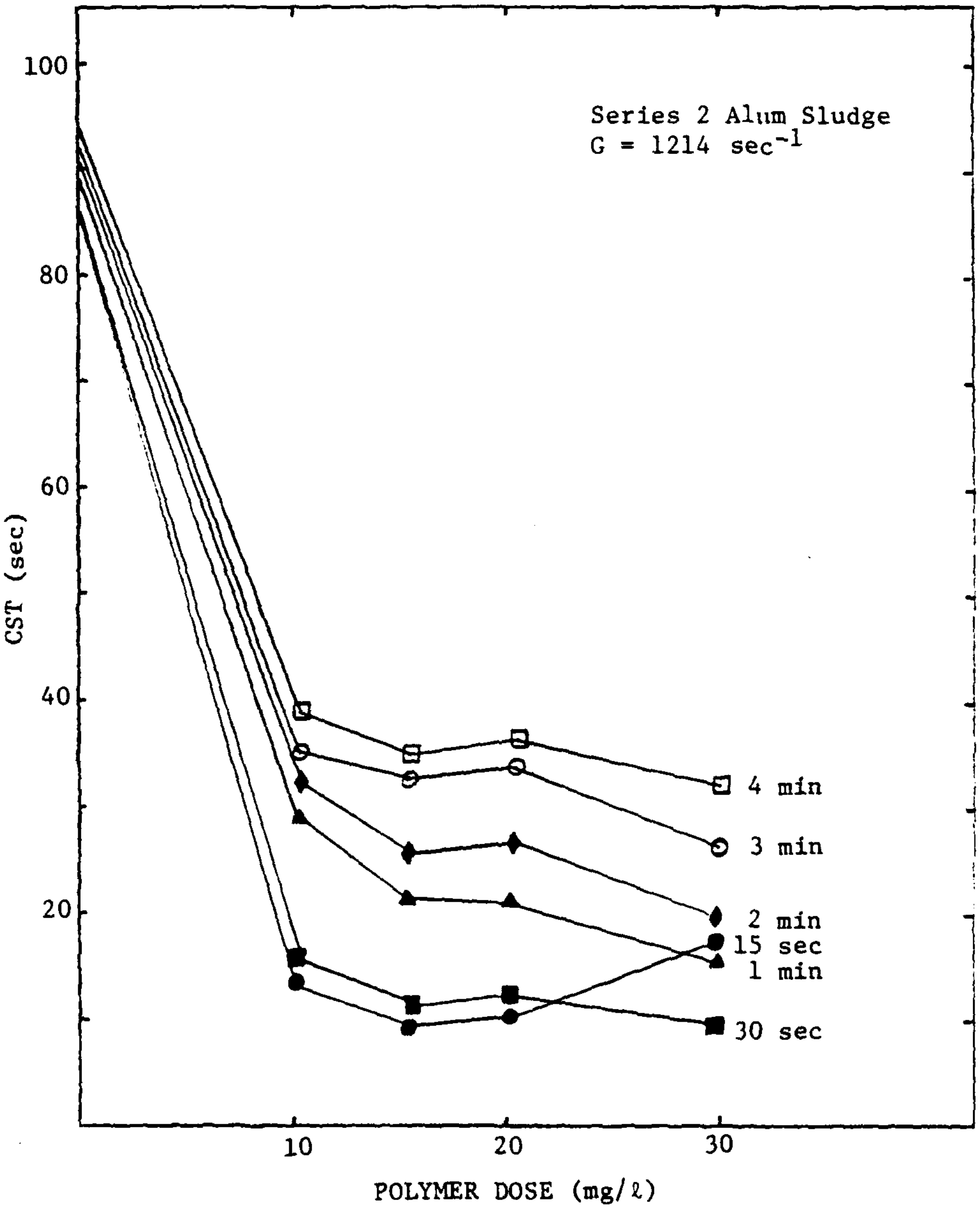

Figure 12. Effect of polymer dose and mix time on alum sludge filterability (G = 1214 sec^{-1}).

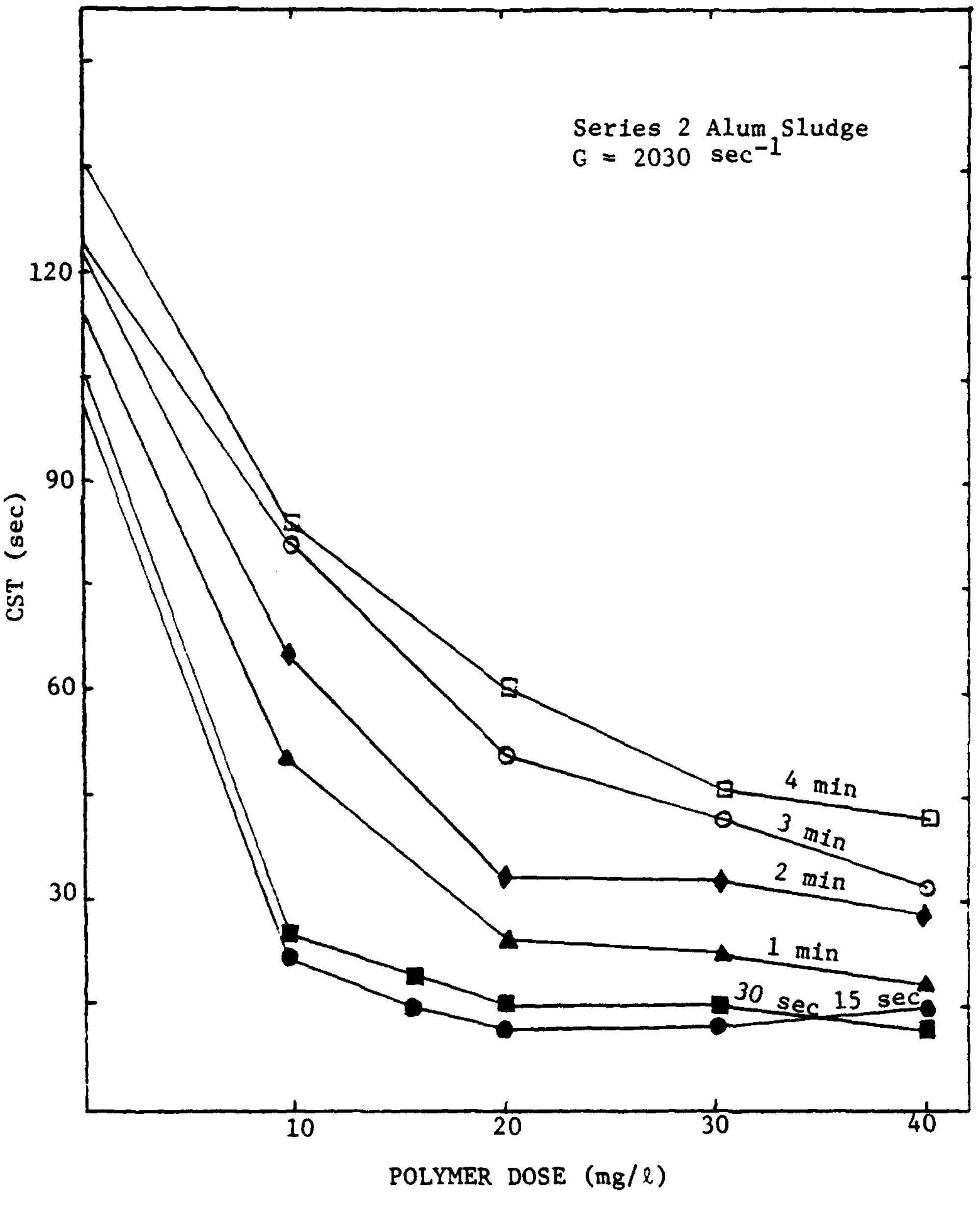

Figure 13. Effect of polymer dose and mix time on alum sludge filterability (G = 2030 sec^{-1}).

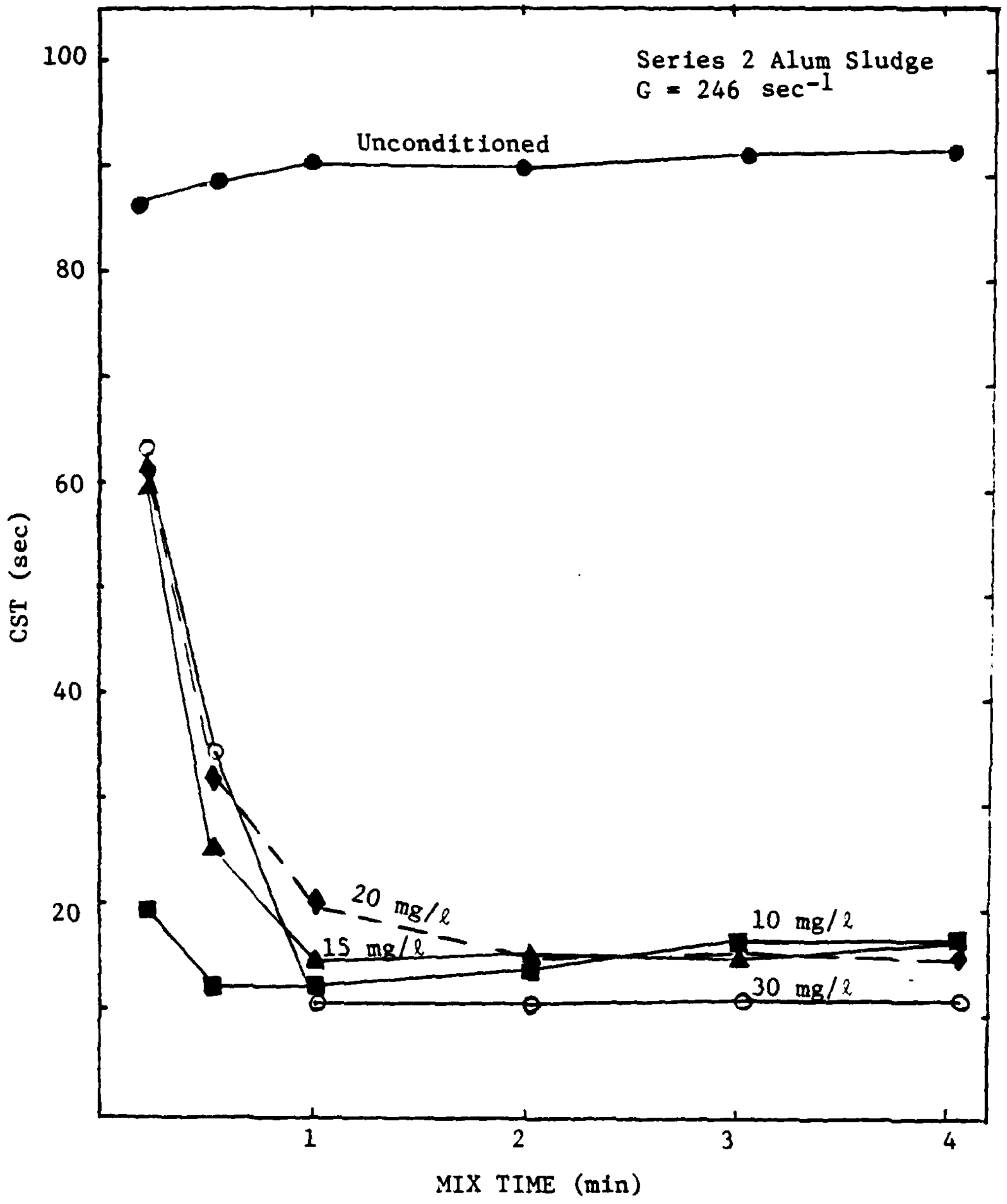

Figure 14. Effect of mix time and polymer dose on alum sludge filterability (G = 246 sec^{-1}).

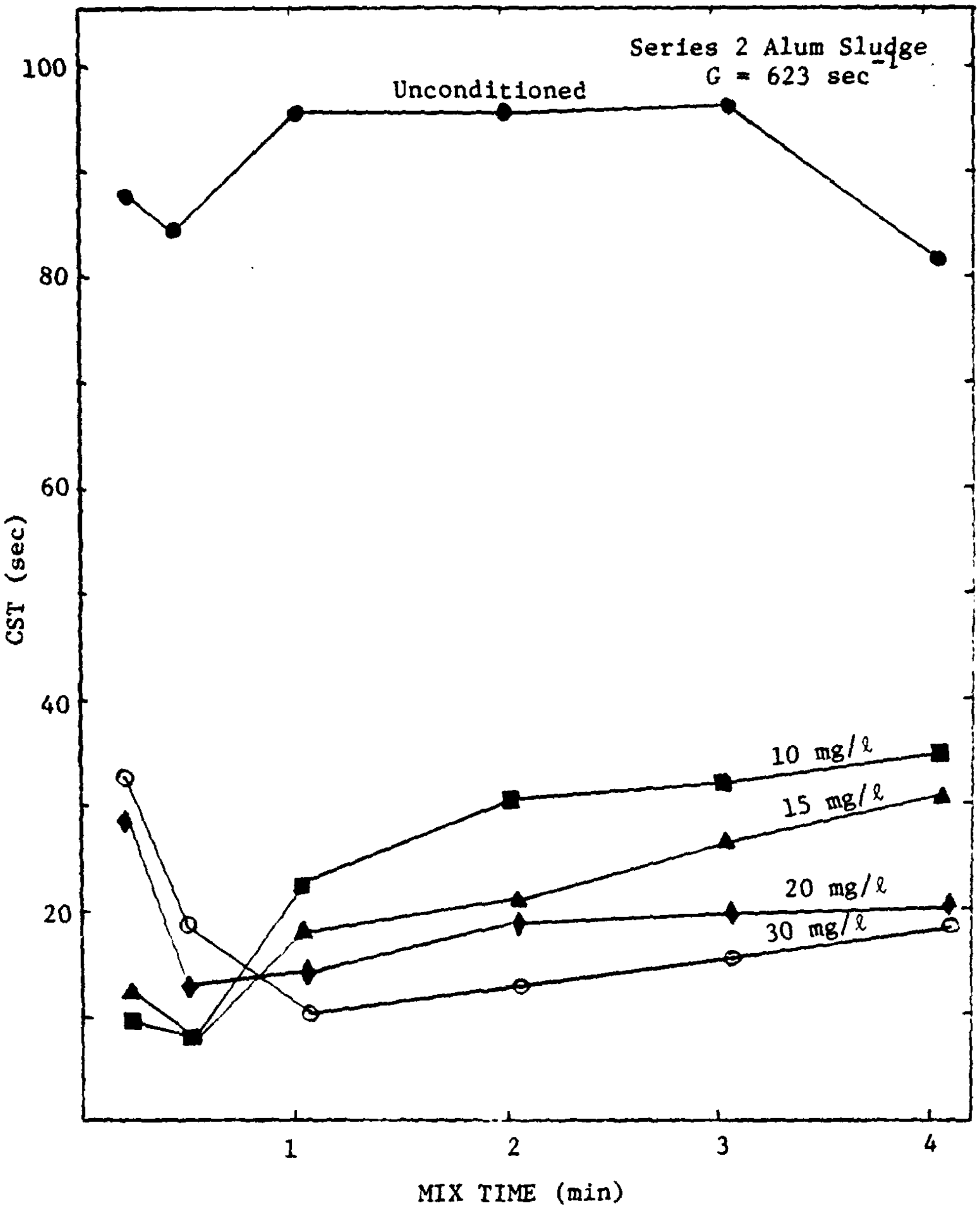

Figure 15. Effect of mix time and polymer dose on alum sludge filterability (G = 623 sec^{-1}).

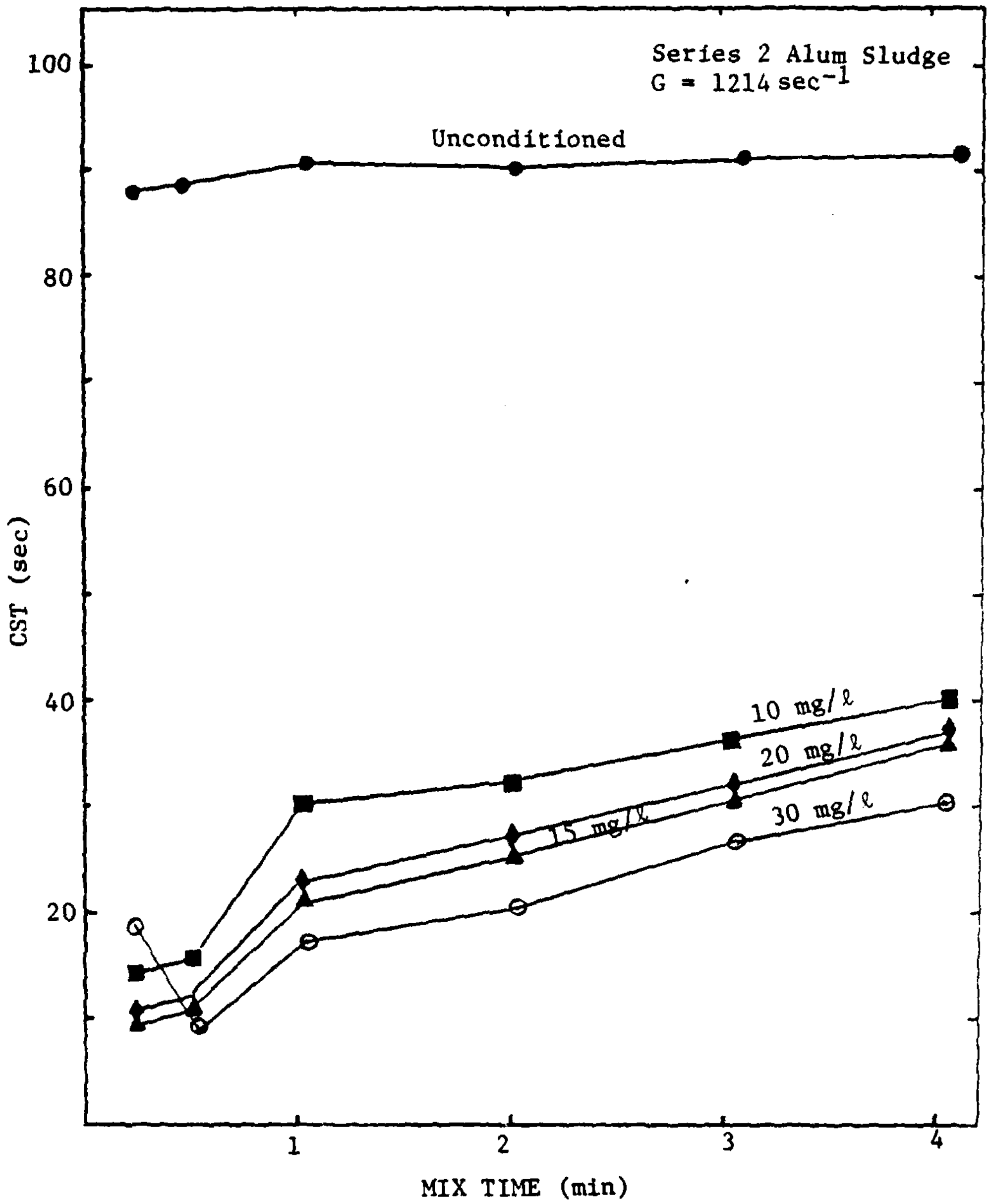

Figure 16. Effect of mix time and polymer dose on alum sludge filterability ($G = 1214\ sec^{-1}$).

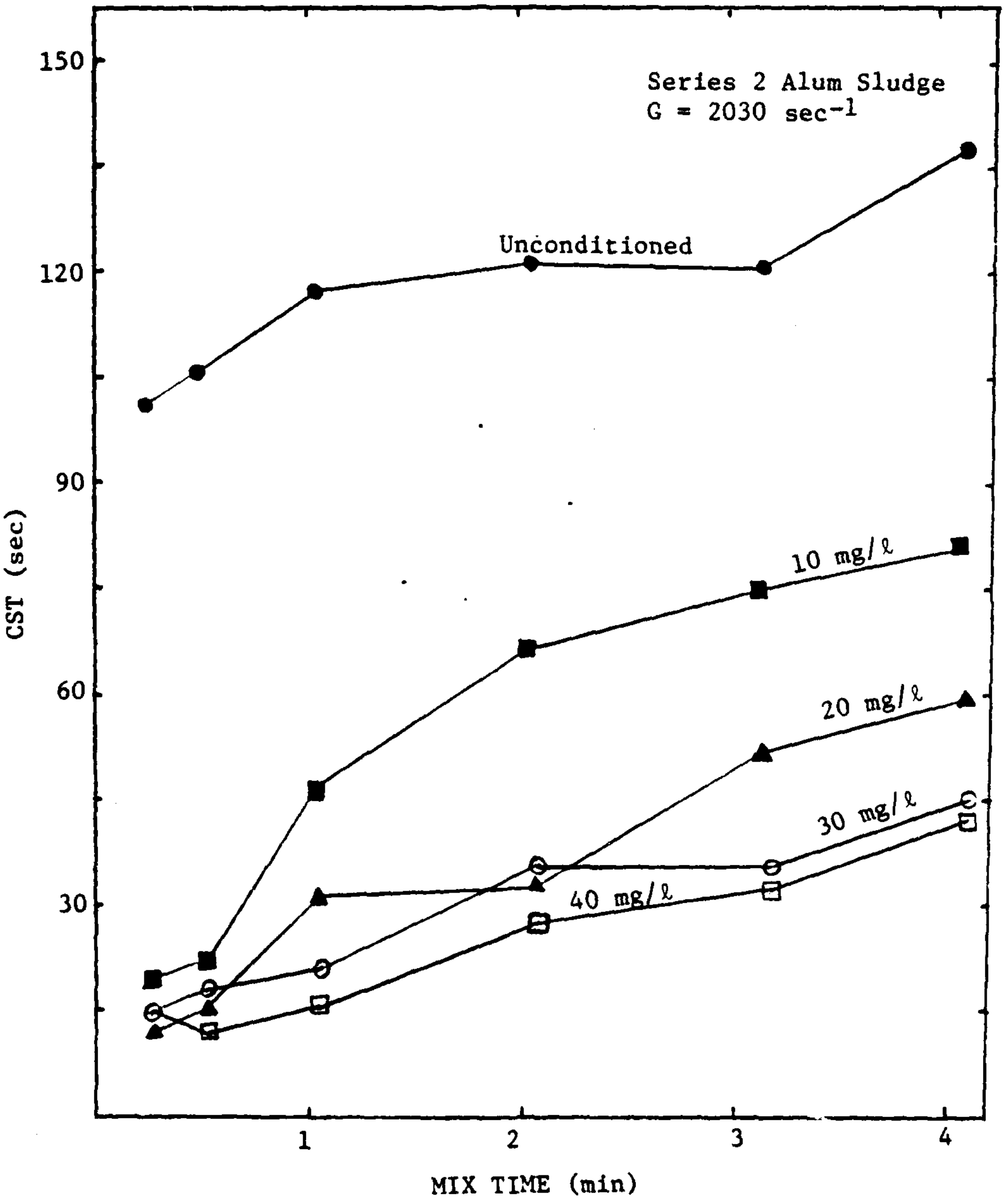

Figure 17. Effect of mix time and polymer dose on alum sludge filterability (G = 2030 sec^{-1}).

Figures 18-21 show the combined effects of mixing intensity and mixing time. Observe in Figure 18 that at a mix time of 15 seconds, a polymer dose of 10 mg/l gave optimal results at all G values, while a dose of 30 mg/l was excessive by comparison. However, succeeding figures show that as the mixing time increased to four minutes, the reverse was true (Figure 21).

From series 2 testing it appeared that a polymer overdose could be corrected by either increasing the mixing time, mixing intensity, or both. However, as mixing time and mixing intensity increased, so did the polymer dose required for optimal performance. At this point a more thorough examination of overdosing and the effects of mixing energy input was felt necessary. This led to series 3 testing.

3. Series 3 Alum Sludge Conditioning

Table III also presents series 3 conditioning data. Experiments were conducted exactly as with series 2, except that much larger polymer doses and mixing times were used. This was done to more vividly illustrate overdosing and the action of mixing energy input in reducing its effects. General trends noted were comparable to those previously discussed.

Figure 22 shows the effect of large polymer dosing on filterability with low intensity mixing. As in series 2 testing, large polymer concentrations resulted in overdosing at short mix times, but marked improvement occurred when mixing times and G values were increased (Figures 23-24).

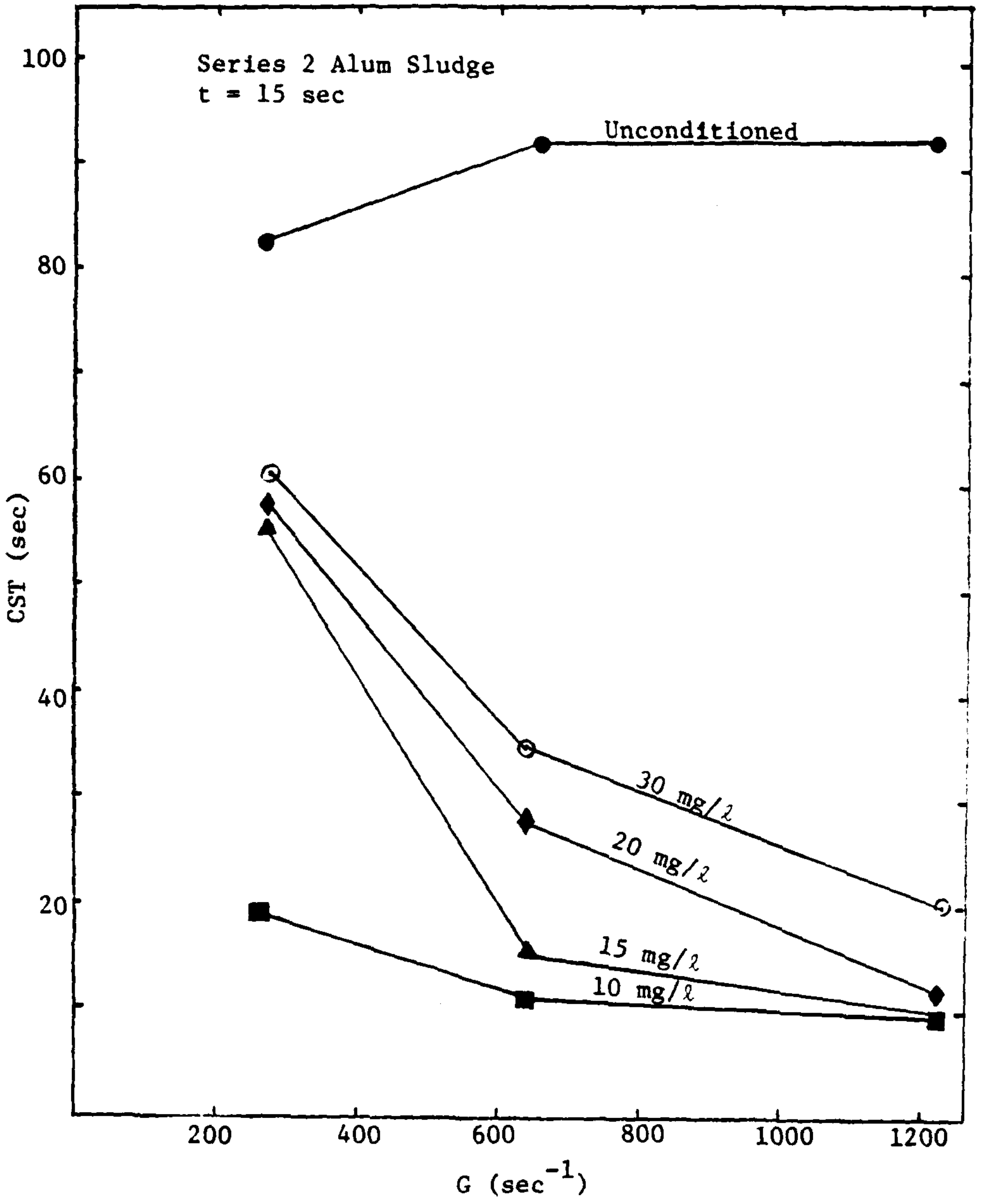

Figure 18. Effect of G value and polymer dose on alum sludge filterability (t = 15 sec).

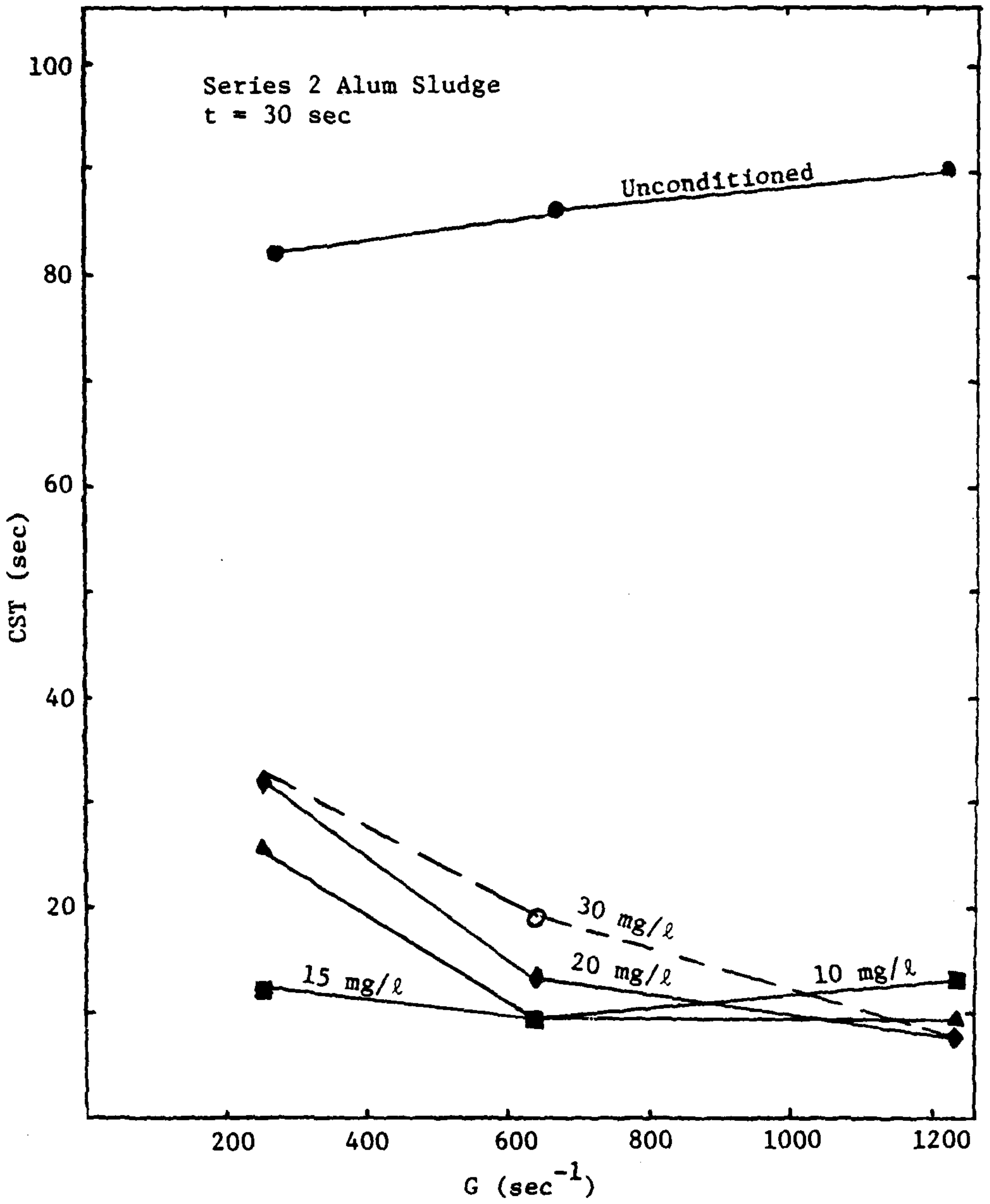

Figure 19. Effect of G value and polymer dose on alum sludge filterability (t = 30 sec).

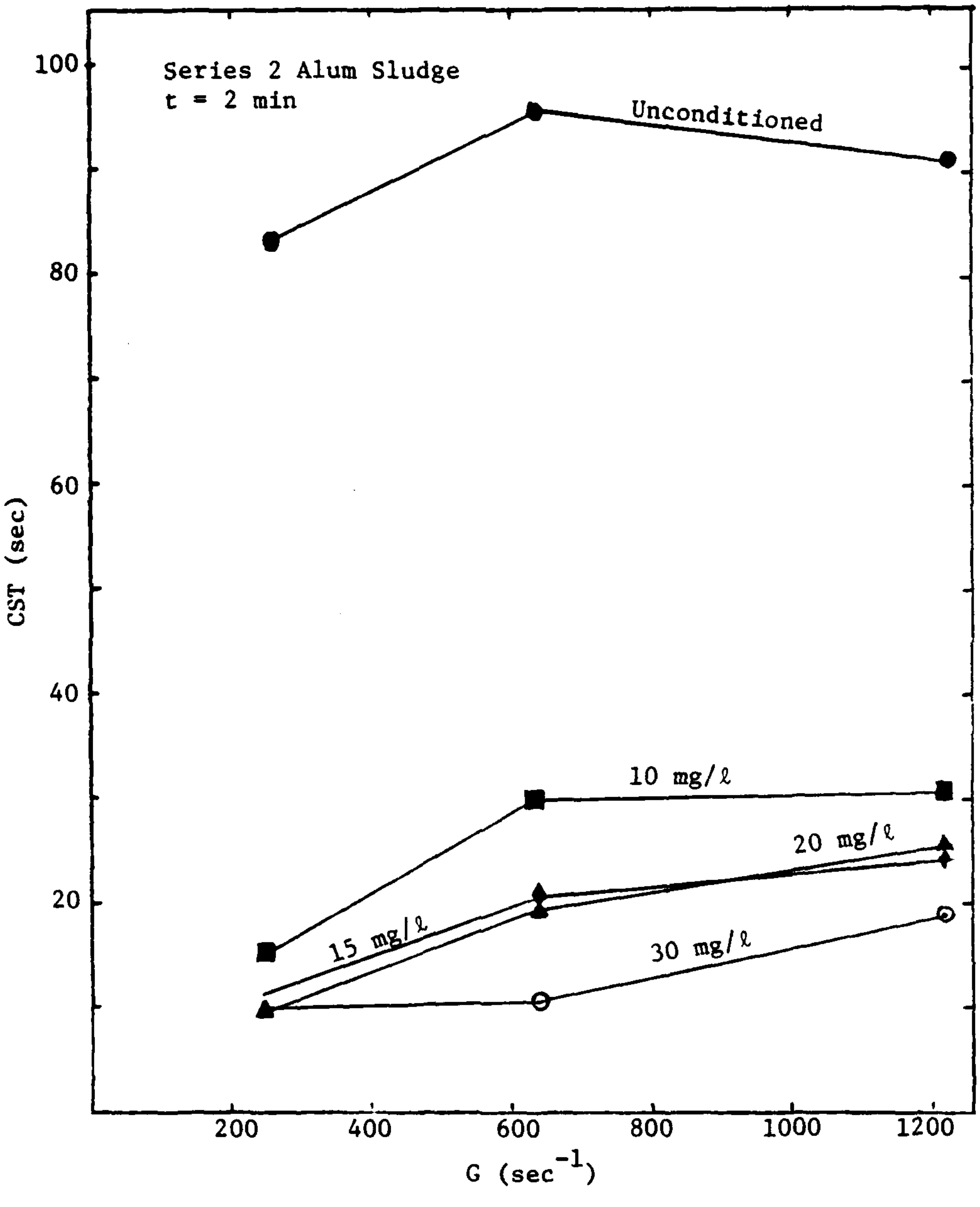

Figure 20. Effect of G value and polymer dose on alum sludge filterability (t = 2 min).

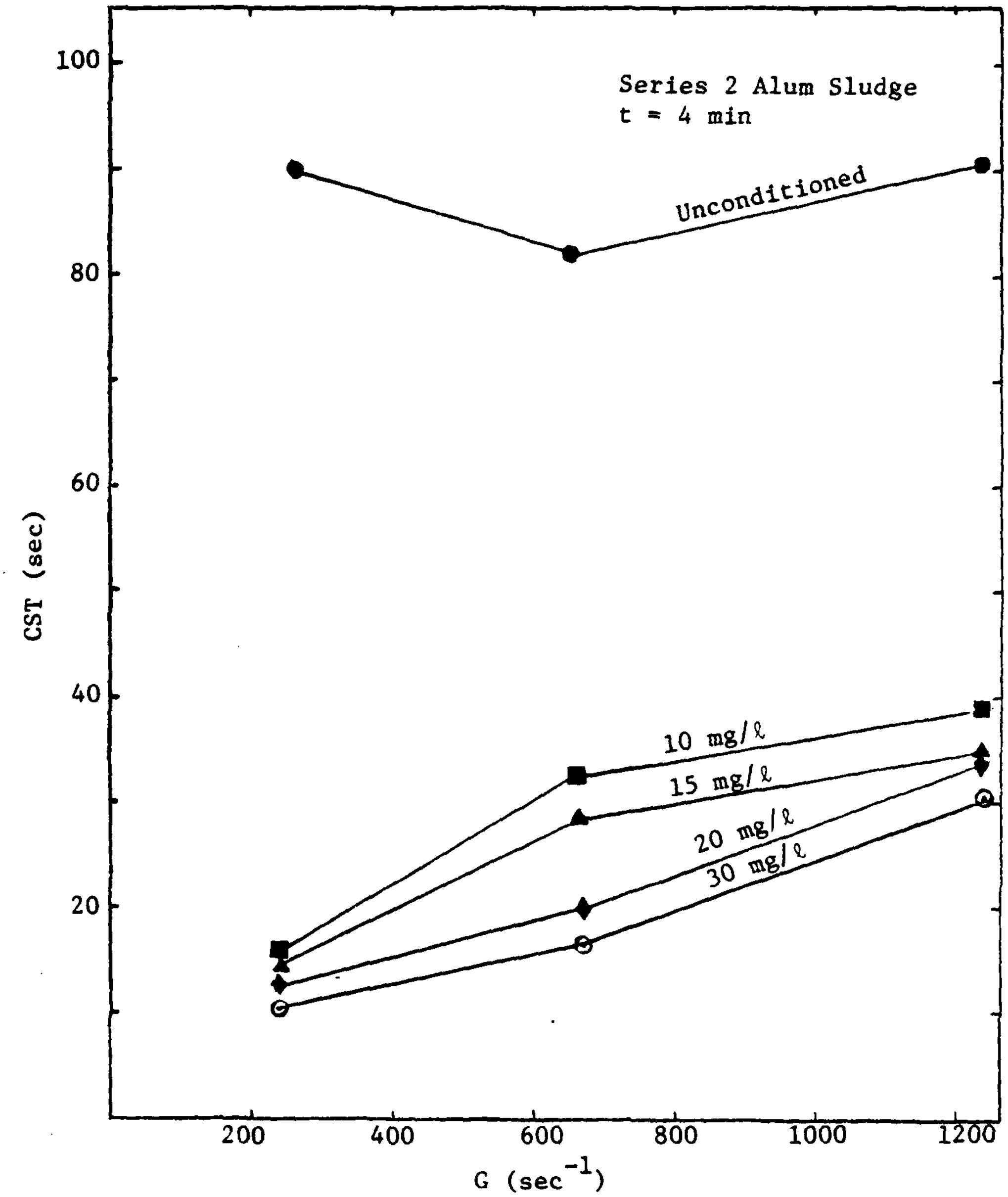

Figure 21. Effect of G value and polymer dose on alum sludge filterability (t = 4 min).

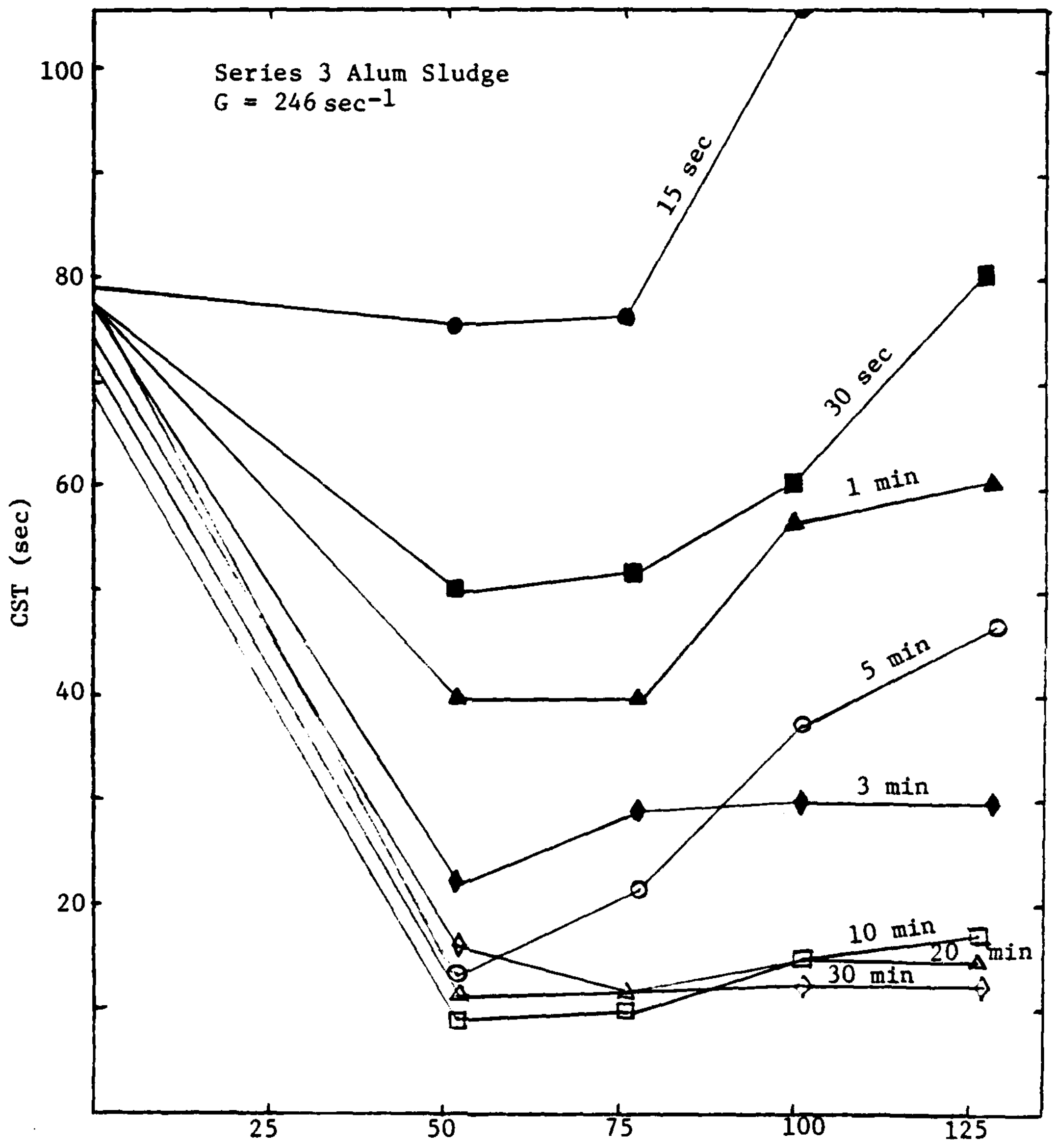

Figure 22. Effect of polymer dose and mix time of alum sludge filterability (G = 246 sec^{-1}).

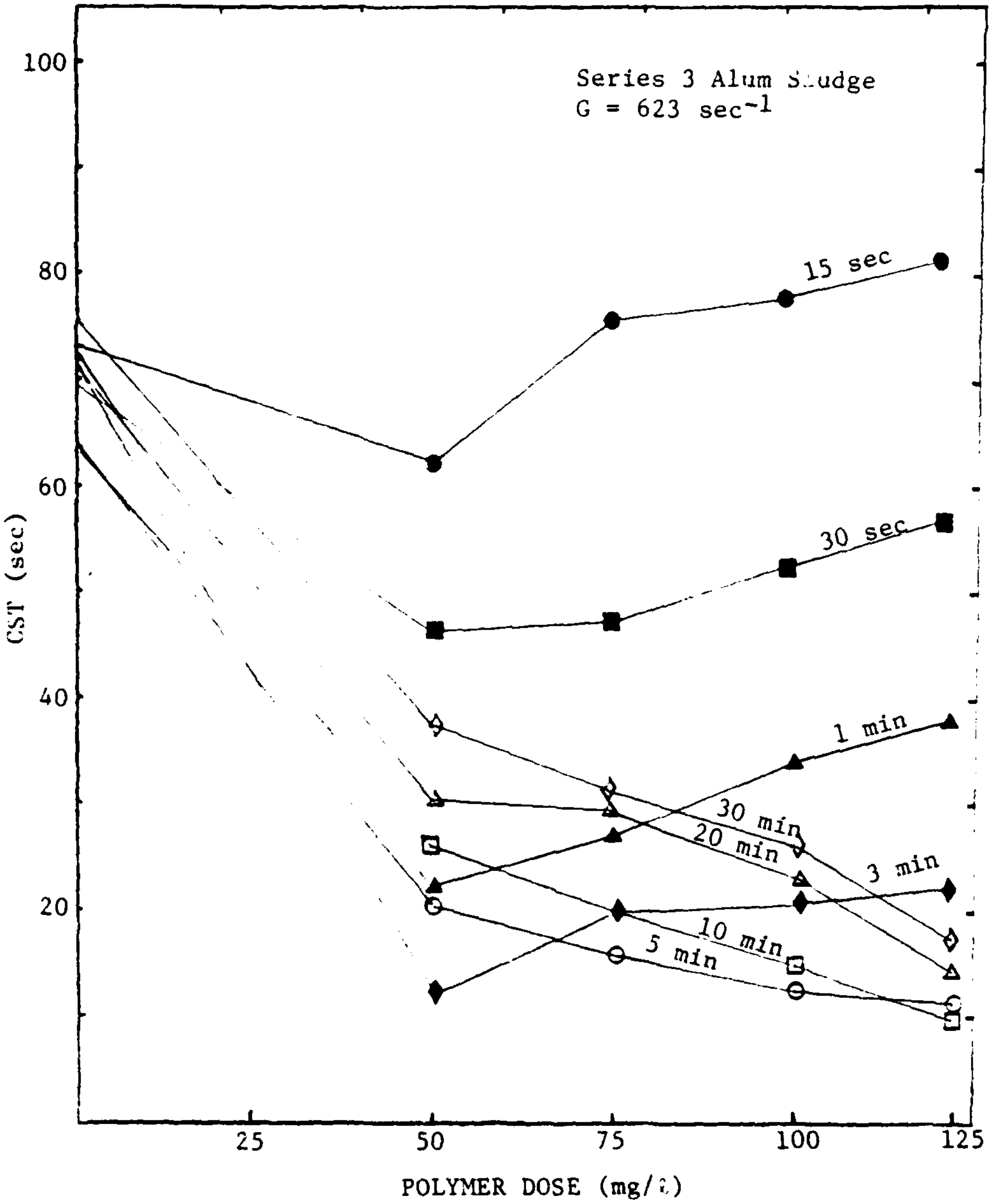

Figure 23. Effect of polymer dose and mix time on alum sludge filterability (G = 623 sec^{-1}).

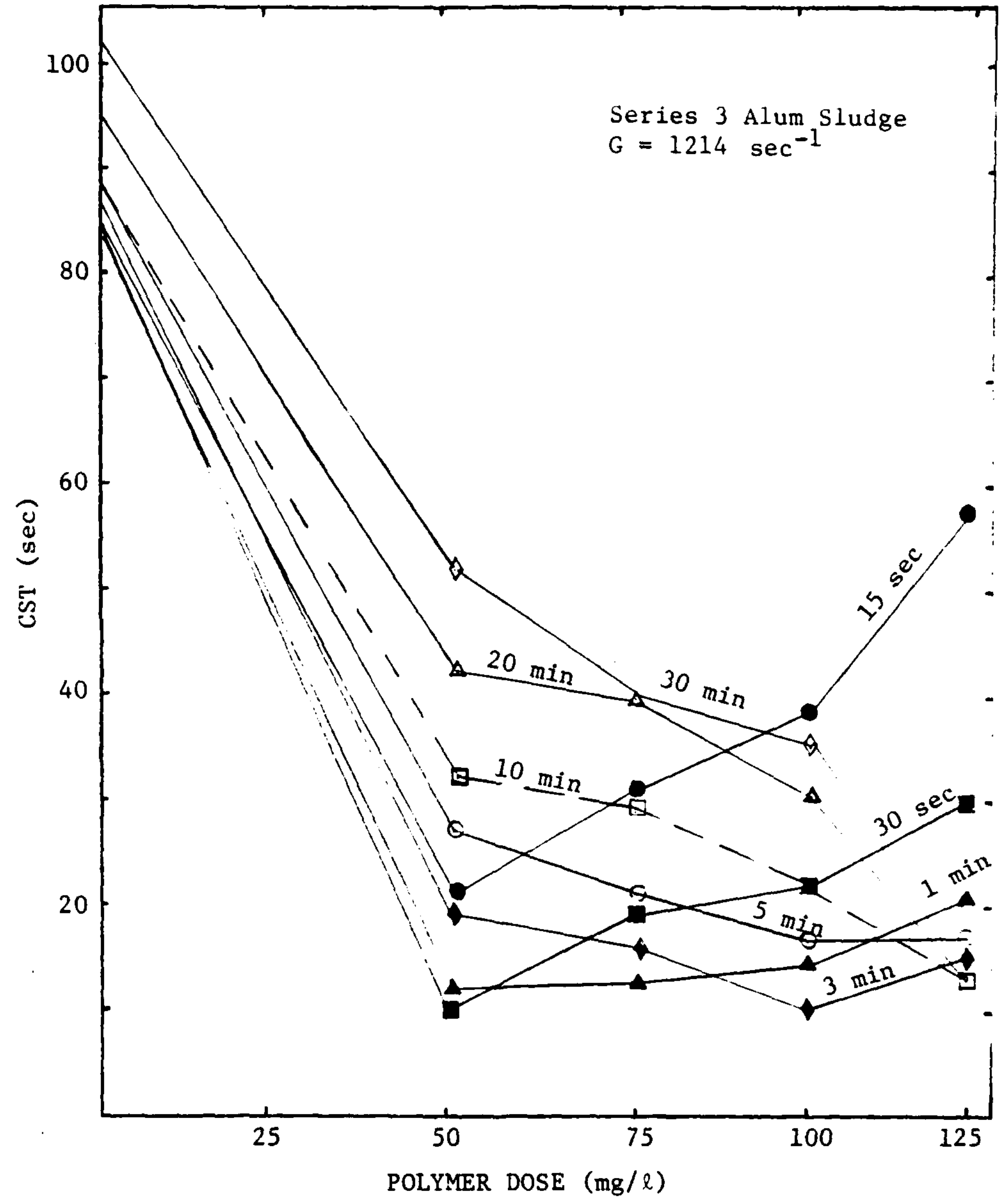

Figure 24. Effect of polymer dose and mix time on alum sludge filterability (G = 1214 sec^{-1}).

Figure 25 further illustrates the effect of mixing time on filterability. Under low intensity conditions, note that at short mix times each polymer dose was excessive, performing only equally well or worse than the unconditioned sludge. As mixing time increased, however, filterability was greatly improved at all doses. Figure 26 and 27 show the added effect of mixing intensity increases. As the G value rose, the magnitude of the initial overdose seen at low mixing times was reduced. Additionally, the performance of the smaller doses began to deteriorate at extended mixing times, although to a lesser degree than in series 2 testing. The highest dose used (125 mg/l) remained stable throughout the entire range of mixing times. Again, smaller doses seemed to give optimal performance at low G values, while larger doses gave optimal performance at high G values.

Figures 28-33 reflect the combined effects of mixing intensity and mixing time. Results were similar to those obtained in series 2 testing. From Figure 28 it can be seen that for brief mixing at low intensity, each dose used was excessive. Performance improved, however, as the G value increased. Also it should be noted that the 50 mg/l dose gave the best results throughout the range of mixing intensities used, while the 125 mg/l dose gave the worst. As in series 2 testing, this trend was reversed as mixing times increased (Figures 29-33). It is also significant to see that the 125 mg/l dose again remained very stable, even after intense mixing (G = 1214 sec^{-1}) for periods up to 30 minutes. Thus it appears that alum sludge can be conditioned to resist deterioration, but to do so requires large polymer doses and substantial mixing energy input.

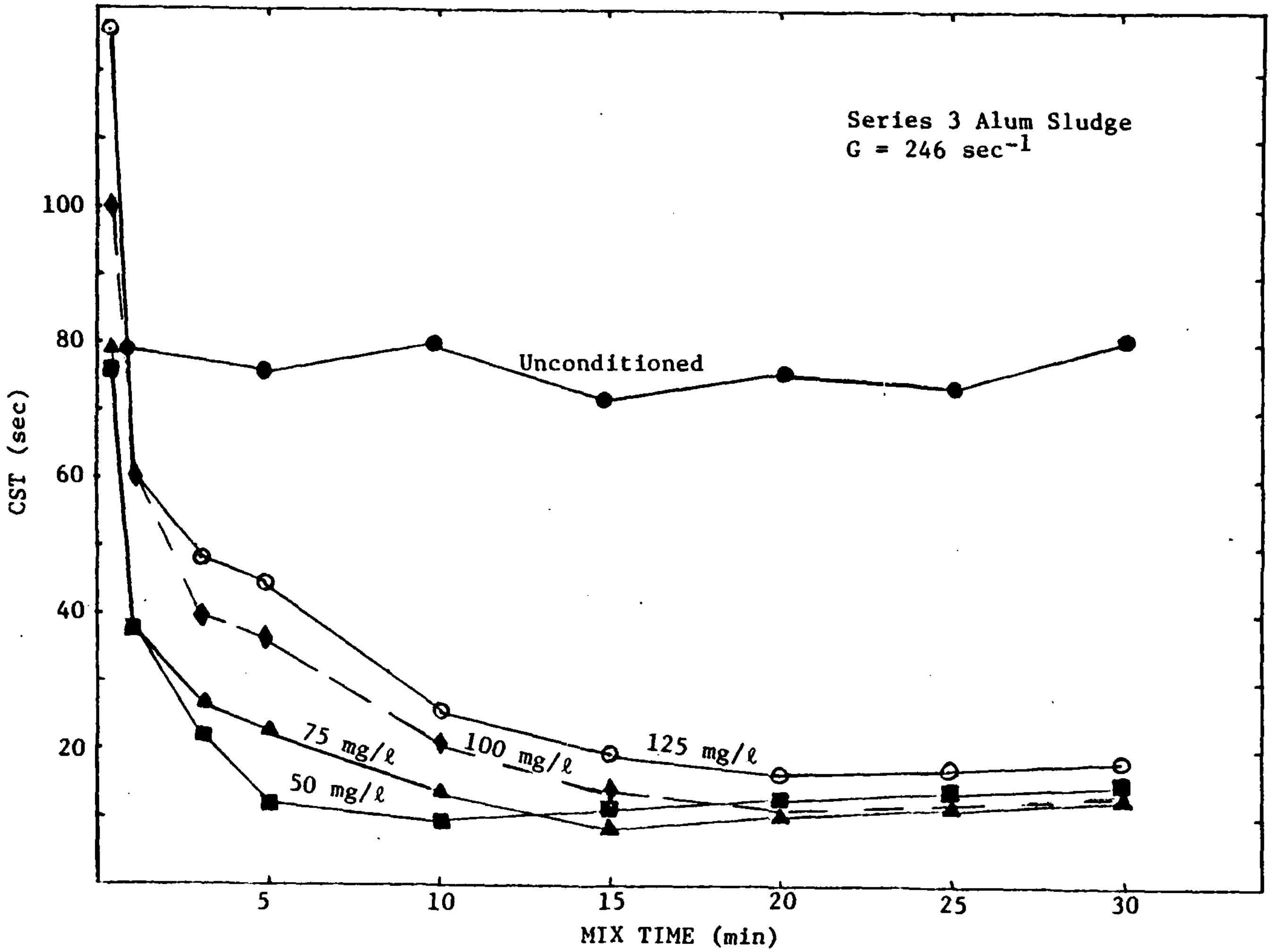

Figure 25. Effect of mix time and polymer dose on alum sludge filterability (G = 246 sec^{-1}).

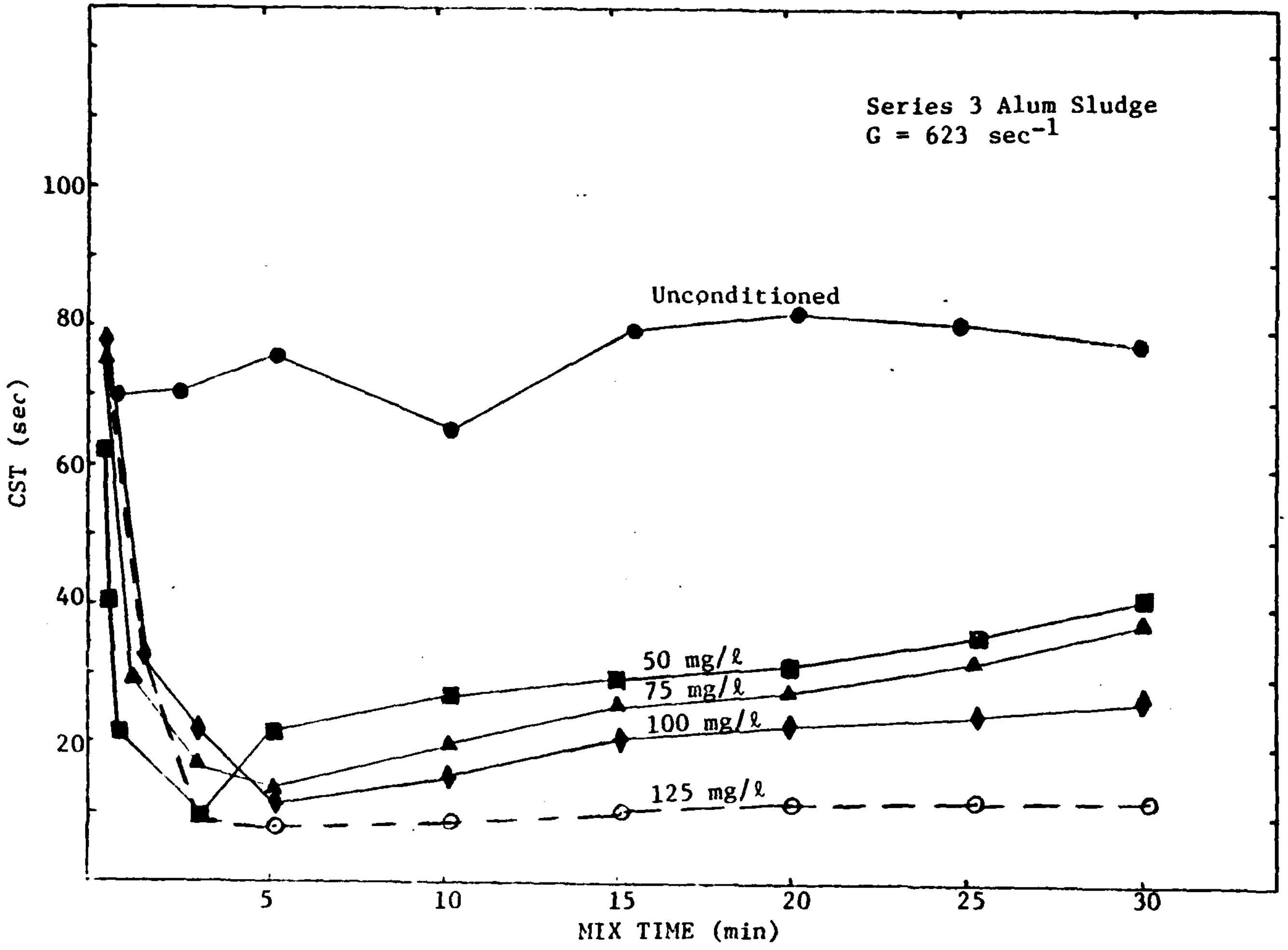

Figure 26. Effect of mix time and polymer dose on alum sludge filterability (G = 623 sec^{-1}).

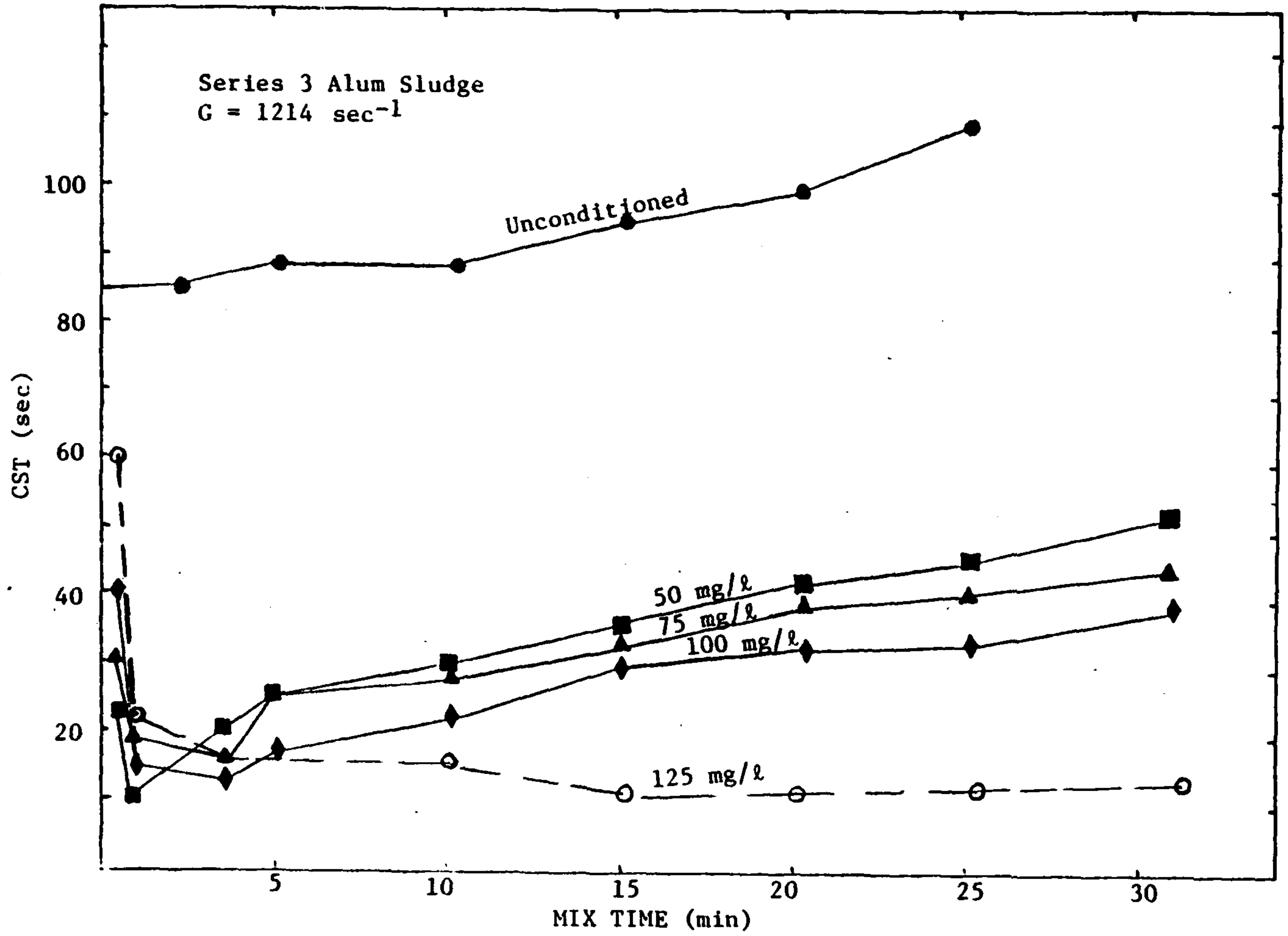

Figure 27. Effect of mix time and polymer dose on alum sludge filterability (G = 1214 sec^{-1}).

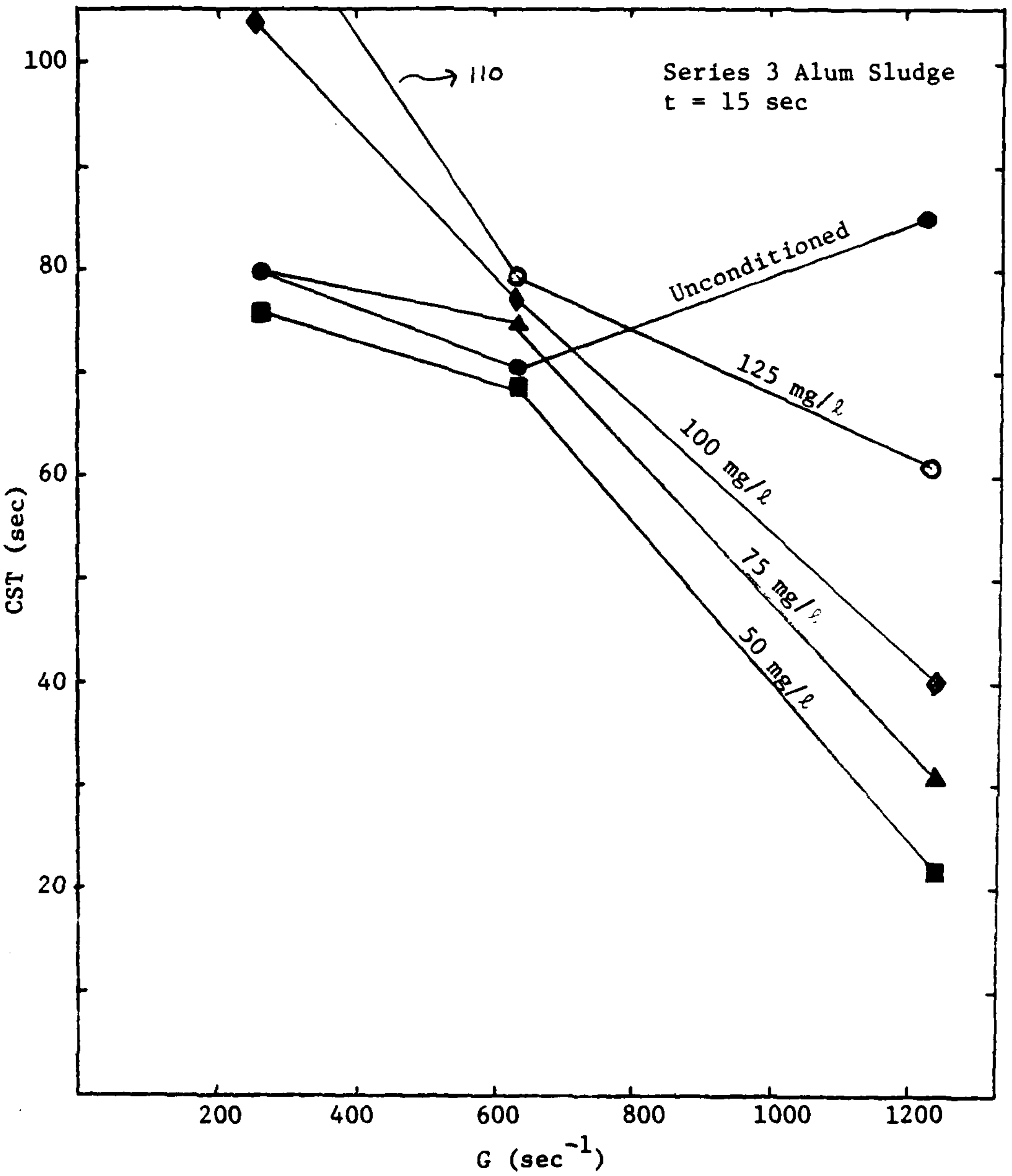

Figure 28. Effect of G value and polymer dose on alum sludge filterability (t = 15 sec).

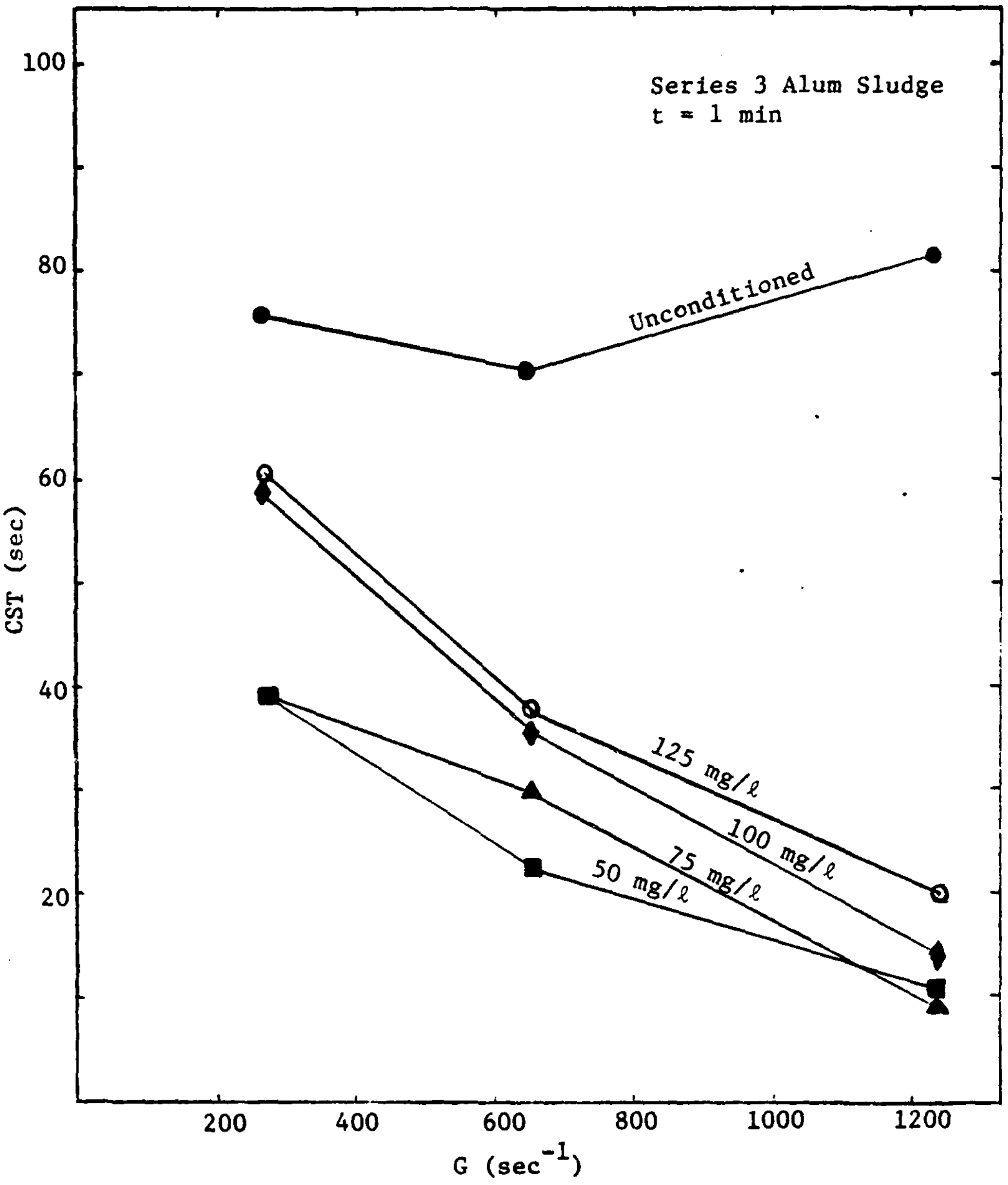

Figure 29. Effect of G value and polymer dose on alum sludge filterability (t = 1 min).

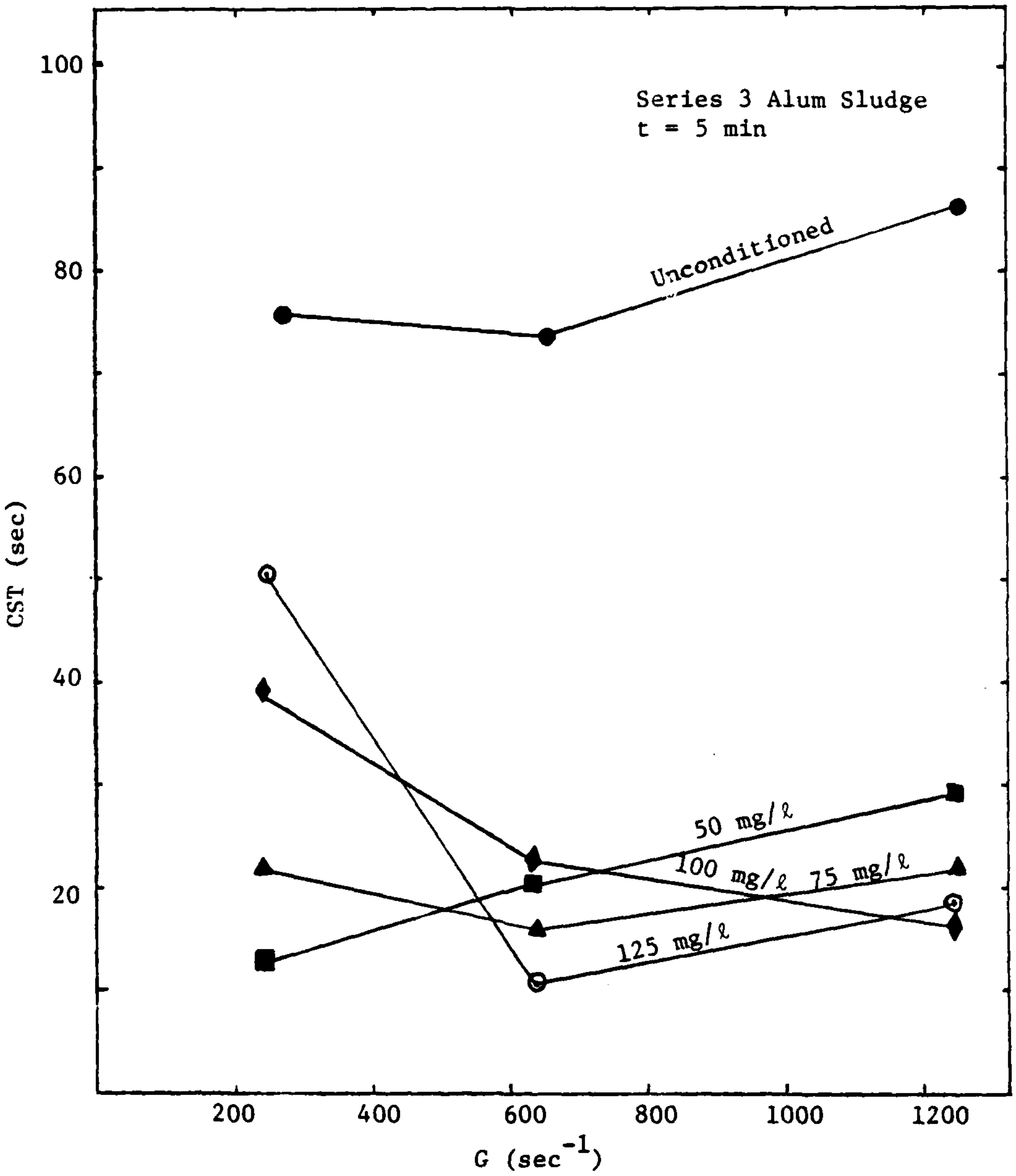

Figure 30. Effect of G value and polymer dose on alum sludge filterability (t = 5 min).

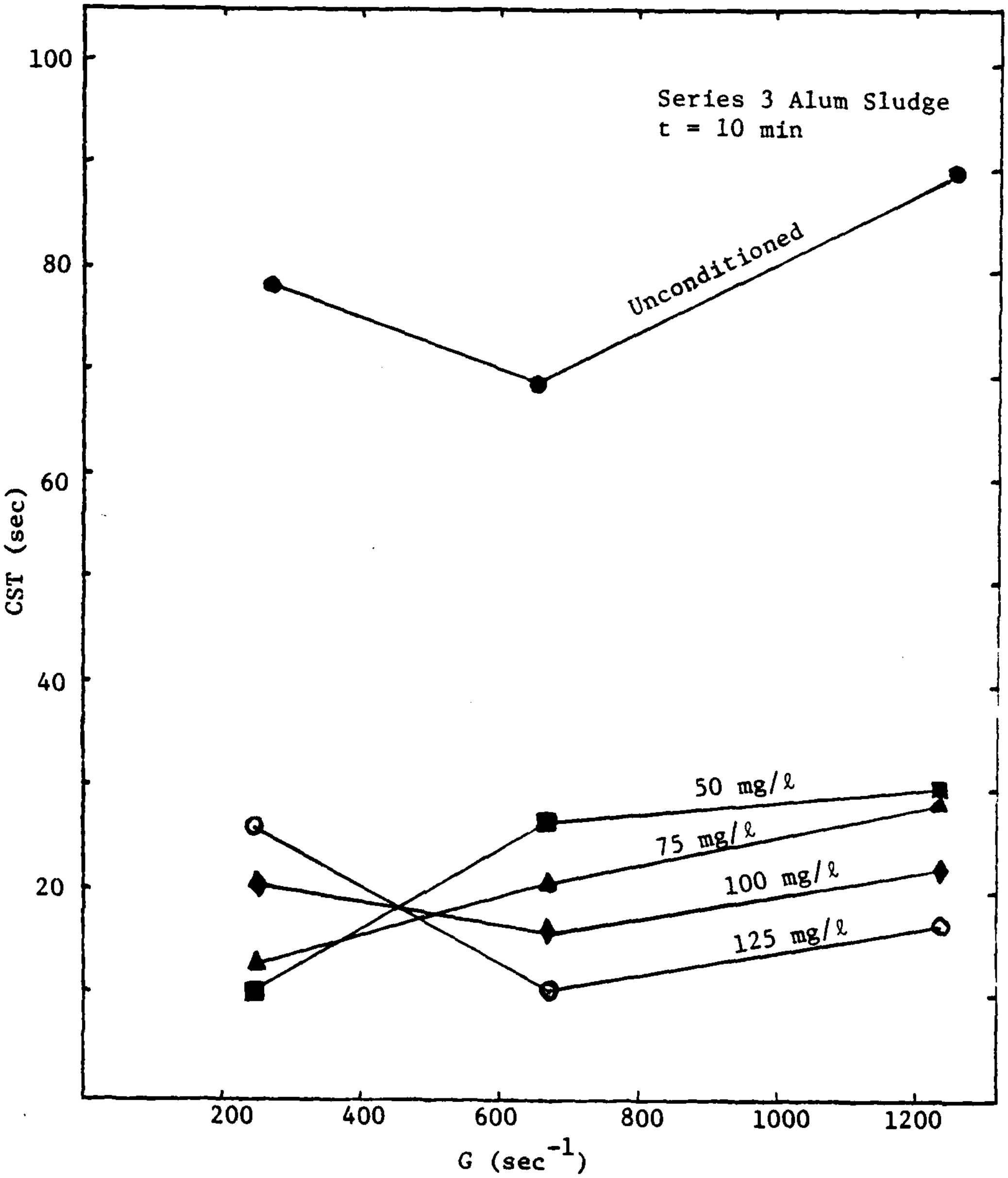

Figure 31. Effect of G value and polymer dose on alum sludge filterability (t = 10 min).

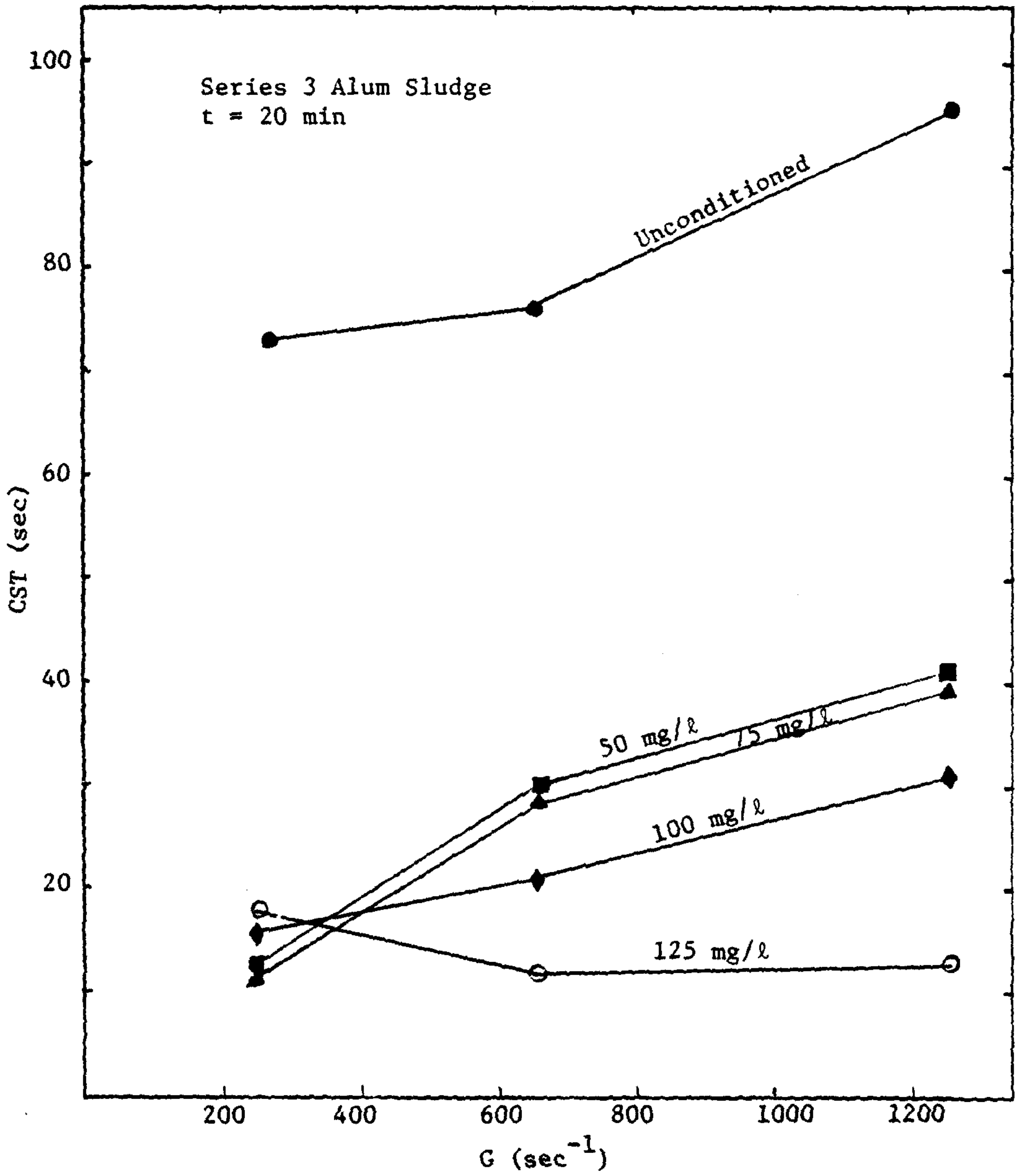

Figure 32. Effect of G value and polymer dose on alum sludge filgerability (t = 20 min).

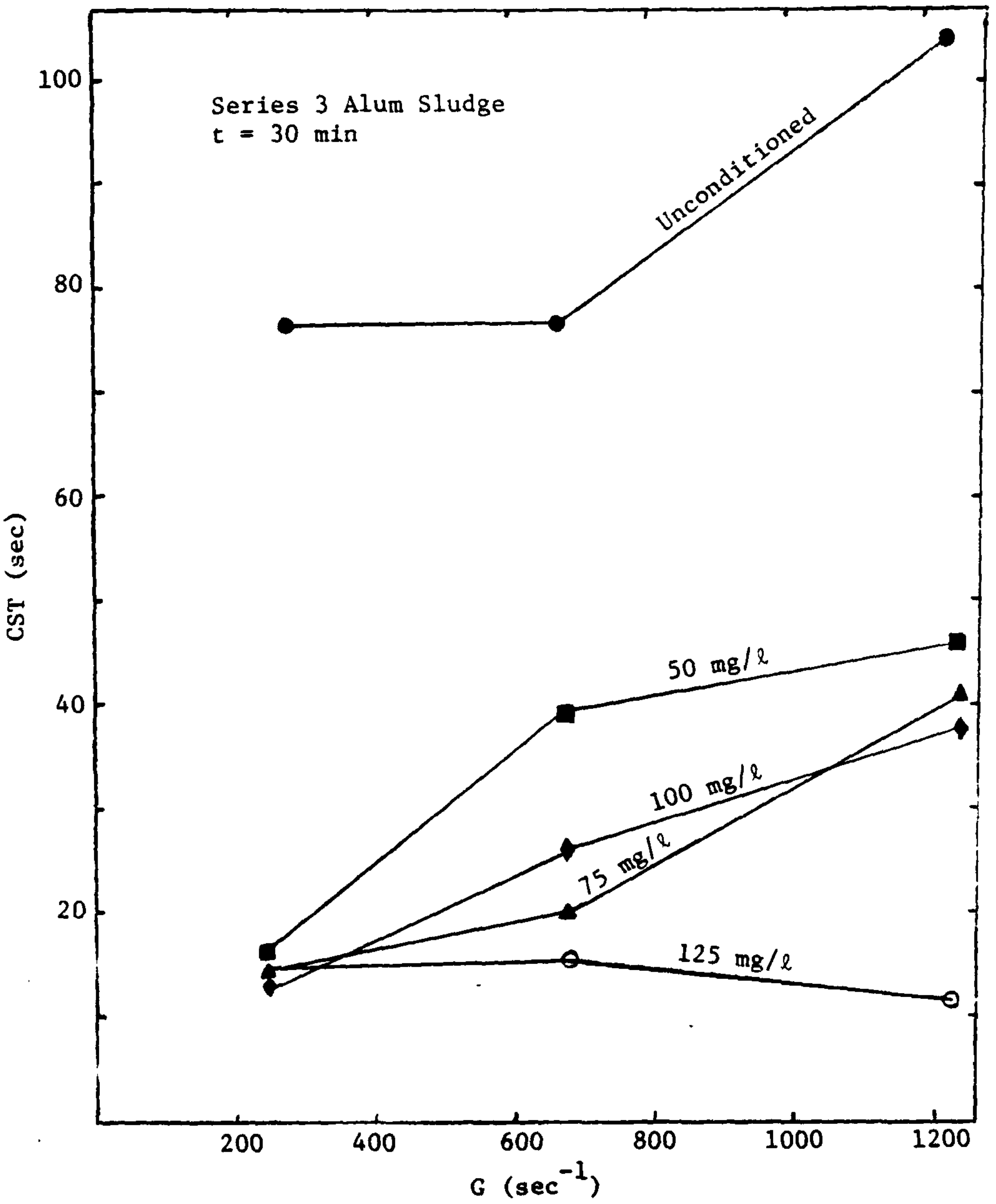

Figure 33. Effect of G value and polymer dose on alum sludge filterability (t = 30 min).

4. Investigation of GT Effect

From an evaluation of the data it appeared that some combination of mixing intensity (G), and mixint time (t) controlled conditioning performance. For chemical coagulations, Letterman et al. (1973) found that the value of G times t could be used to predict removal efficiency. Therefore, in this study the effect of Gt on polymer conditioning was evaluated. In order to evaluate this parameter more completely, a plot was prepared to show how CST varied with Gt for different polymer doses (Figure 34). This graph incorporated and condensed all previous data on alum sludge. (Data points for this plot are not shown due to the large number of points involved). Representative data points are shown in Figure 35.)

Analysis of the data in Figure 34 reveals several important points. First, it showed that the lowest CST reading obtainable was about 10 seconds, and that a variety of dose and Gt combinations would give this same result. For example, at a dose of 5 mg/l and a Gt of 8,000 (low-stress); or [illegible]0 mg/l at a Gt of 90,000 (medium-stress); or 125 mg/l at a Gt of 800,000 (high-stress) all combinations would provide a CST of about 10 seconds. Thus if the dewatering process to be utilized was a low-stress one, such as a drying bed, the first degree of conditioning would probably give optimal results. If it were a medium-stress process, such as vacuum filtration, the second would be desirable. If it were a high-stress process, such as a high-speed centrifuge, the third option would be the optimal choice.

Second, the plot demonstrates the inadequacy of jar testing for estimating conditioning requirements. The 5 mg/l dose gave optimal

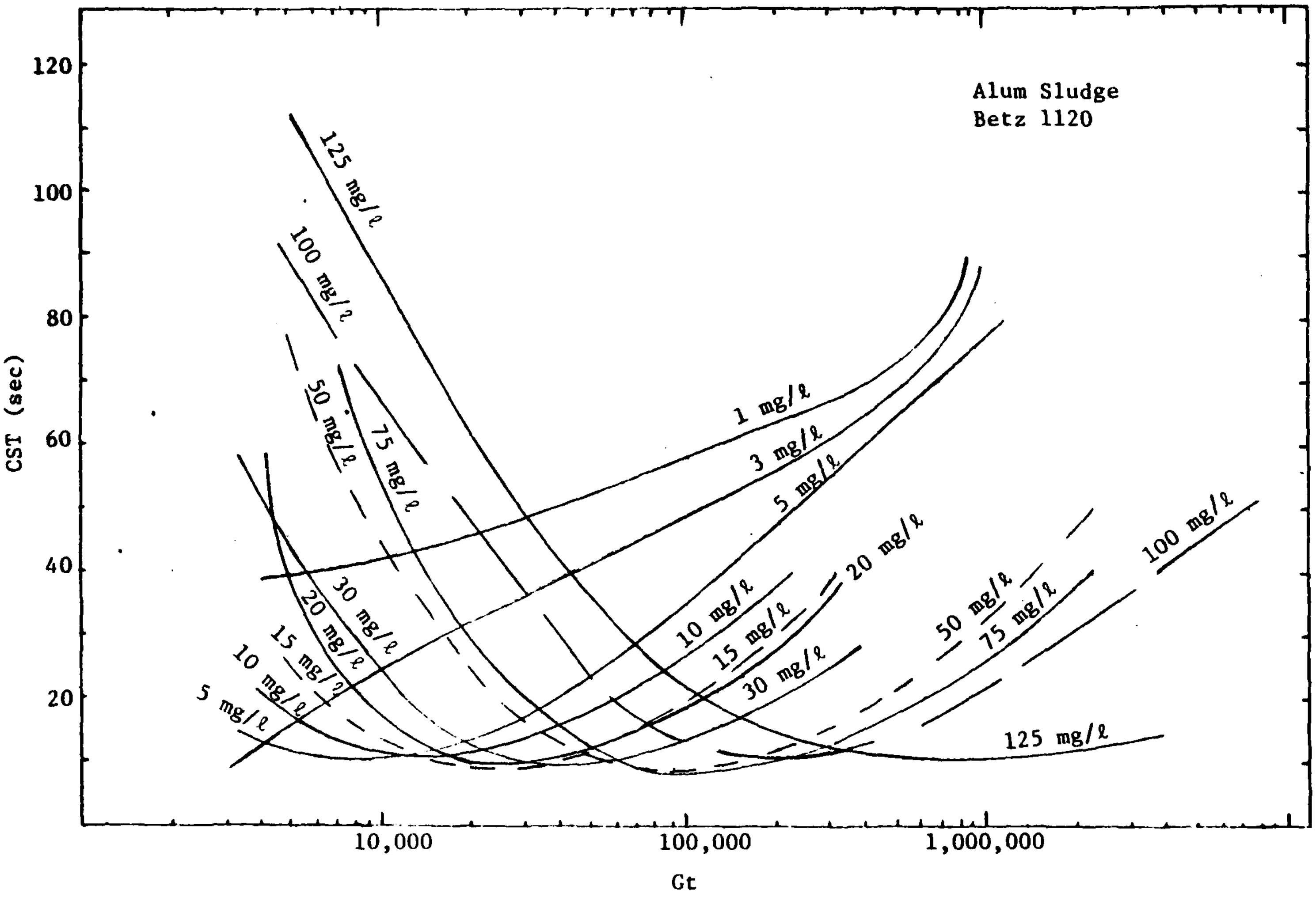

Figure 34. Effect of Gt and polymer dose on alum sludge filterability.

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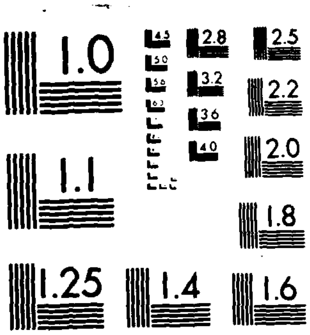

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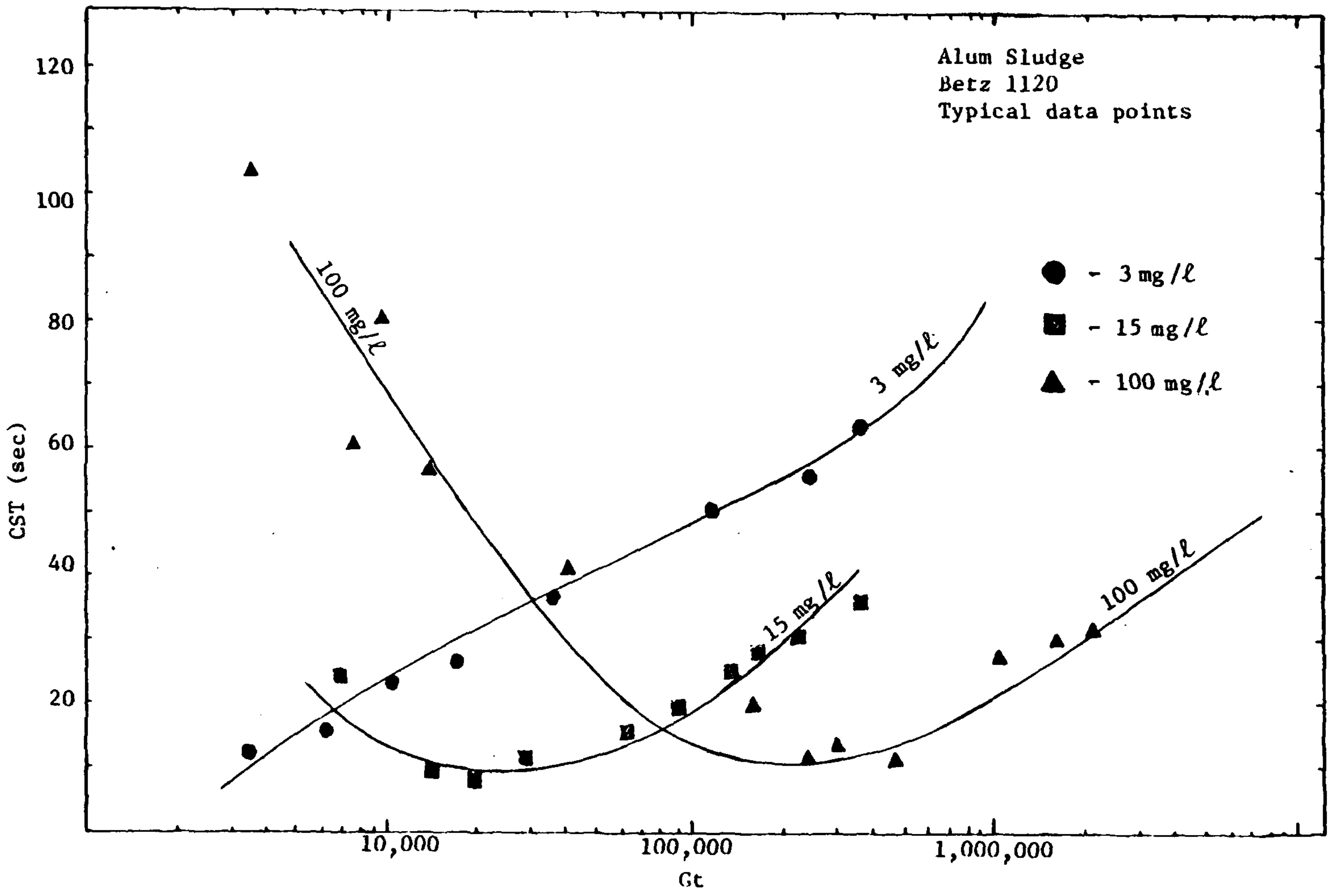

Figure 35. Typical data points for alum sludge CST-Gt plot.

performance at a Gt of 8,000. On a jar test apparatus, this would amount to mixing at 100 rpm for about one minute, which is typical of jar test applications. However, if the sludge were conditioned in this fashion and then passed through a high-speed centrifuge where the Gt is perhaps 1,000,000, it is clear from Figure 34 that filterability would be poor (CST = 80 seconds).

Third, the plot serves to confirm previous theory regarding overdosing and optimum dose requirements. It shows that an overdosed condition could be corrected through application of additional mixing energy input (see the 100 mg/l curve as an example), and that optimum dose levels increase as the mixing energy input (Gt) rises. This latter fact can be seen more clearly in Figure 36.

After establishing these facts, an important question surfaced. Since the Gt value can be generated in an infinite number of ways (i.e. high G and low t, low G and high t, or any combination in between), does it matter what combination of G and t is utilized to produce the optimum Gt? To answer this, samples were tested at different doses and G-t combinations. The results are shown in Table V. For the G values used (246, 623, and 1214 sec^{-1}), it made no appreciable difference how the Gt values were obtained. CST readings within each group were essentially the same. Of course it should be clear that there must be some practical limit to the application of these results. Consider the 50 mg/l dose at a Gt of 90,000. Another way to arrive at this Gt would be to use a G value of 1 sec^{-1} and a t of 90,000 seconds. Obviously, this combination would amount to adding the polymer and letting it sit for 90,000 seconds with essentially no mixing action

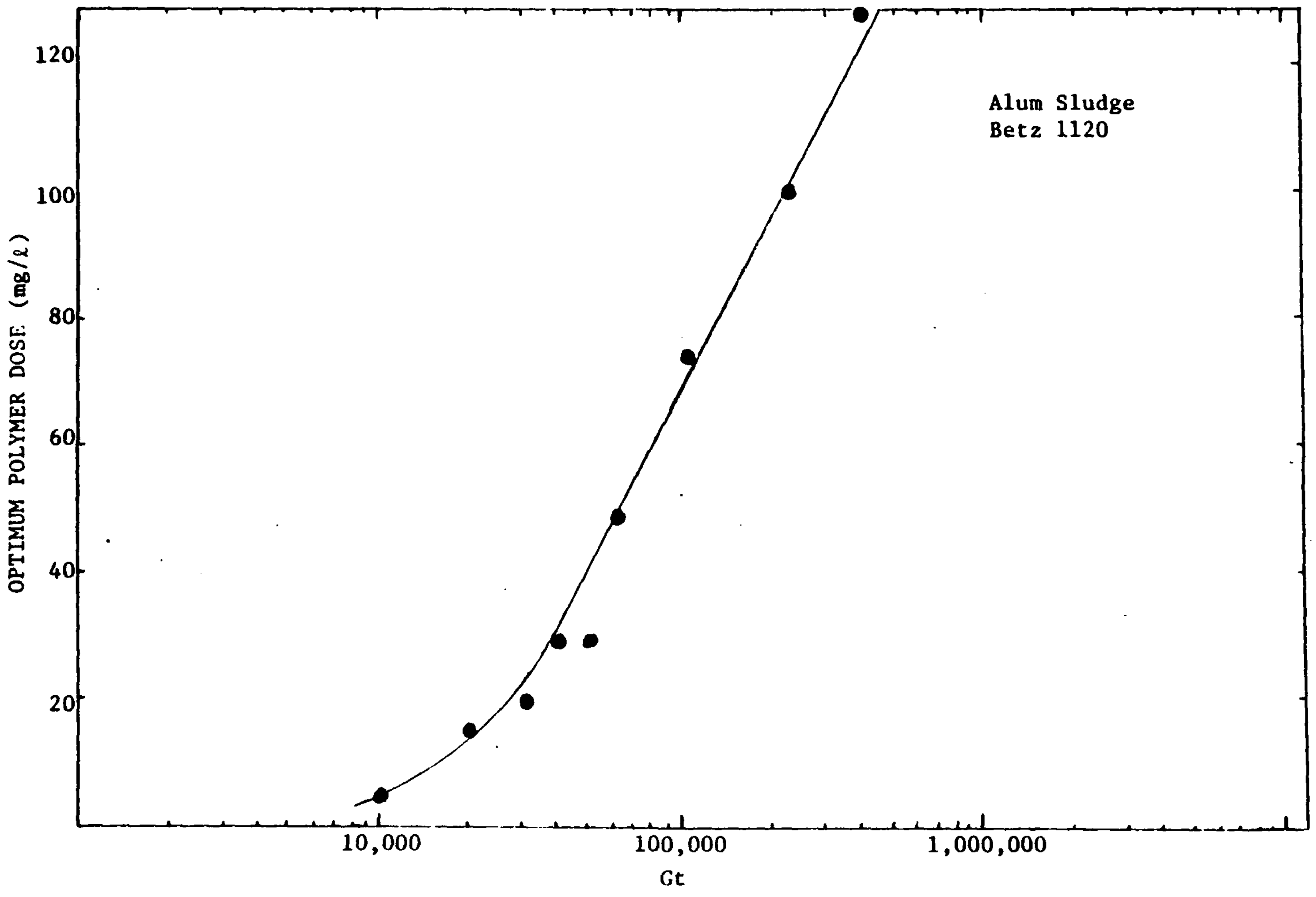

Figure 36. Effect of *Gt* on optimum polymer dose for alum sludge conditioning.

Table V. CST-Gt verification for alum sludge (Betz 1120)

Dose (mg/l)	Gt	G (sec^{-1})	t (sec)	CST (sec)
15	25,000	246	102	11.3
		623	40	11.9
		1214	20	11.9
50	10,000	246	41	47.8
		623	16	43.5
		1214	8	39.1
	90,000	246	366	9.7
		623	145	10.0
		1214	74	8.8
	180,000	246	731	11.8
		623	289	12.6
		1214	148	13.8
125	200,000	246	813	20.5
		623	321	19.3
		1214	165	19.3

at all. Clearly this would not give a satisfactory result. It would therefore appear that G can be traded for t (and vice-versa) only within a certain range of G to t ratios. In these experiments, the G to t ratio ranged from about 0.5 to 60. If G and t values were applied that fell far outside this range in either direction, it is likely that the same reproducibility of CST values would not have been obtainable.

At this point, alum sludge experiments were essentially completed, and attention was directed toward activated and primary sludge conditioning. After the CST-Gt plot was developed for alum sludge, it was decided to conduct only the minimum amount of experiments necessary to develop similar plots for the remaining sludge types. Accordingly, the conditioning data for the activated and primary sludges are as shown in Table IV.

5. Activated Sludge #1 and #2 Conditioning

The CST-Gt plot for activated sludge #1 is shown in Figure 37. Results obtained differed greatly in one respect from alum sludge. Observe that there was essentially a single, optimum Gt (about 7,000) regardless of polymer dose. In other words, it was almost impossible to overdose the activated sludge. Beyond that, there were several similarities to the alum sludge. As Gt increased, the dewatering rate at each dose decreased, with deterioration being more pronounced at the lower doses. This is probably due to particle breakup. Also note that the largest dose (200 mg/1) proved to be the most stable over the range of all Gt values. As with alum, larger doses produced stronger

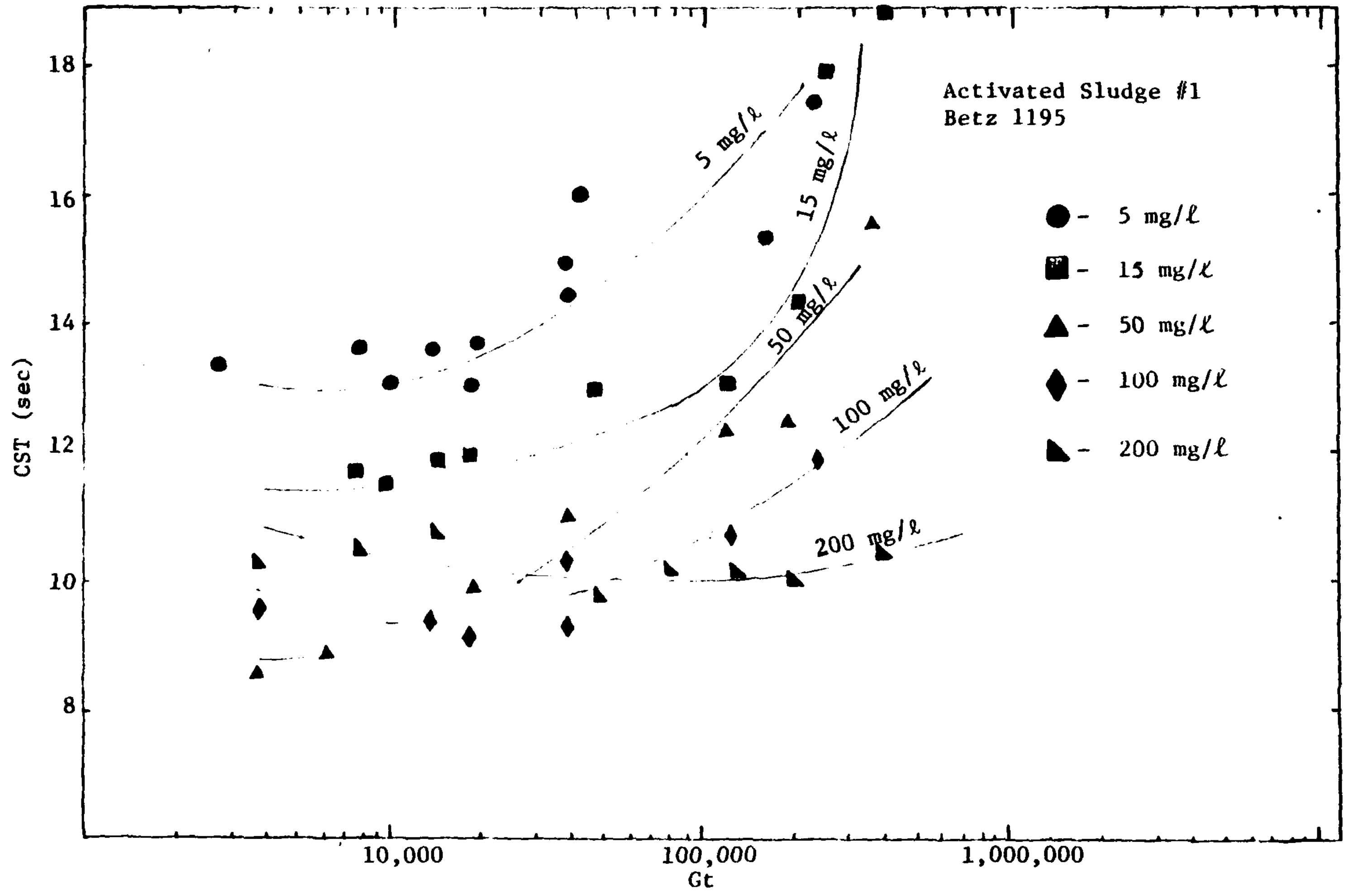

Figure 37. Effect of Gt and polymer dose on activated sludge #1 filterability.

floc under intense mixing energy input.

At first it was thought that the excellent dewatering characteristics of the unconditioned sludge (CST about 17 seconds) accounted for the optimum Gt condition. This led to the conducting of identical experiments on activated sludge #2, which exhibited much poorer unconditioned dewatering characteristics (CST about 75 seconds). As can be seen in Figure 38, however, the results were virtually identical. At that point, CST-Gt verification tests were made on both activated sludges at a 50 mg/l dose. Results are shown in Table VI. Once again, the G-t combinations utilized gave essentially the same CST readings within each group, substantiating data obtained during alum sludge testing.

The only explanation that could be offered for the same optimum Gt at all polymer doses was that excess polymer probably did not occupy attachment sites at low Gt values, and merely remained in solution in a colloidal form when Gt values increased. It is also possible that a large percentage of polymer was utilized in particle charge neutralization reactions, thereby reducing the tendency to overdose.

6. Primary Sludge Conditioning

Conditioning data for primary sludge are also given in Table IV. CST-Gt plots are shown in Figures 39-43. Separate figures were used for each polymer dose due to the unusual reaction of the sludge to high G values. Figure 39 shows that for the 5 mg/l dose, any Gt involving the G value 1214 sec^{-1} resulted in extensive deterioration of filterability. The remaining Gt values where a G of 246 and 623 sec^{-1}

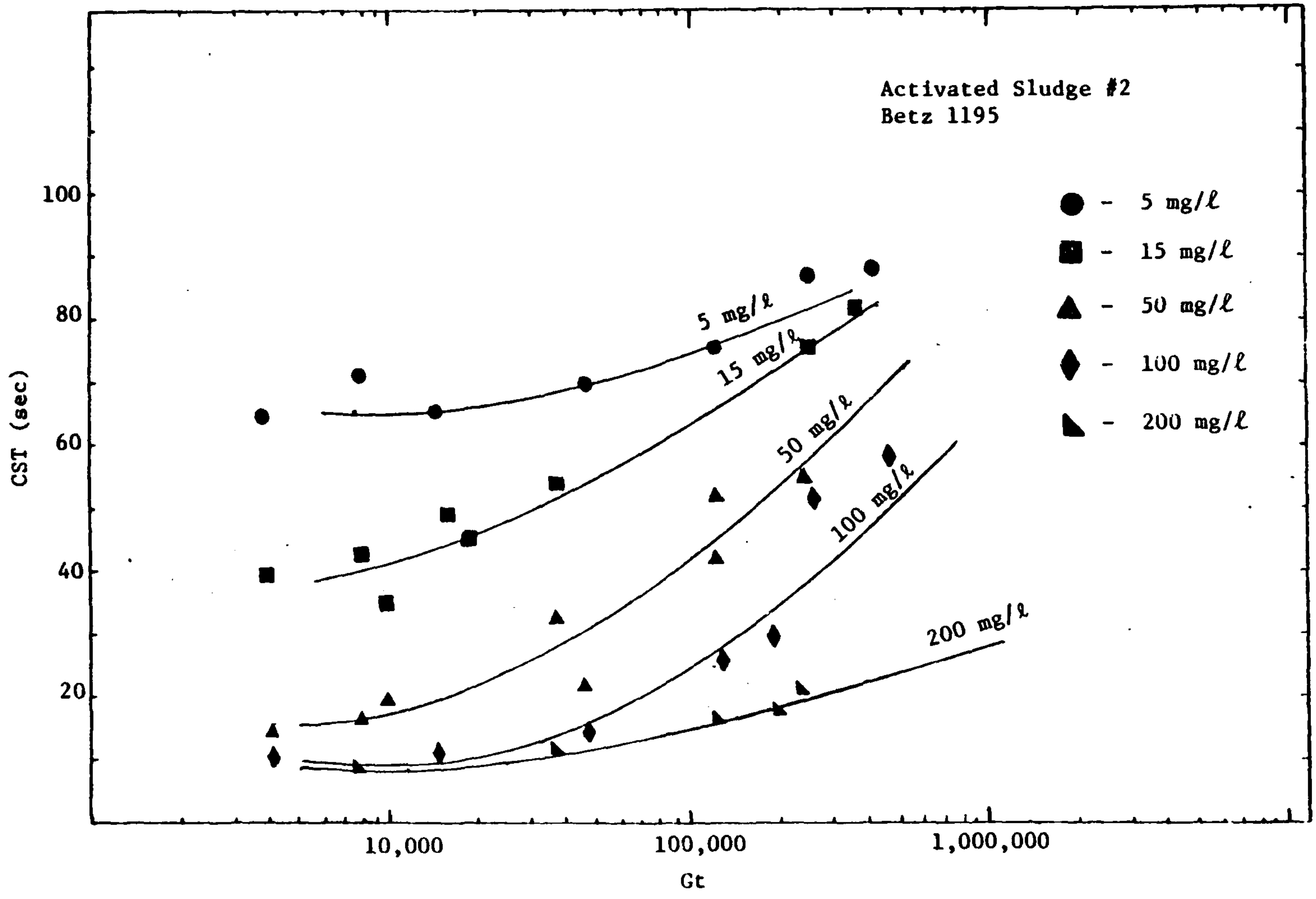

Figure 38. Effect of Gt and polymer data on activated sludge #2 filterability.

Table VI. CST-Gt verification for activated sludge #1 and #2 (Betz 1195)

Dose (mg/l)	Gt	G (sec^{-1})	t (sec)	CST (sec)
50	10,000	246	41	10.2
		623	16	11.6
		1214	8	12.0
	90,000	246	366	11.4
(Activated #1)		623	145	12.9
		1214	74	13.6
	180,000	246	731	12.6
		623	289	13.9
		1214	148	14.0
50	10,000	246	41	17.7
		623	16	18.7
		1214	8	17.8
	90,000	246	366	33.0
(Activated #2)		623	145	44.4
		1214	74	41.0
	180,000	246	731	33.3
		623	289	41.5
		1214	148	48.8

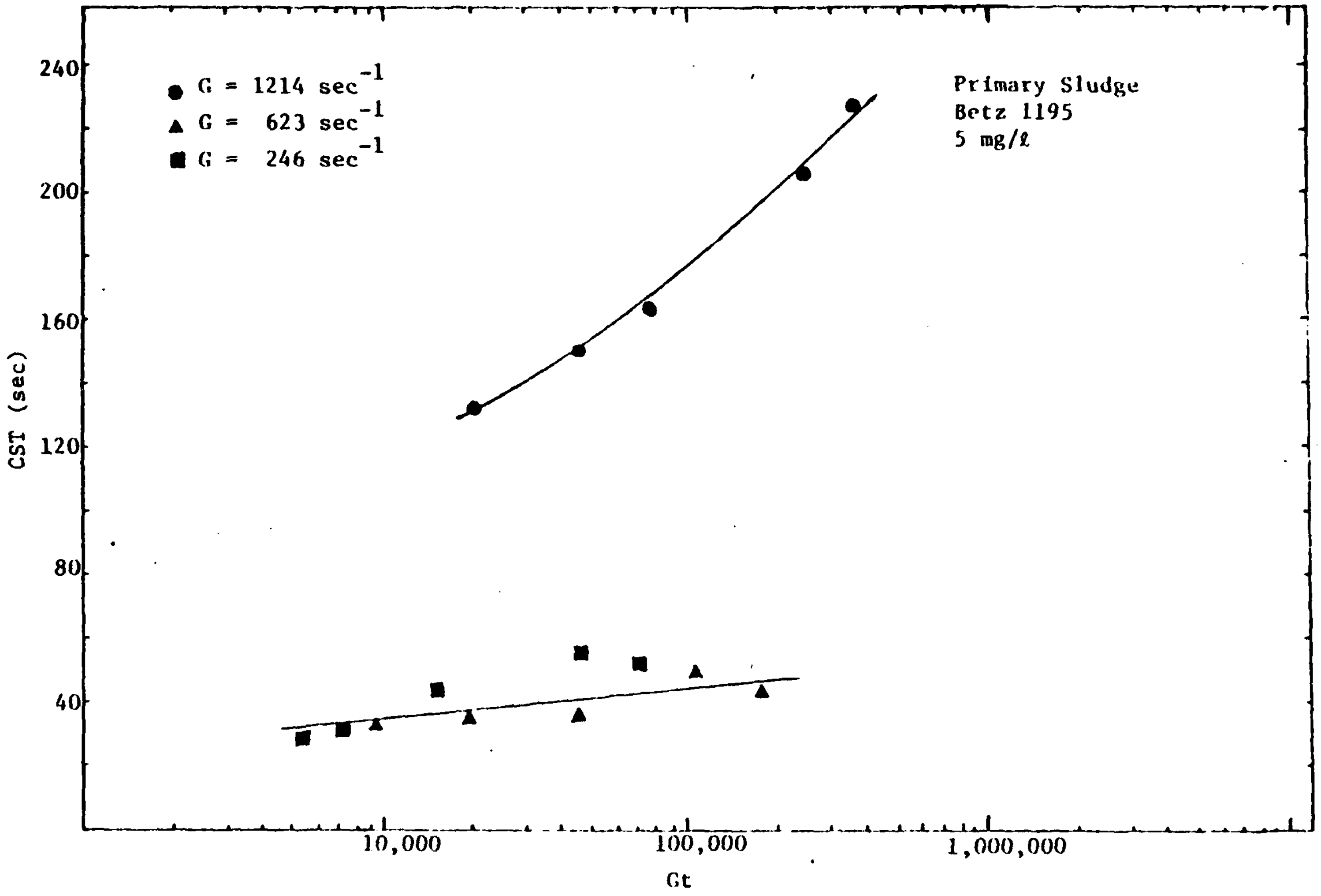

Figure 39. Effect of Gt on primary sludge filterability at 5 mg/ℓ polymer dose.

were employed gave results similar to those obtained with activated sludge. The 15 mg/l dose (Figure 40) gave even more unusual results. Each G value gave a separate and distinct response to polymer conditioning. As polymer doses increased to 50 mg/l and beyond (Figures 41-43), results closely paralleled activated sludge. In other words, there was again a single optimum Gt value regardless of polymer dose, and the filtering rate at each dose decreased as Gt increased beyond the optimum. Deterioration was again minimal at the maximum dose (200 mg/l), and overdosing was not observed within the range of doses used.

The sensitivity of primary sludge floc to the high G value was unexpected and prompted further investigation. The plots clearly showed that at the 5 and 15 mg/l doses, the concept of trading G for t would not hold as with the alum and activated sludges. For doses at and above 50 mg/l, however, it appeared that it would hold. Verification tests for the 50 mg/l dose indicate that reproducible results are in fact obtainable.

The question then was why did the primary sludge exhibit extreme sensitivity to high G values at low polymer doses when the other sludges did not? It is postulated that the reason is the nature of the sludge particle itself. Flocculation theory suggests that fragmented floc particles will tend to re-agglomerate on their own once shear stresses cease. If this were true for alum and activated sludge, but not for primary, then this would account for the significantly different behavior. To test the theory, unconditioned CST readings were obtained for unconditioned alum, activated, and primary sludge samples.

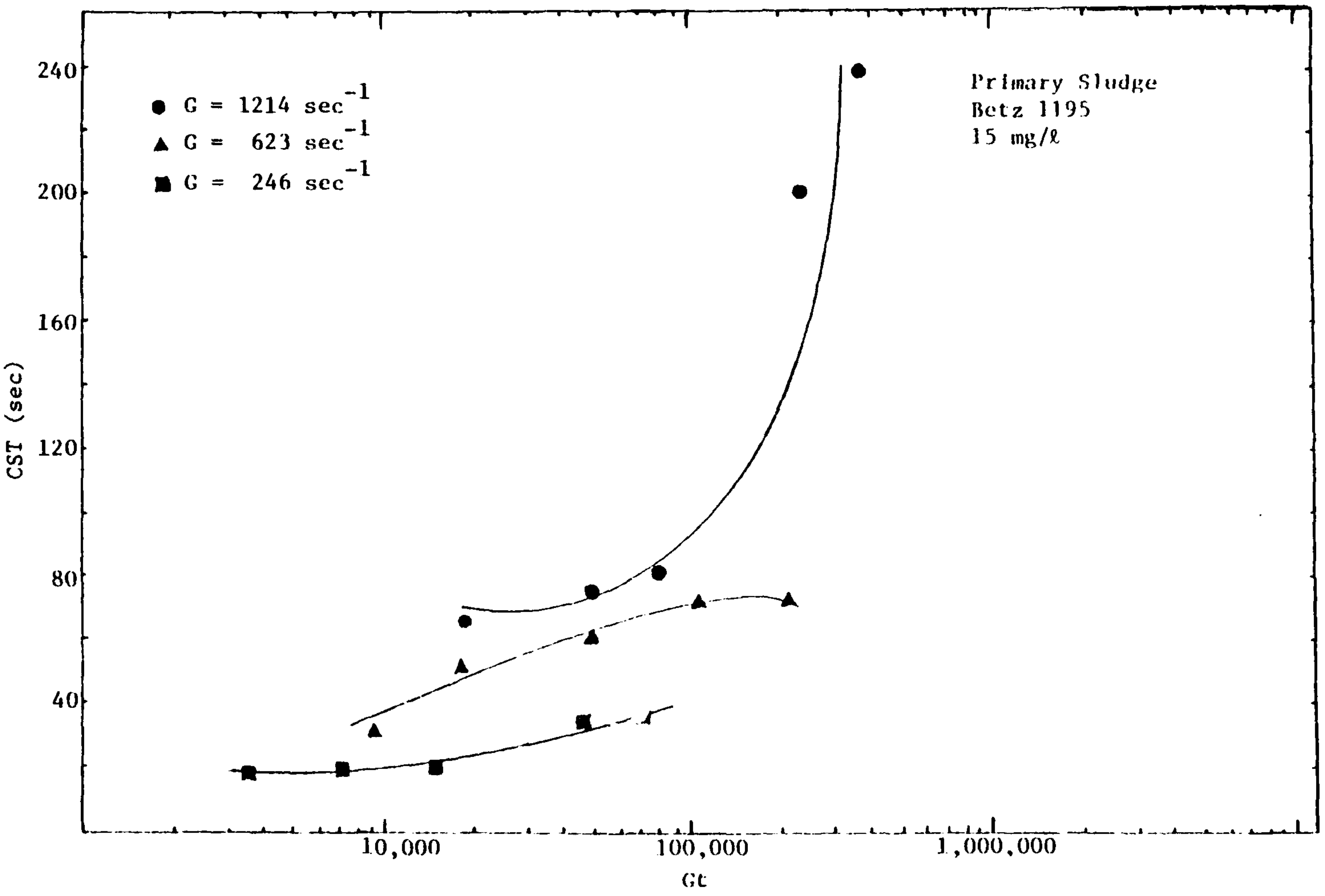

Figure 40. Effect of Gt on primary sludge filterability at 15 mg/ℓ polymer dose.

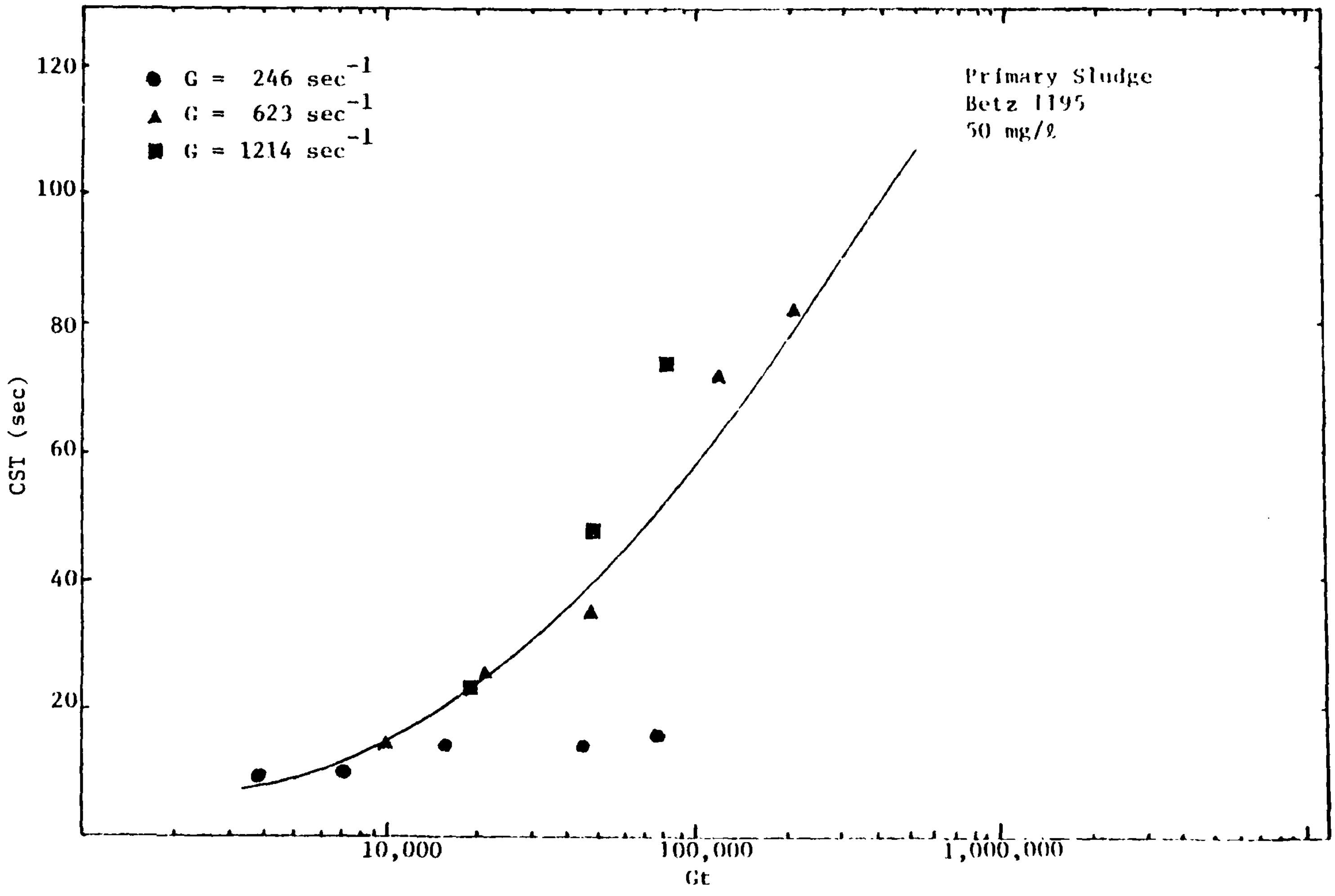

Figure 41. Effect of Gt on primary sludge filterability at 50 mg/ℓ polymer dose.

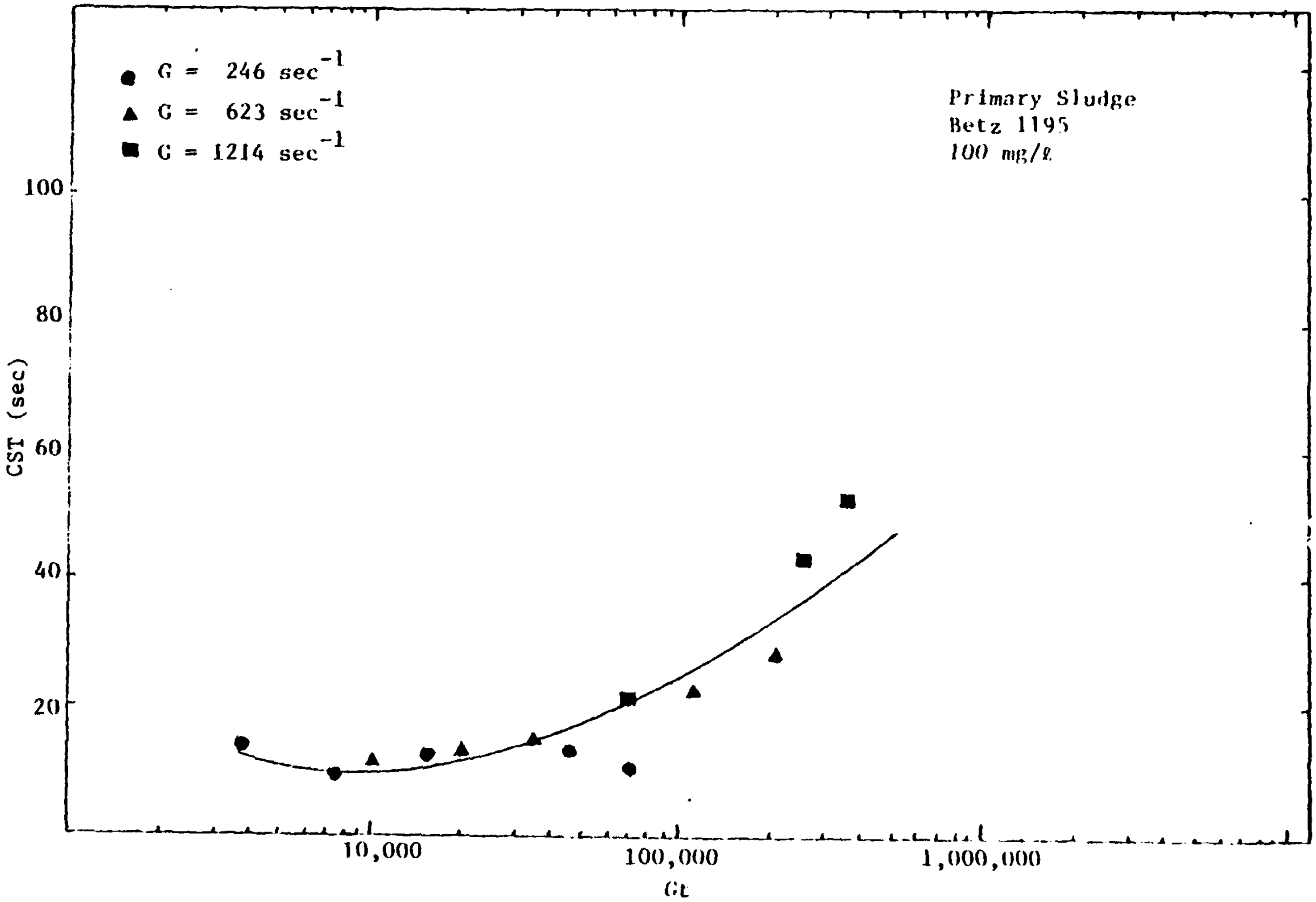

Figure 42. Effect of Gt on primary sludge filterability at 100 mg/ℓ polymer dose.

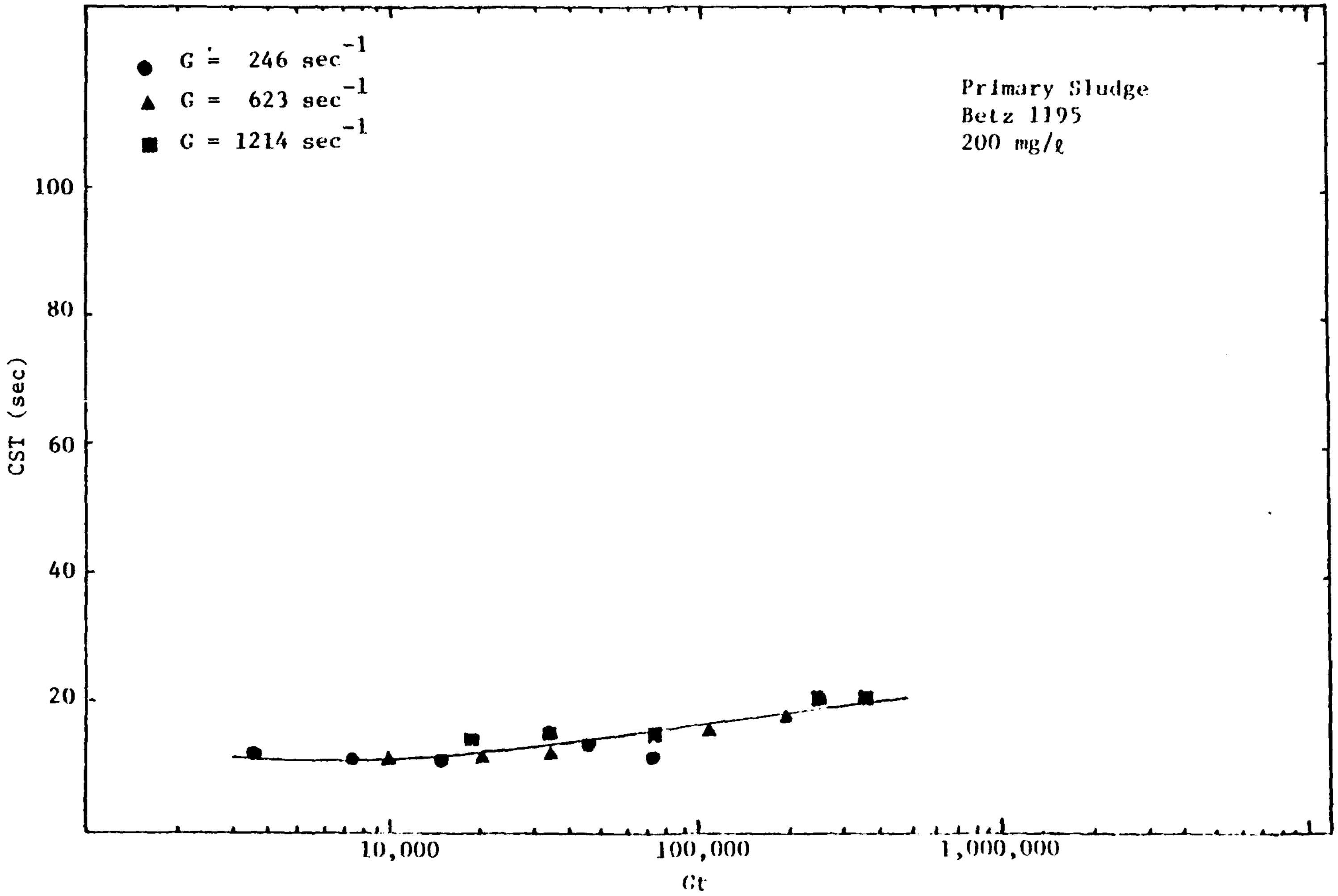

Figure 43. Effect of Gt on primary sludge filterability at 200 mg/ℓ polymer dose.

Then each sample was mixed at a G value of 1214 sec^{-1} for 5 minutes and allowed to sit undisturbed. Samples were then withdrawn and CST readings taken at 5 minute time intervals for periods up to 60 minutes. The results of these tests are shown in Figures 44-46. In the case of alum and activated sludges, initial CST readings reflected deterioration from the base values, but the readings improved and nearly duplicated the original values within the 60 minute time frame. For primary sludge this was not the case. Note that Figure 46 shows a base CST of 29.9 seconds, which deteriorated to more than 160 seconds after initial mixing. Even after 60 minutes of sitting, the CST had only improved to about 125 seconds. Apparently the primary sludge particles did not tend to re-agglomerate on their own. It is evident however from previous discussion that this unique characteristic of primary sludge particles can be compensated for by increasing the polymer dose.

Table VII. CST-Gt verification for primary sludge (Betz 1195)

Dose (mg/l)	Gt	G (sec^{-1})	t (sec)	CST (sec)
50	10,000	246	40	16.1
		623	16	17.0
		1214	8	15.6
	90,000	246	366	65.9
		623	145	72.0
		1214	74	69.3
	180,000	246	731	88.9
		623	289	103.1
		1214	148	106.3

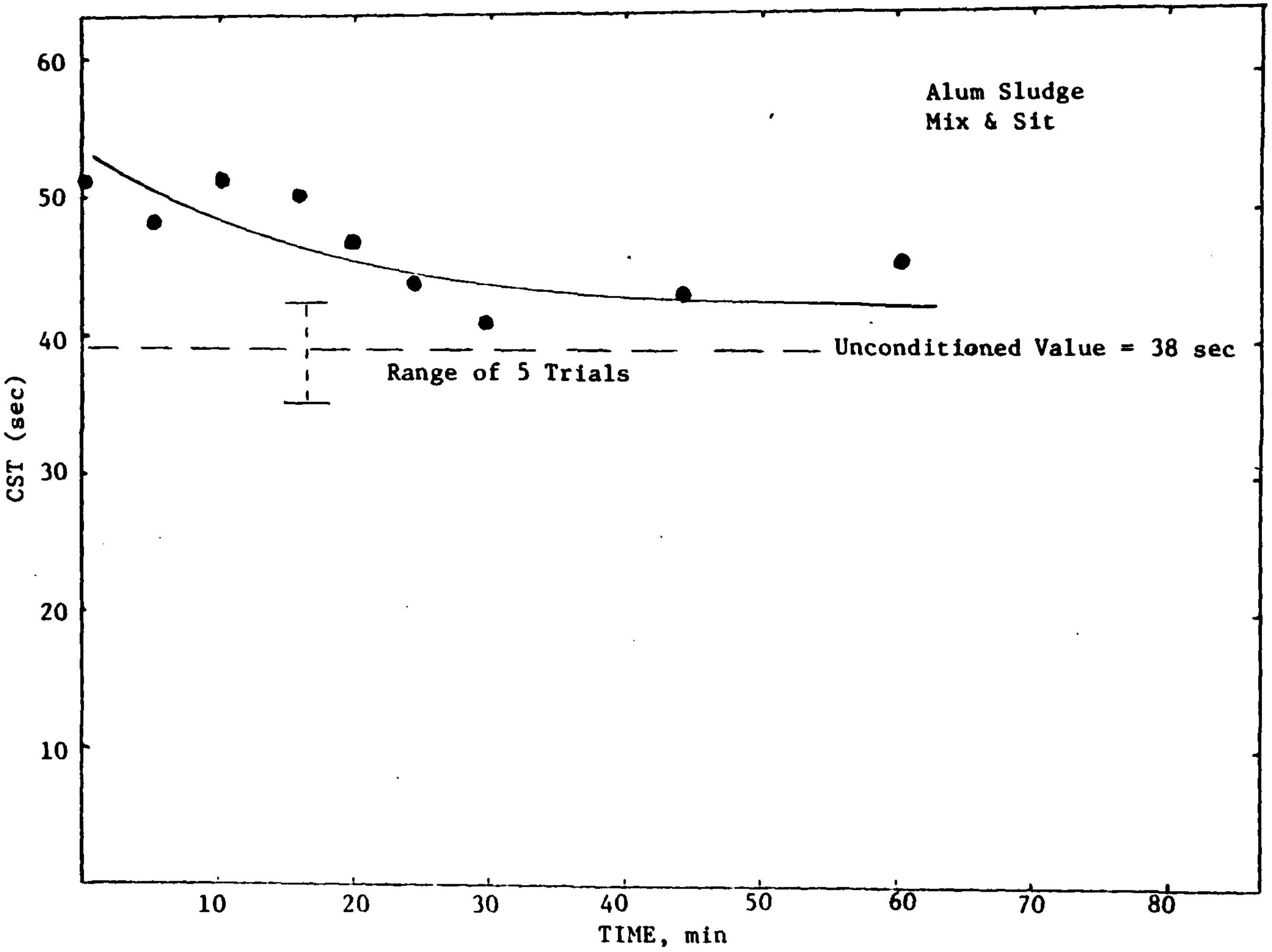

Figure 44. Effect of sitting on undosed alum sludge filterability.

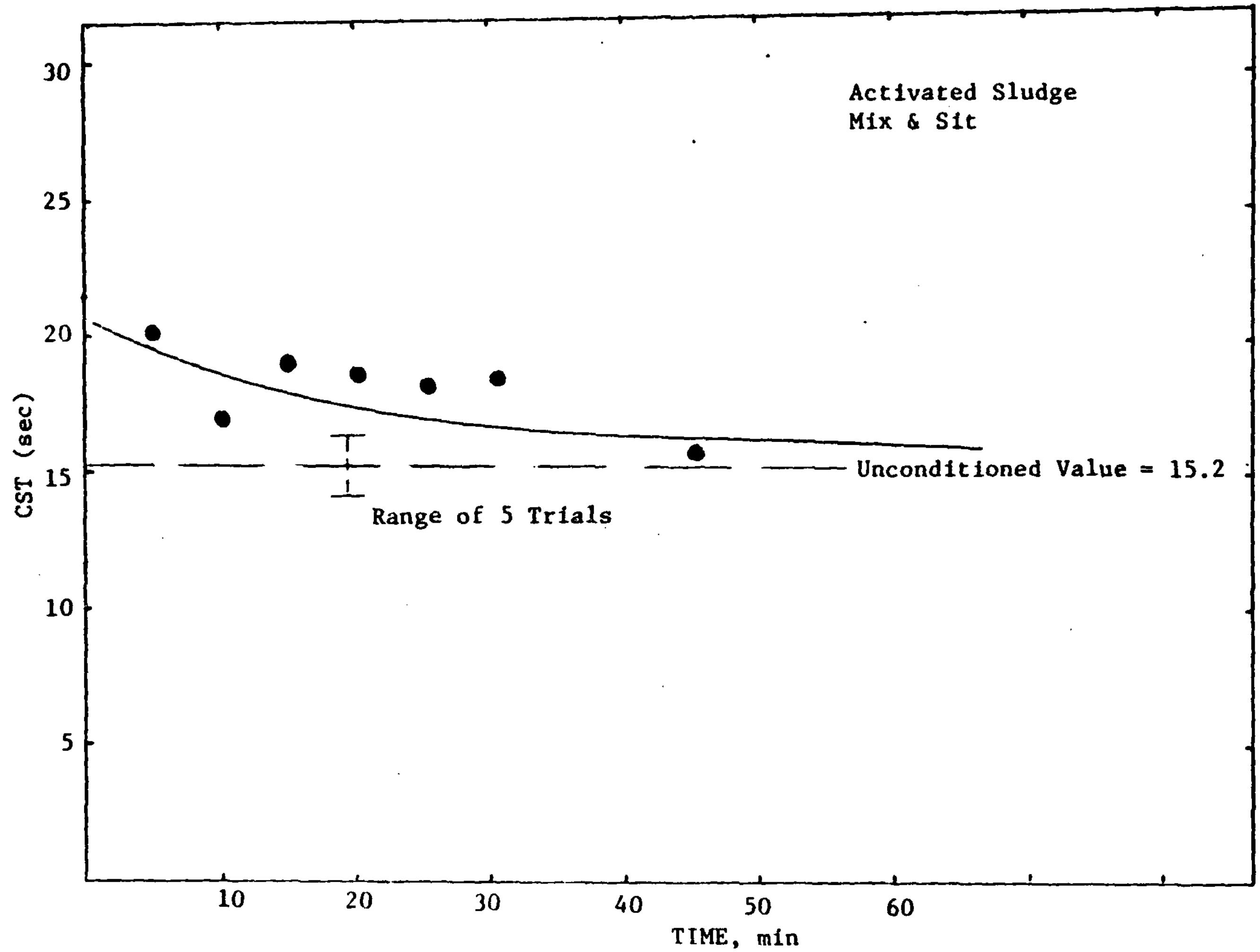

Figure 45. Effect of sitting on undosed activated sludge filterability.

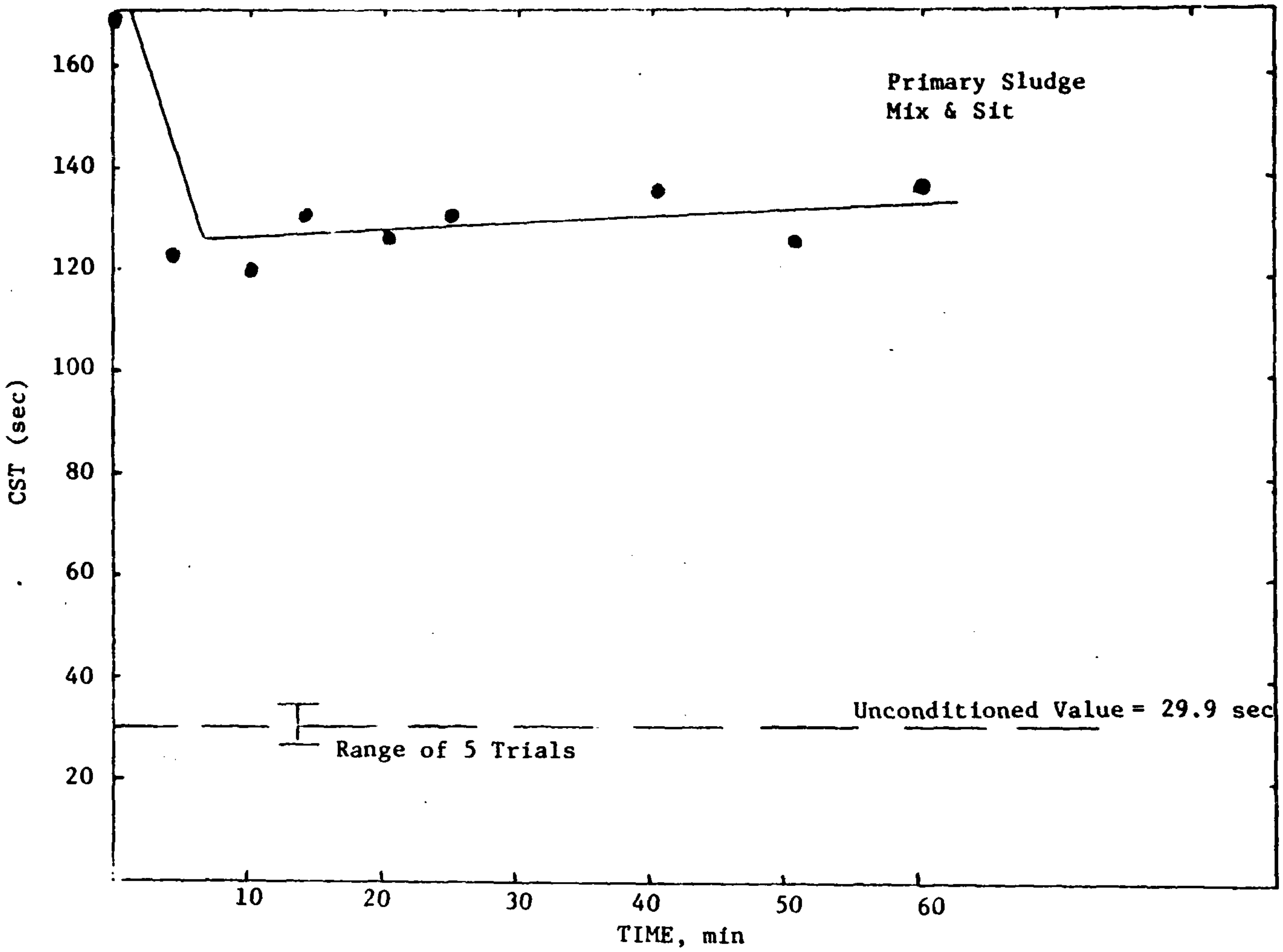

Figure 46. Effect of sitting on undosed primary sludge filterability.

V. SUMMARY AND CONCLUSIONS

From the results of this research it is evident that polymer dose and total mixing energy input (Gt) are the two most important parameters governing high-stress sludge conditioning. The mechanism of polymer action during conditioning appears to be that of increasing particle size. For a given sludge, it is possible to establish a polymer dose and Gt value that will maximize mean particle size, thereby optimizing filterability.

In the case of alum sludge, several polymer dose-Gt combinations can be used to achieve the same optimal performance. These range from low dose-low Gt to high dose-high Gt products. Actual selections should be based on the stress levels anticipated during dewatering. Generally speaking, the higher the Gt value, the more polymer required for optimal performance. When applying the required Gt, any combination of G and t within the ideal range of G to t ratios will yield the desired result. This fact is particularly significant for applications where the G value of mixing equipment may be fixed.

For activated and primary sludges, a single optimum Gt seems to exist regardless of polymer dose used. Filterability, however, improves as the polymer dose increases. As with alum sludge, G may be traded for t within the ideal range of G to t ratios. This does not apply, however, to primary sludge when polymer doses under 50 mg/l are utilized. Primary sludge particles appear to be extremely sensitive to high-intensity mixing. Deterioration of particle size is extensive after only short exposure to high G values ($G = 1215\ sec^{-1}$). This problem can be corrected through use of large polymer doses.

Collectively, data obtained for each sludge type illustrate the effects of polymer dose, mixing time, and mixing intensity on sludge filterability. For a given polymer dose, there is a corresponding mix time and/or mix intensity that will maximize filterability for that dose. Increasing the mix time and/or mix intensity beyond those levels will result in deterioration of filterability. When large polymer doses are used with alum sludge, poor performance may result at low Gt values. This tendency to overdose seems to result from excess colloidal polymer occupying attachment sites on the polymer molecules. This condition can be corrected through additional mixing energy input. Significant overdosing was not observed with activated and primary sludges.

Finally, the reliability of standard jar test devices in predicting polymer requirements for high-stress applications appears to be questionable. The low G values generated by these devices do not adequately simulate the stress levels inherent with mechanical dewatering equipment.

Given the above finding, the results of this research support the following conclusions:

1. Jar testing devices using low G mixing energies will tend to underpredict polymer dose requirements in cases where sludges are to be subjected to high-stress dewatering. This is especially true for primary sludges.

2. Alum, activated, and primary sludges can be conditioned to dewater readily during high-stress processes.

3. When conditioning alum, activated, and primary sludges, optimum polymer requirements increase as mixing energy input (Gt) increases.

4. Once an optimum Gt has been established for a given polymer dose, any combination of G and t within the ideal range of G-t ratios will give optimal dewatering results (for alum and activated sludges only). This will hold true for primary sludges only at high polymer doses.

5. Primary sludge particles exhibit extensive deterioration when subjected to high G values, regardless of mix time. This problem can be corrected through use of large polymer doses. Sitting alone is ineffective in restoring primary sludge floc.

6. Alum and activated sludge particles exhibit minor deterioration when subjected to high Gt. The particles tend to re-agglomerate on their own after a short period of sitting, dewatering at essentially the same rate as before mixing.

7. Activated and primary sludges appear to be resistant to polymer overdosing. A single optimum Gt exists regardless of polymer dose.

VI. LITERATURE CITED

Argaman, Y., "Turbulence in Orthokinetic Flocculation." PhD Dissertation, University of California, Berkeley (1968).

Argaman, Y., and Kaufman, W.J., "Turbulence and Flocculation." Journal SED, ASCE. Vol. 96, SA2, 223-241 (1970).

Bargman, R.D., Garber, W.F., and Nagamo, J., "Sludge Filtration and Use of Synthetic Organic Coagulants at Hyperion." Sewage and Industrial Wastes. Vol. 30, 9, 1079-1100 (1958).

Baskerville, R.C., and Gale, R.S., "A Simple Automatic Instrument for Determining the Filterability of Sewage Sludges." Journal WPCF. Vol. 67, 3, 233-241 (1968).

Birkner, F.E., and Morgan, J.J., "Polymer Flocculation Kinetics of Dilute Colloidal Suspensions." Journal EED, ASCE. Vol. 60, 2, 175-191 (1968).

Bugg, H.M., King, P.H., and Randall, C.W., "Polyelectrolyte Conditioning of Alum Sludge." Journal AWWA. Vol. 62, 12, 792-795 (1970).

Camp, T.R., "Flocculation and Flocculation Basins." Transactions ASCE. Vol. 120, 1-16 (1955).

Camp, T.R., "Floc Volume Concentration," Journal AWWA. Vol. 60, 5, 656-673 (1968).

Cornwell, D.A., and Bishop, M.M., "Determining Velocity Gradients." Proceedings of the AWWA, Seminar on Coagulation and Filtration: Back to Basics, St. Louis, June 7, 1981.

Edzwald, J.K., Upchurch, J.B., and O'Melia, C.R., "Coagulation in Estuaries." Environmental Science and Technology. Vol. 8, 1, 58-63 (1974).

Environmental Protection Agency, "Evaluation of Dewatering Devices for Producing High Solids Sludge Cake." U.S. Environmental EPA 600/2-79-123, Office of Research and Development, Cincinnati, Ohio (1979).

Environmental Protection Agency, "Dewatering Municipal Wastewater Sludges." U.S. Environmental Protection Agency, EPA-625/1-82-0, Research and Development, Cincinnati, Ohio (1982).

Farrell, J.B., Smith, J.E., Dean, R.B., Grossman III, E., and Grant, O. L., "Natural Freezing for Dewatering Aluminum Hydroxide Sludges." Journal AWWA. Vol. 62, 12, 787-791 (1970).

Glenn, R.W., Judkins, J.F. Jr., and Morgan, J.M., "Filterability of Water Treatment Plant Sludge." Journal AWWA. Vol. 65, 6, 414-417 (1973).

Goodman, B.L., "Chemical Conditioning of Sludges: Six Case Histories." Water and Wastes Engineering. Vol. 3, 2, 62-65 (1966).

Goodman, B.L., "Polymers: What They Are, How They Act." Water and Wastes Engineering. Vol. 3, 7, 68-70 (1966).

Goodman, B.L., and Witcher, G., "Polymer Aided Sludge Treatment." Journal WPCF. Vol. 37, 12, 1643-1656 (1965).

Hannah, S., Cohen, J.M., and Robeck, G.G., "Measurement of Floc Strength by Particle Counting." Journal AWWA. Vol. 59, 7, 843-858 (1969).

Harris, H.S., Kaufman, W.J., and Krane, R.B., "Orthokinetic Flocculation in Water Purification." Journal SED, ASCE. Vol. 92, SA6, 95-111 (1966).

Haugan, B.E., and Mininni, G., "Characterization, Treatment, and Use of Sewage Sludge." Proceedings of the Second European Symposium, Vienna, Oct. 21-23, 1980.

Karr, P. R., "Factors Influencing the Dewatering Characteristics of Sludge." PhD Dissertation, Clemson University, S.C. (1976).

Keith, F.W., and Little, T.H., "Centrifuges in Water and Wastewater Treatment." Chemical Engineering Progress. Vol. 65, 11, 77-80 (1969).

Knocke, W.R., Ghosh, M.M., and Novak, J.T., "Vacuum Filtration of Metal Hydroxide Sludges." Journal EED, ASCE. Vol. 106, EE2, 363-376 (1980).

Krasaukas, J.W., "Review of Sludge Disposal Practices." Journal AWWA. Vol. 61, 5, 228 (1969).

La Mer, V.K., "Coagulation Symposium Introduction." Journal Colloid Science, Vol. 19, 291-293 (1964).

Lawler, D.F., O'Melia, C.R., and Tobiason, J.E., Particulates in Water: Characterization, Fate, Effects, and Removal. American Chemical Society, Washington, D.C. (1980).

Letterman, R.D., Quon, J.E., and Gemmell, R.S., "Influence of Rapid Mix Parameters on Flocculation." Journal AWWA. Vol. 65, 11, 716-722 (1973).

Morris, R.H., "Polymer Conditioned Sludge Filtration." Water and Waste Engineering. Vol. 2, 3, 68-70 (1965).

Neubauer, W.K., "Waste Alum Sludge Treatment." Journal AWWA. Vol. 60, 7, 823-824 (1968).

Novak, J.T., and Calkins, D.C., "Sludge Dewatering and Its Physical Properties." Journal AWWA. Vol. 67, 1, 42-45 (1975).

Novak, J.T., and O'Brien, J.H., "Polymer Conditioning of Chemical Sludges." Journal WPCF. Vol. 47, 10, 2397-2410 (1975).

Novak, J.T., and Piroozford, M., "Application of Polymers for Water Plant Sludge Conditioning." Journal AWWA. Conference of Proceedings, 1981.

O'Brien, J.H., and Novak, J.T., "Effects of pH and Mixing on Polymer Conditioning of Chemical Sludges." Journal AWWA. Vol. 69, 11, 600-604 (1977).

O'Melia, C.R., "Scientific Basis of Flocculation." Proceedings of the NATO Advanced Study Institute on the Scientific Basis of Flocculation, Christ's College, Cambridge, U.K., July 3-15, 1977.

Parker, D.S., Kaufman, W.J., and Jenkins, B., "Floc Breakup in Turbulent Flocculation Processes." Journal SED, ASCE. Vol. 98, SA1, 79-99 (1972).

Randall, C.W., Turpin, J.K., and King, P.H., "Activated Sludge Dewatering: Factors Affecting Drainability." Journal WPCF. Vol. 43, 1, 102-122 (1971).

Sato, T., and Ruch, R., Stabilization of Colloidal Dispersions by Polymer Adsorption. Dekker, New York, N.Y., 155p. (1980).

Sharon, L., "Polyelectrolyte Conditioning of Sludge." Water and Waste Engineering. Vol. 4, 8, 50-52 (1967).

Steel, E.W., and McGhee, T.J., Water Supply and Sewerage. McGraw-Hill, Inc., New York, N.Y. 665 p. (1979).

Stumm, W., and O'Melia, C.R., "Stoichiometry of Coagulation." Journal AWWA. Vol. 60, 5, 514-539 (1968).

Stump, V.L., and Novak, J.T., "Polyelectrolyte Selection for Direct Filtration." Journal AWWA. Vol. 71, 6, 338-342 (1979).

Thomas, C.M., "The Use of Filter Presses for Dewatering of Sludges." Journal AWWA. Vol. 43, 2, 93-101 (1971).

Thomas, D.G., "Turbulent Disruption of Flocs in Small Particle Size Suspensions." Journal AICE. Vol. 10, 4, 517-523 (1964).

Vesilind, P.A., Treatment and Disposal of Wastewater Sludges. Ann Arbor Science, Ann Arbor, Michigan, 323 p. (1980).

Water Pollution Control Federation, "Sludge Dewatering." Manual of Practice #20, Washington, D.C. (1969).

Water Pollution Control Federation, "Utilization of Municipal Wastewater Sludge." Manual of Practice #2, Washington, D.C. (1971).

Weber, W., Physiochemical Processes for Water Quality Control. Wiley Interscience, New York, N.Y., 640 p. (1972).

VII. APPENDIX

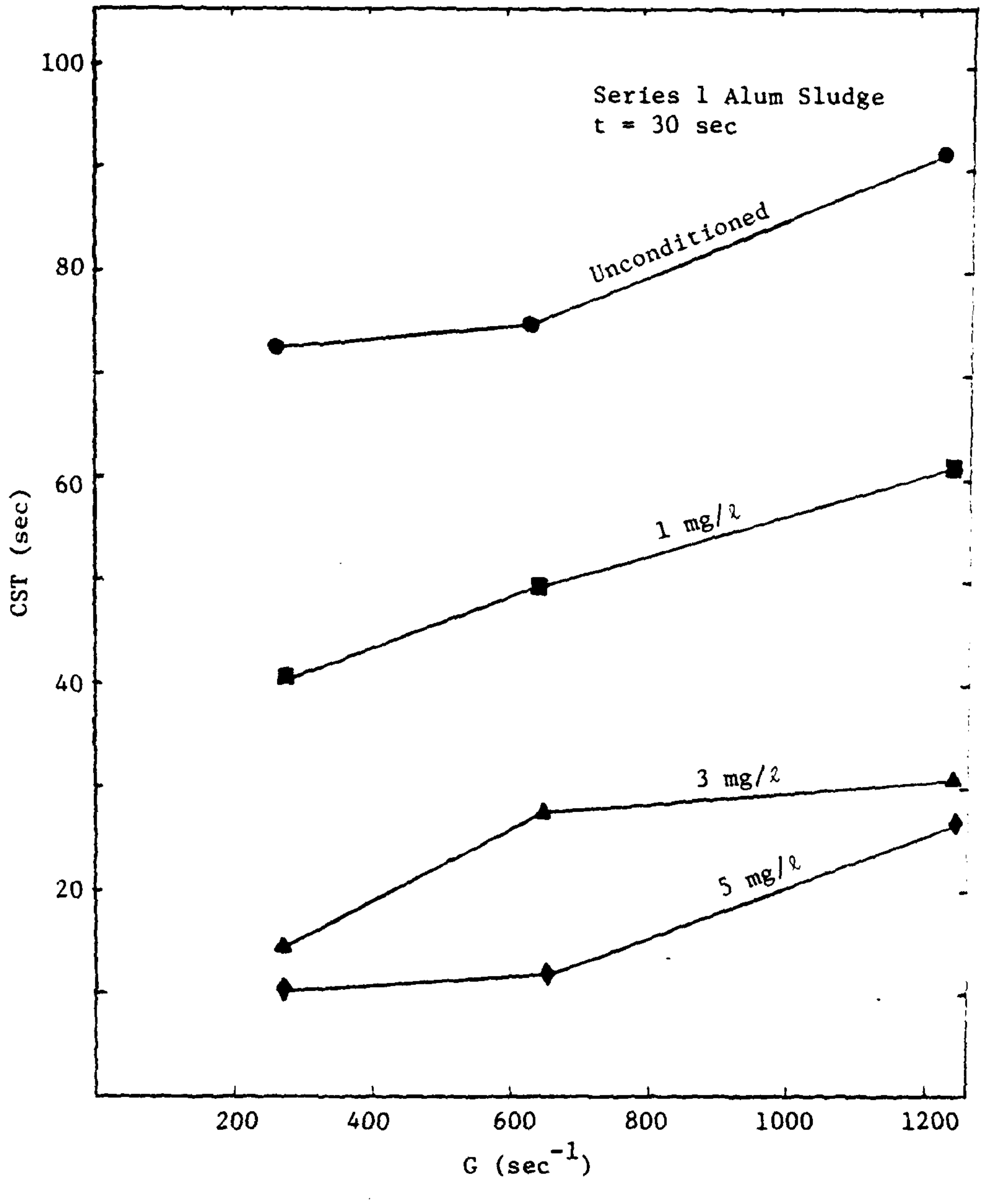

Figure 47. Effect of G value and polymer dose on alum sludge filterability (t = 30 sec).

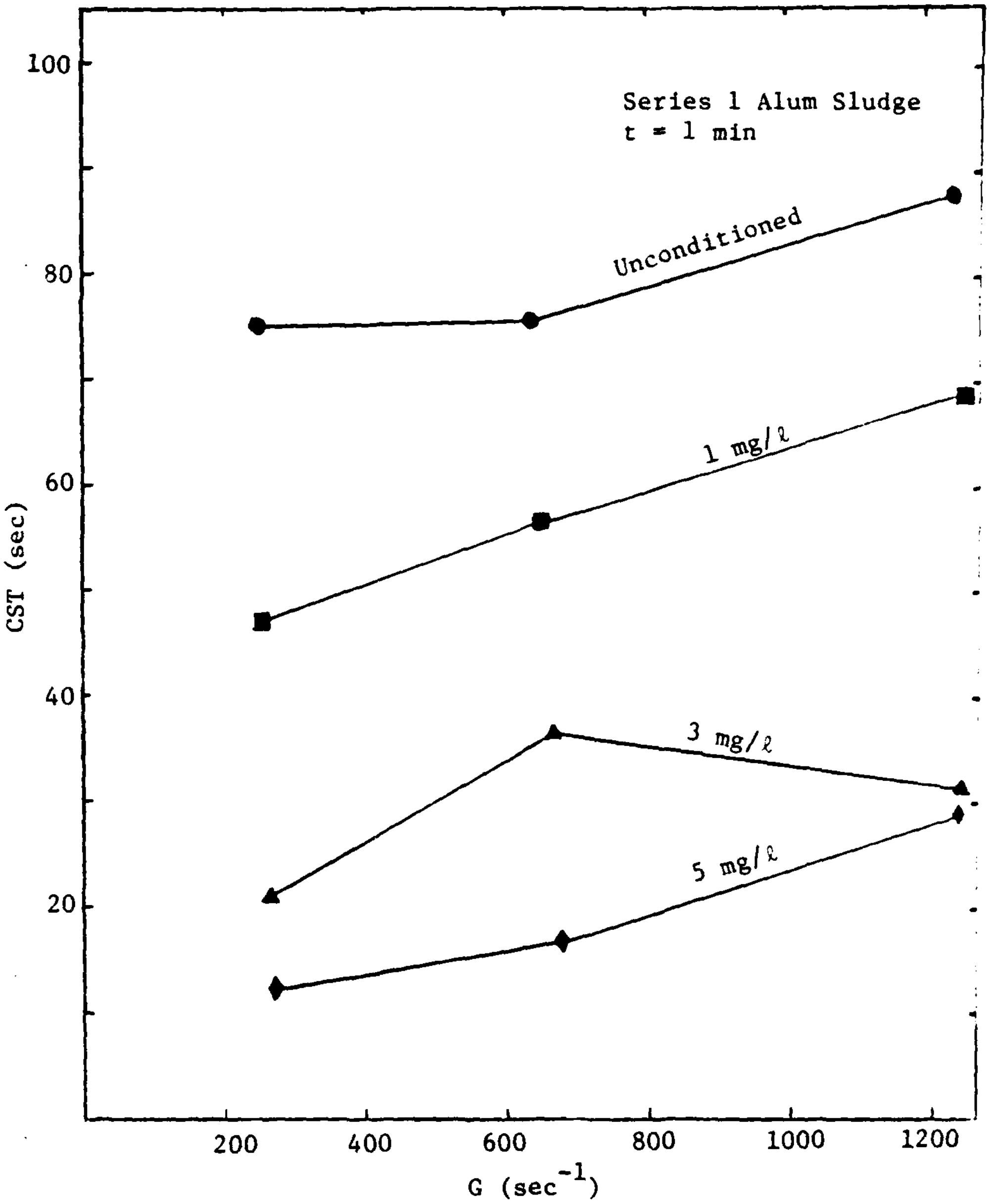

Figure 48. Effect of G value and polymer dose on alum sludge filterability (t = 1 min).

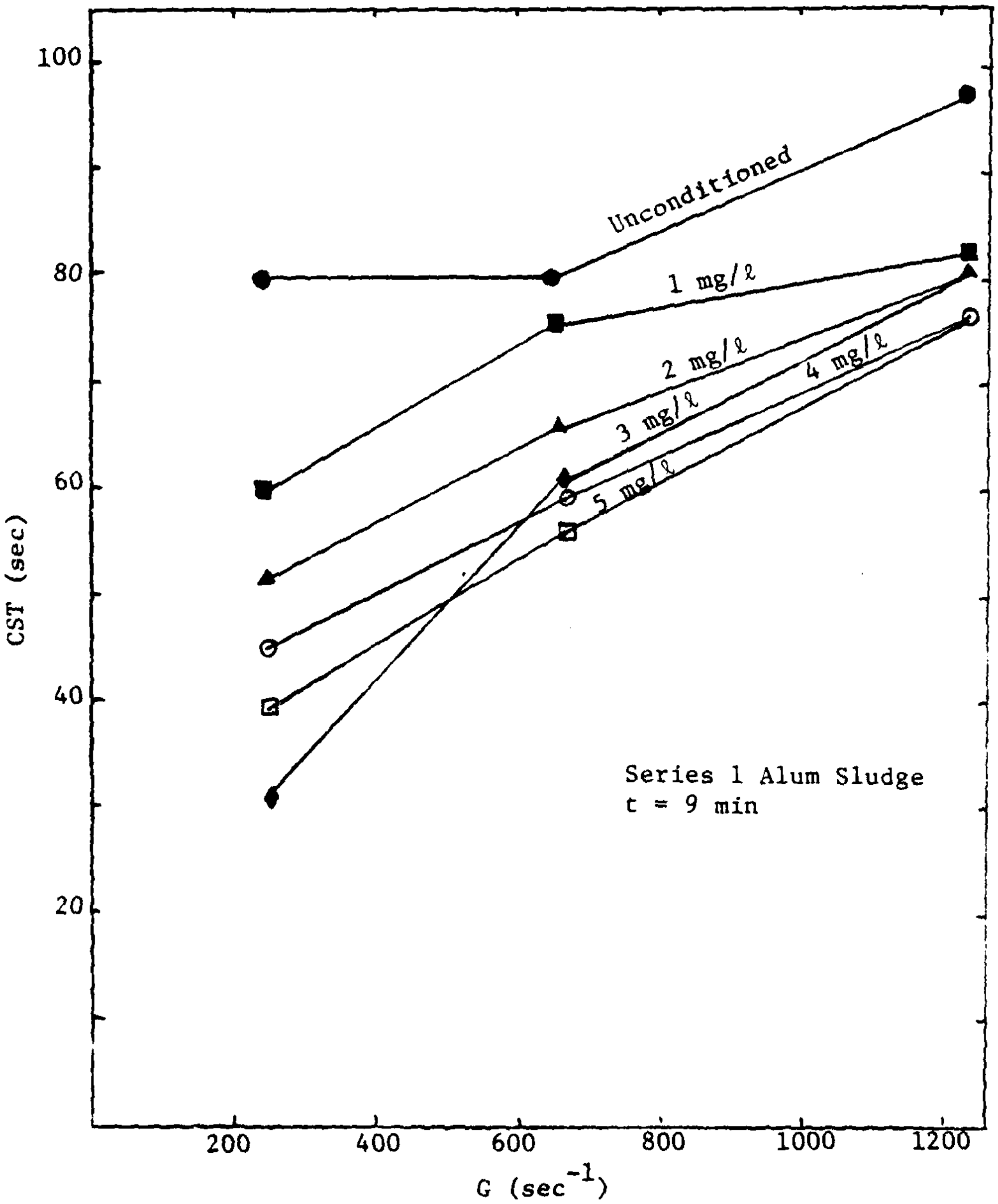

Figure 49. Effect of G value and polymer dose on alum sludge filterability (t = 9 min).

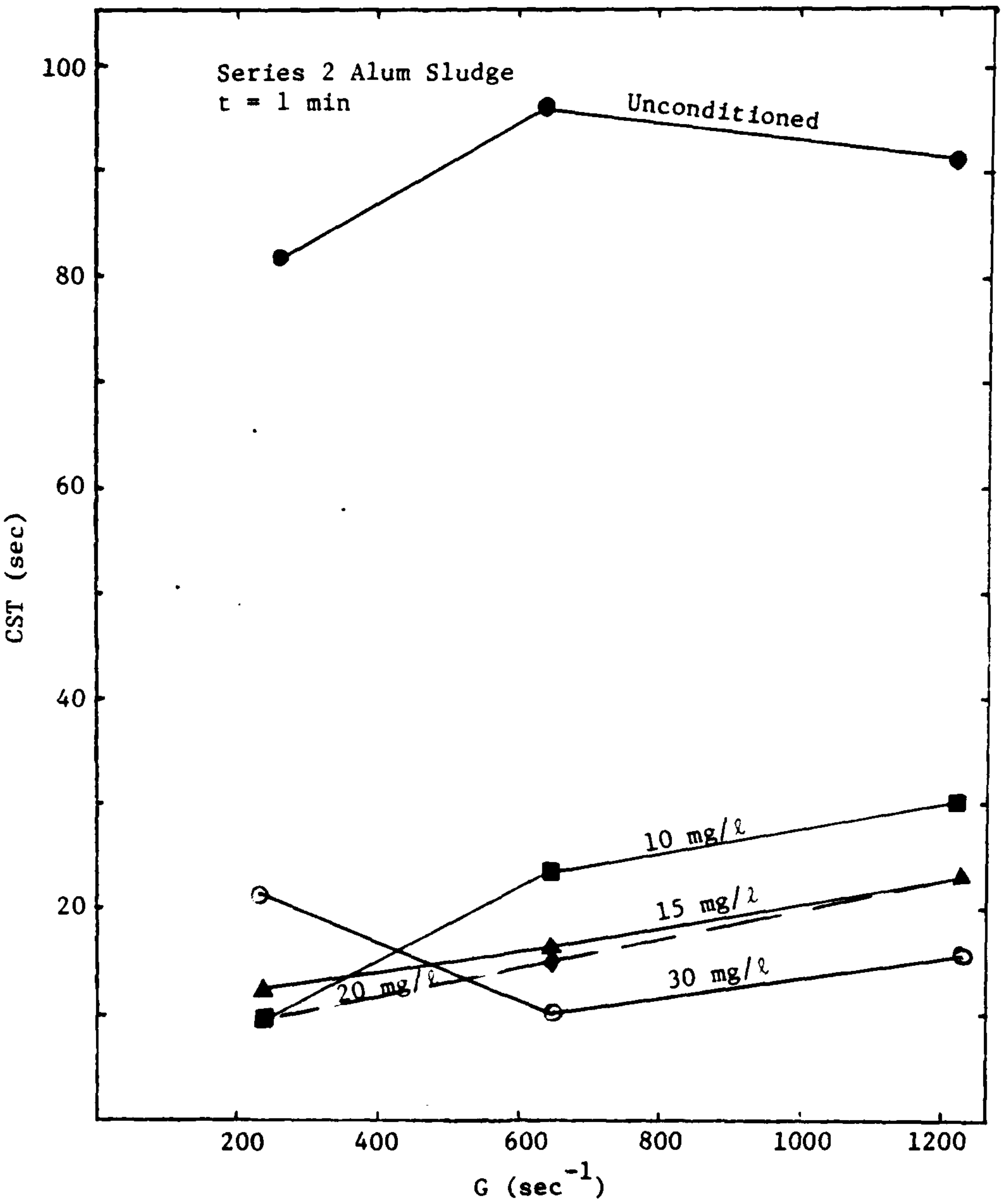

Figure 50. Effect of G value and polymer dose on alum sludge filterability (t = 1 min).

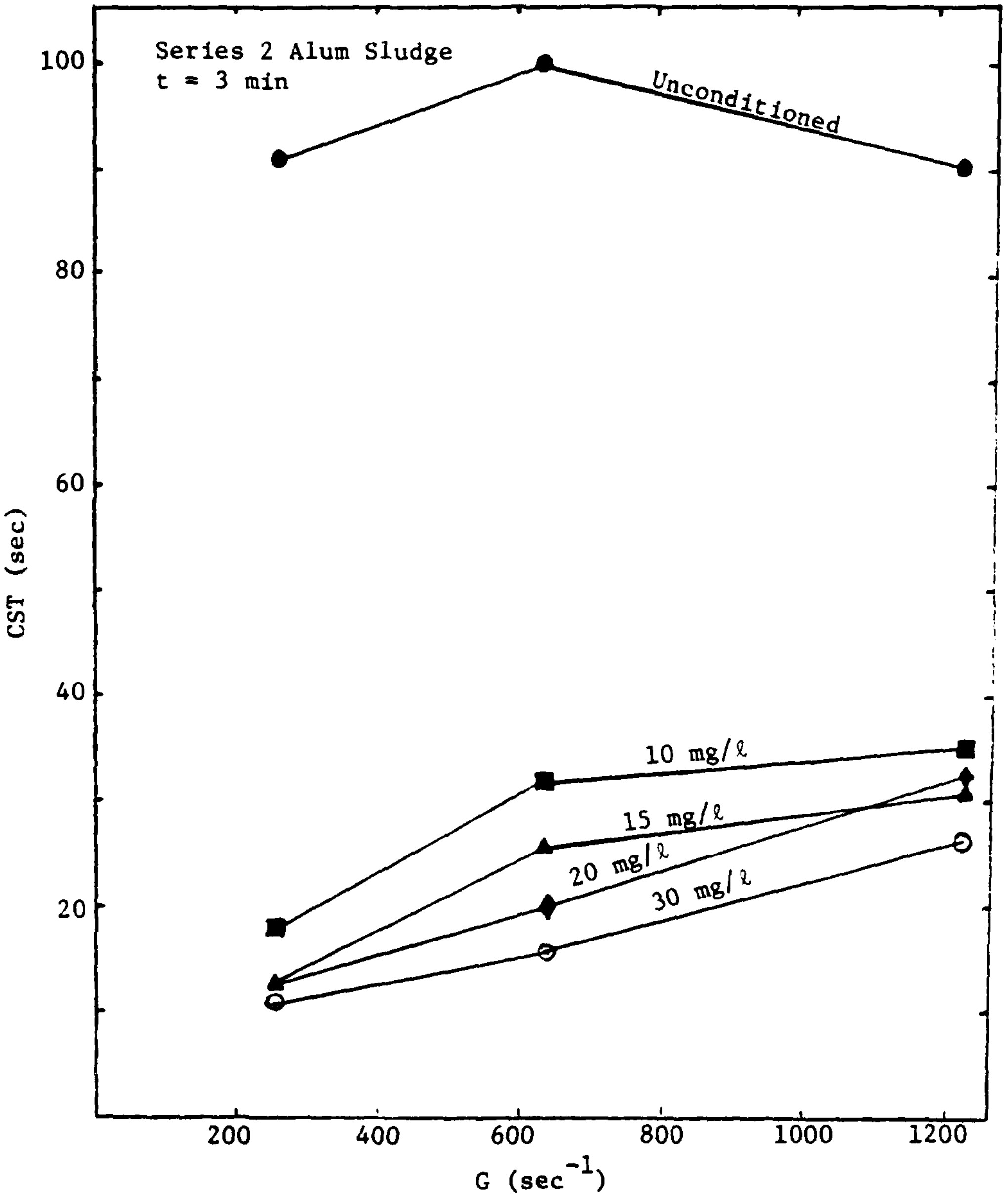

Figure 51. Effect of G value and polymer dose on alum sludge filterability (t = 3 min).

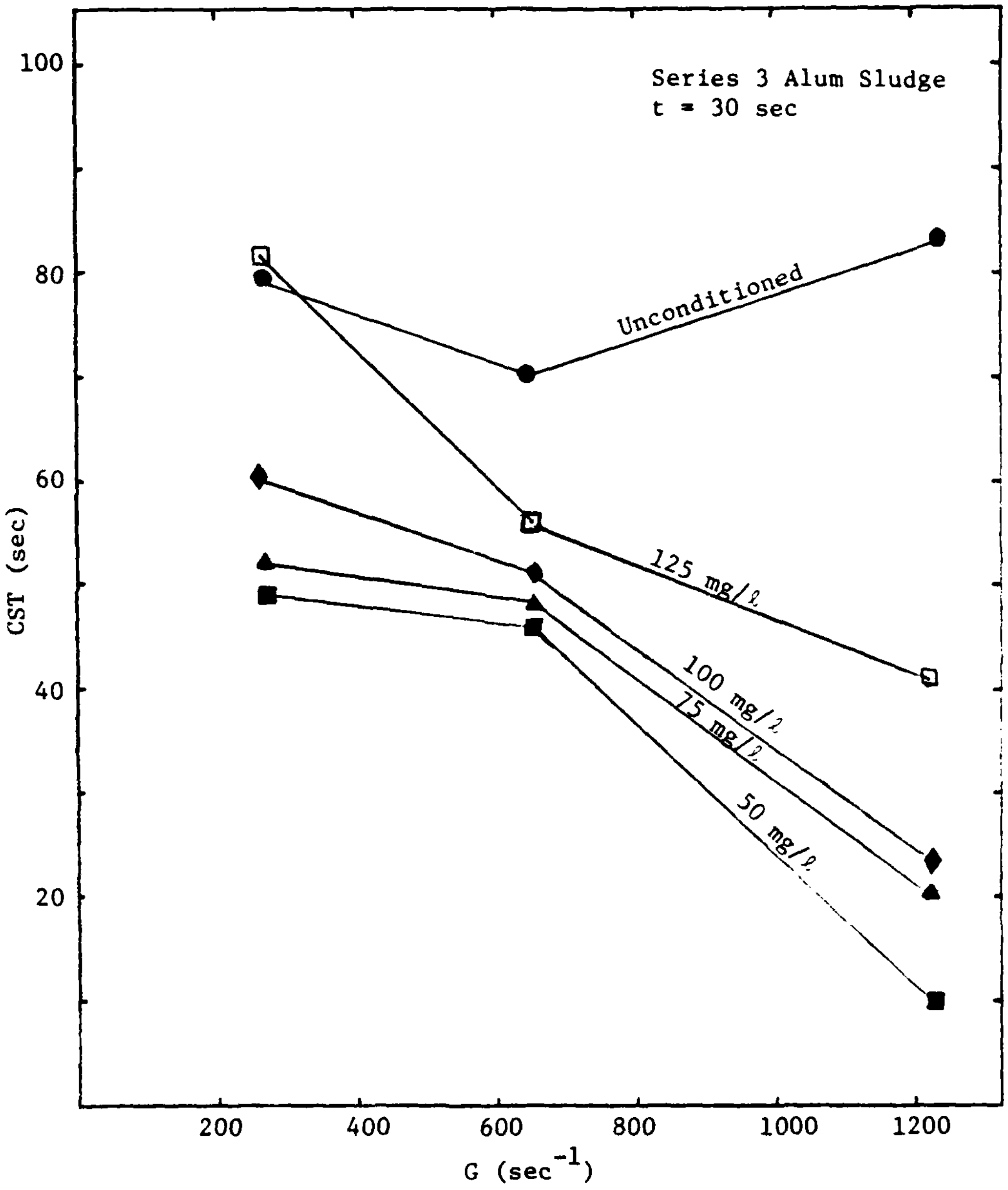

Figure 52. Effect of G value and polymer dose on alum sludge filterability (t = 30 sec).

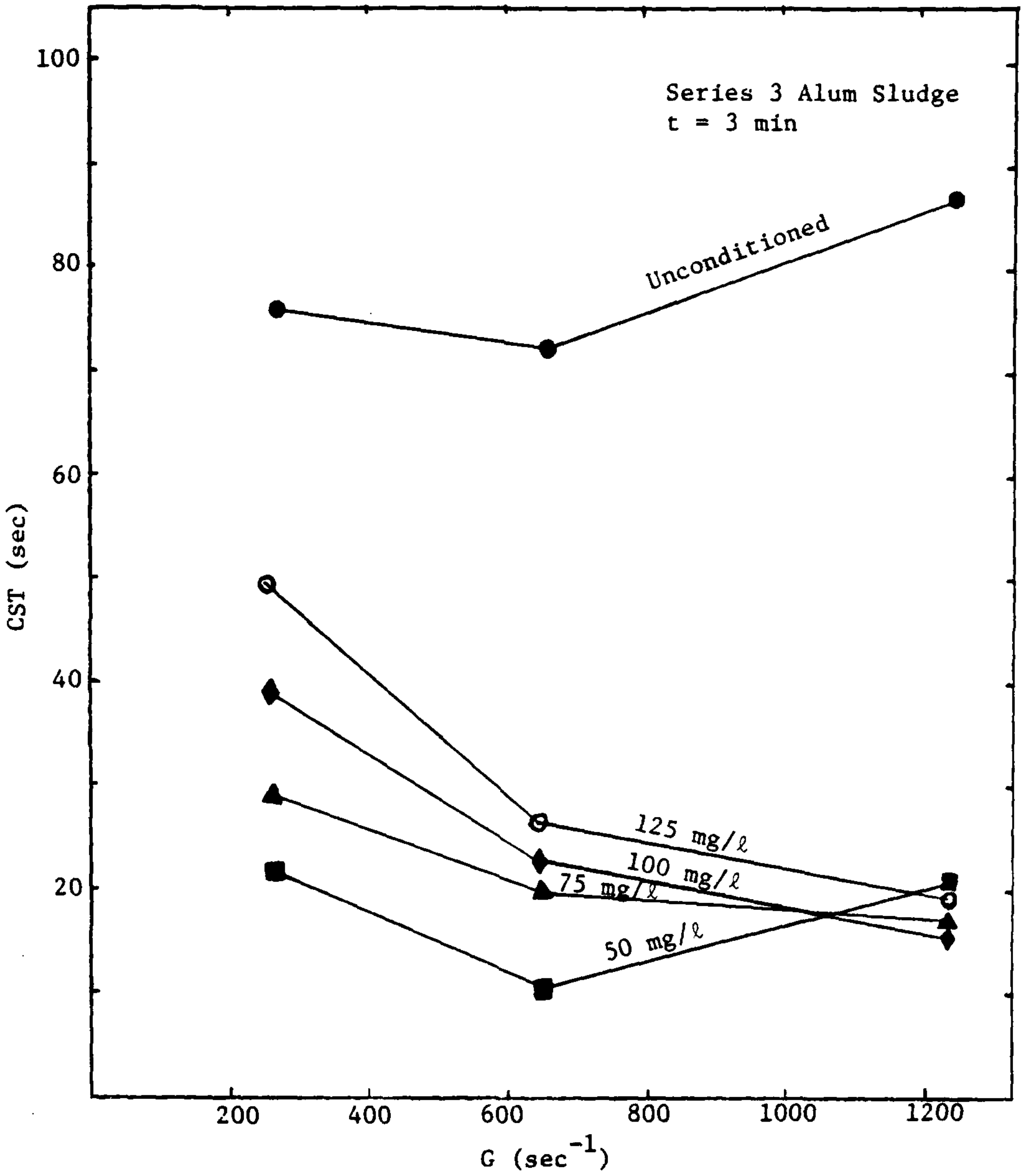

Figure 53. Effect of G value and polymer dose on alum sludge filterability (t = 3 min).

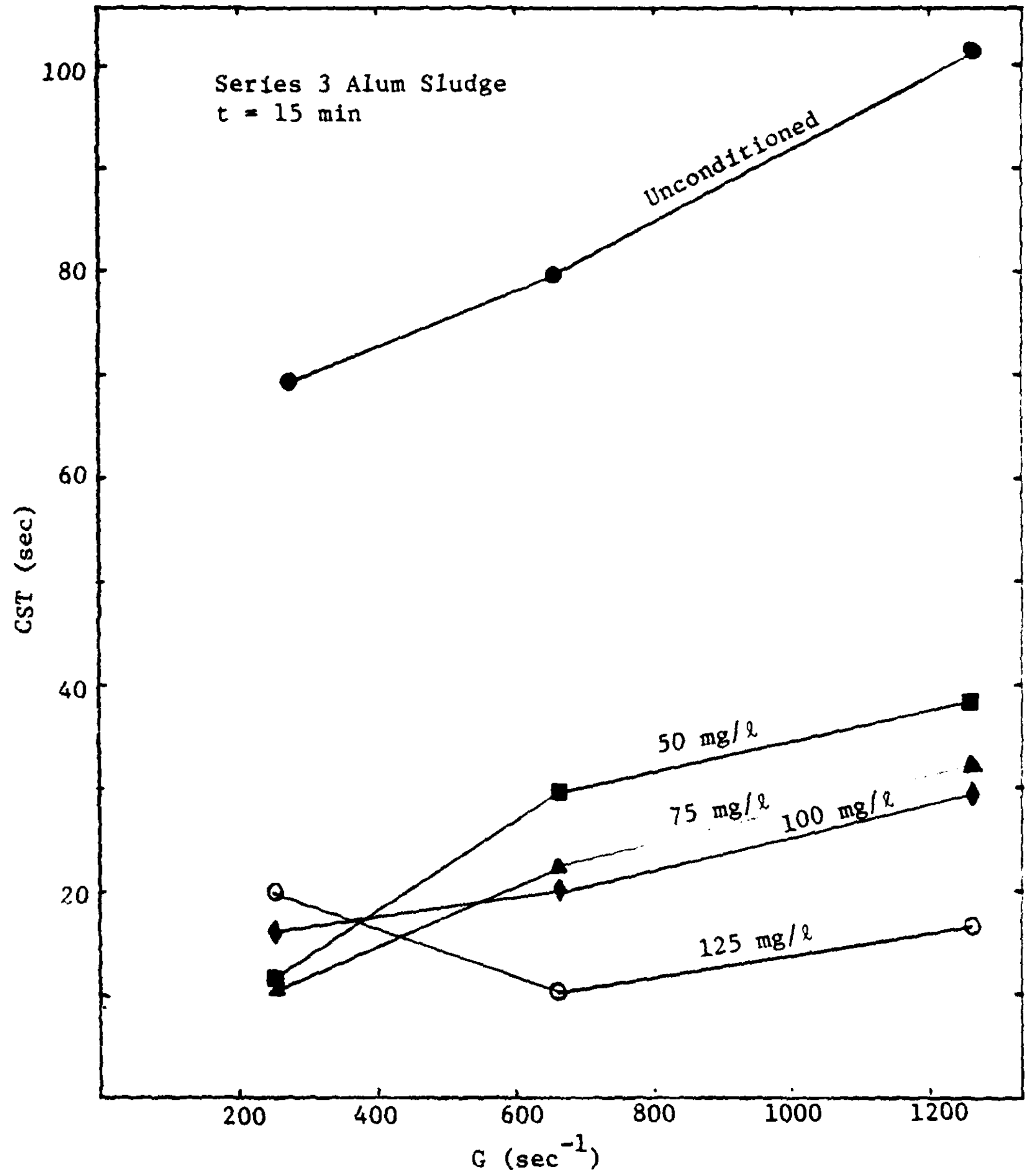

Figure 54. Effect of G value and polymer dose on alum sludge filterability (t = 15 min).

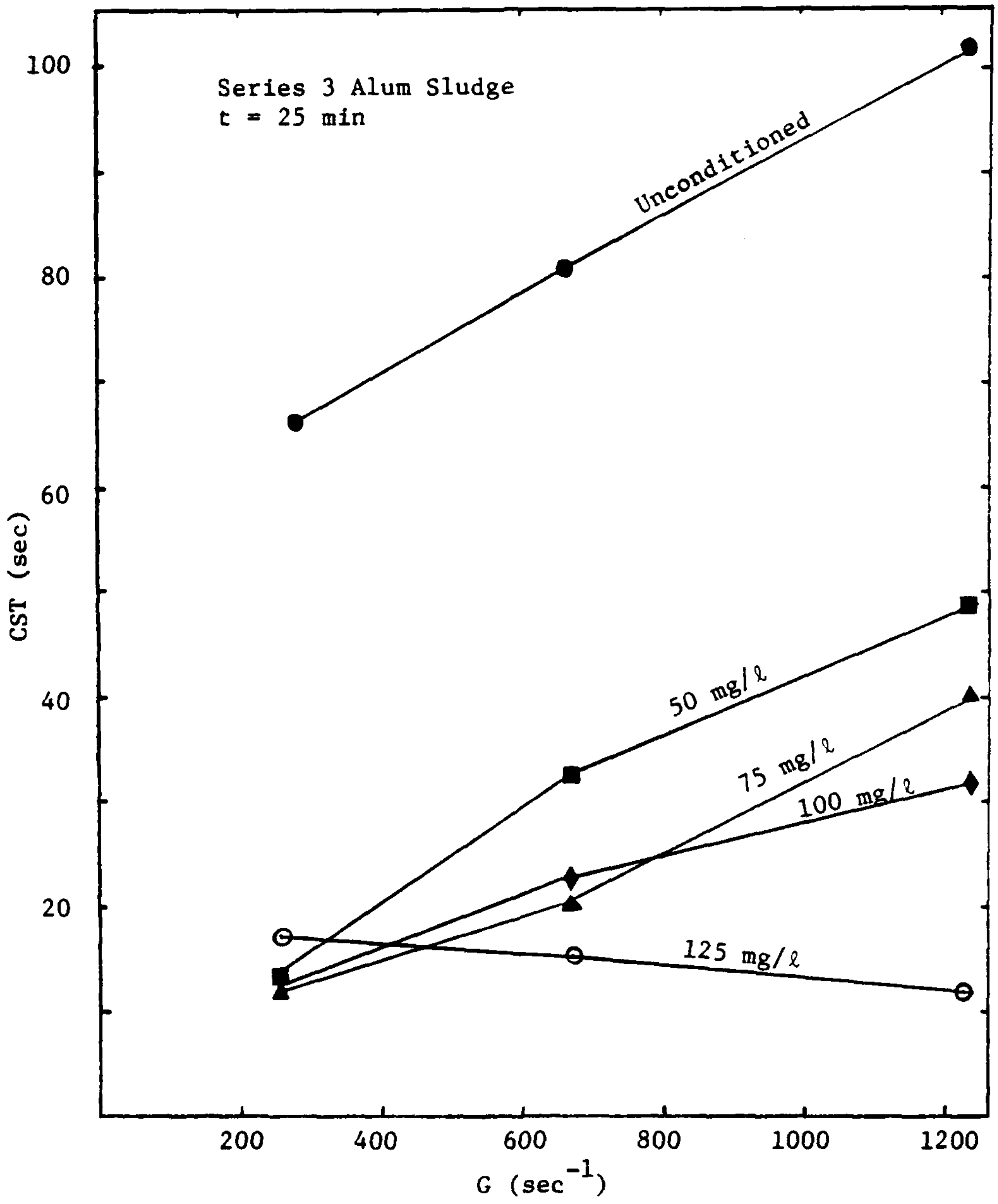

Figure 55. Effect of G value and polymer dose on alum sludge filterability (t = 25 min).

VIII. VITA

Christopher Paul Werle was born on November 3, 1949 in Newport, Rhode Island. He graduated from Woodbridge Senior High School, Woodbridge, Virginia, in June, 1967. He entered Virginia State College in September 1967, and earned a Bachelor of Science degree in Mathematics in May, 1971. He entered Virginia Polytechnic Institute and State University in September 1982 to pursue a Master of Science degree in Environmental Science and Engineering. He is currently serving on active duty with the United States Army, where he holds the rank of Major, Corps of Engineers.

THE EFFECTS OF HIGH-STRESS POLYMER CONDITIONING ON THE FILTERABILITY OF WATER AND WASTEWATER SLUDGES

by

Christopher Paul Werle

(ABSTRACT)

Tests were run on samples of alum, activated, and primary sludges obtained from water and wastewater treatment plants in southwest Virginia. The purpose of the testing was to determine if the sludges could be conditioned with polymers under high stress and still provide good filterability. Tests were conducted using a variable speed mixer with mixing intensities ranging from 246 to 2030 sec^{-1}. Both anionic and cationic high molecular weight polymers were used during conditioning. The capillary suction test (CST) was used to measure relative changes in filterability.

Results indicated that alum, activated, and primary sludges can be conditioned to dewater readily during high-stress processes. In this regard, the standard jar test device was found to be inadequate in predicting polymer dose requirements in cases where high-stress dewatering processes are to be used. The most significant parameters governing high-stress conditioning were found to be polymer dose and total mixing energy input (Gt). It was discovered that once an optimum Gt had been established for a given polymer dose, any combination of G and t within the ideal range of G to t ratios could be used with no appreciable loss in filtering performance.

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