EFFECT OF SOLIDS RETENTION TIME ON ACTIVATED SLUDGE PROPERTIES AND EFFLUENT QUALITY

by

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(ABSTRACT)

The effect of solids retention time (SRT) or sludge age on activated sludge properties and effluent quality was investigated using laboratory scale reactors. It was found that an increase in SRT resulted in an increase in effluent solution polysaccharide, with the < 3,000 daltons (3K) size fraction contributing up to 68 percent of solution polysaccharides. The feed consisted of low molecular weight, readily degradable protein, suggesting that the observed increases in protein and polysaccharide were due to increased release of exocellular microbial product (EMP). The increase in solution protein and polysaccharide resulted in an increase in effluent chemical oxygen demand (COD). The increase in effluent COD was not accompanied by a similar increase in effluent biological oxygen demand (BOD), indicating that the EMPs released were resistant to biodegradation. At the highest SRT, the resistance to shear decreased and the capillary suction time (CST) increased. Following an initial increase, the sludge volume index (SVI) decreased at higher SRT.

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TABLE OF CONTENTS

I. LIST OF FIGURES

II. INTRODUCTION

The activated sludge process relies on a consortium of microorganisms to convert wastewater components into a form that can be easily removed. The microorganisms accomplish this by using the organic matter present in the influent for growth and then flocculating into rapidly settling aggregates. The conversion of organic matter to flocculating cells results in changes in size distribution and properties of components in the wastewater stream. These changes include production of exocellular microbial product (EMP) that may be discharged in the effluent.

It has been known for some time that the effluent organics from activated sludge processes contain a large proportion of material generated by the cell's called EMP, but the reasons for variations in the concentration and composition are not well understood. Also, the characteristics of the solids distribution (particulate, colloidal, and dissolved) have not been thoroughly investigated. Finally, the variations in characteristics associated with operation of the system, especially sludge age (Θ_c), are poorly understood although this subject had been of interest to the profession for many years (Bisogni and Lawrence, 1971; Saunders and Dick, 1981; Zentkovich, 1982).

When considering the reuse of wastewater or the dewatering of biosolids, size distribution and composition resulting from treatment become very important. Generally, under the proper conditions, larger particles are easily removed with small doses of coagulant while small particles are typically removed by sweep floc (i.e., large coagulant doses). More specifically, when the wastewater effluent constituents are high in molecular weight and hydrophobicity, good removal by coagulation can be expected. When the wastewater effluent constituents have low molecular weight and are hydrophilic, poor

removal by coagulation can be expected. The primary extracellular polymers found in wastewater effluent are proteins and polysaccharides. The size distribution of each can influence the cost to dewater or reclaim the wastewater. An understanding of how sludge age impacts particle size distribution of protein, polysaccharide, and chemical oxygen demand (COD) could be useful to persons reclaiming or dewatering activated sludge.

More information about the role of sludge age and its impact on certain extracellular polymers and COD size distribution may provide economic savings in the reclamation and dewatering of activated sludge effluents. The goal of this research was to contribute information pertaining to this topic by :

1. quantification of effluent biological oxygen demand (BOD), COD, protein, polysaccharide and their contribution to given size distributions as related to sludge age.
2. examination of parameters such as capillary suction time (CST), shear strength, and sludge volume index (SVI) as they relate to SRT.
3. provide a mechanism for these changes.

III. LITERATURE REVIEW

The activated sludge process relies on a consortium of microorganisms to convert wastewater components into a form that can be easily removed. There are typically two main objectives to the process. First, the microbes degrade the influent wastewater components utilizing its energy for growth. The degradation is dependent on solids retention time (SRT) and results in a reduction of BOD. The second objective is the flocculation and settling of the microorganisms, resulting in an acceptable quantity of suspended solids in the effluent. EMP production impacts both the before mentioned parameters, and the goal of this literature review to is explain these impacts.

3.1 Nature of EMP in Activated Sludge

Activated sludge flocs contain microorganisms, debris, exocellular polymers, and inorganic cations (Eriksson and Alm, 1991; Bruus *et al*., 1992; Higgins and Novak, 1997a). EMPs are part of a three-dimensional matrix that holds activated sludge flocs together (Novak and Haugan, 1981; Eriksson and Alm, 1991; Bruus *et al*., 1992; Higgins and Novak, 1997a). Keiding and Nielsen (1995) found that these extracellular polymeric substances are loosely bound to the activated sludge floc. Exocellular polymers can originate from degradation products, lysis products, and organic complex formation through condensation reactions (Saunders and Dick, 1981). Urbain *et al*. (1993) further described possible origins as metabolic excretions or the leaking of exocellular constituents.

Some researchers have examined EMP quantities to determine their relationship to growth state. For example, Andreadakis (1993) citing Kristensen *et al*. (1992) and Haung *et al*. (1985) stated that after a certain point, increasing the SRT will decrease the biomass active fraction. A decreasing active fraction can result from a buildup of non-degradable biomass debris, EMPs, and influent material resistant to degradation. Saunders and Dick (1981) found one source of EMP to be the large amount of lysis that occurs at high SRTs. Eriksson and Alm (1991) found that readily extractable exocellular polymer amounts were higher with increasing SRT.

Effluent EMPs can also be influent substrate that was not adequately degraded. Saunders and Dick (1981) stated that the assumption made by Daigger and Grady (1977) that all organic matter in the effluent was the result of extracellular microbial product formed during degradation was perhaps correct for wastewaters containing easily degradable substrate, but it may not be the case for treating wastewaters with complex substrate. For example, Confer and Logan (1997b) found that material resistant to degradation, in their high molecular weight protein degradation study, was probably hydrolyzed influent fragments produced during degradation. Since protein and polysaccharide are major components of domestic wastewater (Metcalf and Eddy, 1991), the size of the molecules to be degraded is important to effluent quality and treatment efficiency. Furthermore, Haldane and Logan (1994) stated that the recalcitrant nature of polysaccharides is due to the large amount of enzymes required for their degradation.

3.2 EMP Concentrations in Activated Sludge

EMP extraction typically yields proteins, polysaccharides, and nucleic acids (Barber and Veenstra, 1986; Eriksson and Alm, 1991; Urbain *et al*., 1993; Jorand *et al*., 1995). Many researchers have found polysaccharides to have the highest concentration of the EMPs measured (Pavoni *et al*., 1972; Horan and Eccles, 1986), while other researchers have found protein to be the largest contributor to EMPs (Vallom and McLoughlin, 1984; Higgins and Novak 1997c). In EMP extraction studies many researchers have used different methods, and consequently the results may not reflect bound EMP quantities. For example, Novak and Haugan (1981) showed that the method of extraction by Pavoni *et al*. (1972) was inadequate to remove polymer associated with activated sludge flocs. Furthermore, they found that the centrifugation method produced results that were not significantly different from simply allowing the sludge to settle and testing the supernatant. As a result, careful attention should be paid to the extraction method when comparing results.

Some researchers have found a connection between the production of EMPs and the SRT of the activated sludge. Andreadakis (1993) encountered an increasing sludge polysaccharide content at higher SRT, but at the highest SRT found decreasing sludge polysaccharide content. This was explained by citing Postgate and Hunter (1962), Pavoni *et al*. (1972), Gaudy *et al*. (1971), Yang and Gaudy (1974), and Yang and Chen (1977) in saying that the reduction is due to acclimation to substrate conditions and production of enzymes able to hydrolyze the EMP. To further the idea of the need for many enzymes to degrade polysaccharides, Haldane and Logan (1994) found 54 percent of accumulated polysaccharides during the degradation of a large molecular weight protein by pure culture

to be small fragments (less than 10,000 daltons). An accumulation of polysaccharide material with increasing SRT was noted by Bisogni and Lawrence (1971), but the SRTs in their research were not as high as those of Andreadakis (1993). In an aerobic digestion study, Murthy and Novak (in press) also found a release of polysaccharide material. Furthermore, at these high SRTs a large amount of lysis occurs, thus contributing to the pool of EMPs in solution.

3.3 EMP Role in Settling, Dewatering, Bioflocculation, and Shear

When settling becomes a problem in activated sludge plants, the result is usually a discharge of solids in the effluent. Research indicates that with endogenous growth the production of EMP increases (Bisogni and Lawrence, 1971; Pavoni *et al*., 1972; Saunders and Dick, 1981), and some researchers have indicated that these relatively high SRTs are associated with improved settling characteristics (Bisogni and Lawrence, 1971; Pavoni *et al*., 1972; Saunders and Dick, 1981; Vallom and McLoughlin, 1984). Many of these same researchers have further associated this improvement in settling characteristics with the increase in EMP production. However, Urbain *et al*. (1993) found that relatively high concentrations of protein, polysaccharide, and DNA resulted in a worsening of settling characteristics as measured by SVI.

Much research has been dedicated to finding out which EMP plays the most important role in bioflocculation, and the results are varied. Bruus *et al*. (1992) and Wahlberg *et al*. (1992) suggested that polysaccharides were most important to flocculation, while others have indicated that protein is more important to flocculation (Barber and Veenstra, 1986; Eriksson and Alm, 1991; Urbain *et al*., 1993; Jorand *et al*.,

1995; Higgins and Novak, 1997c). Higgins and Novak (1997c) suggested that the protein, lectin, is important in the flocculation of microbial cells and used enzymes to show that deflocculation occurred to a greater extent when extracellular proteins were degraded but not when extracellular polysaccharides were degraded.

Conditioning sludge with polymer, Novak et al. (1977) and Novak and Haugan (1980) found that excess available negative biocolloid sites in the bulk solution and in the flocs resulted in an increase in polymer demand. Furthermore, they found the polymer demand is primarily impacted by soluble anionic biocolliods and of less importance is the demand of the floc particles. As previously mentioned, flocculation is believed to occur in the endogenous growth phase when EMP production is believed to be at its maximum. Therefore, a high degree of flocculation would require less polymer for conditioning. In contrast, a low SRT where growth is dispersed would require more polymer conditioning.

A floc that is held together by a loosely bound matrix will be less resistant to shear than a floc that is more dense. Eriksson and Alm (1991) showed that flocs from relatively long SRTs were more dense than flocs from relatively short SRTs. The preceding information suggests that the flocs from longer SRTs are more resistant to shearing forces. Higgins and Novak (1997a) found that over time, flocs could be strengthened by the addition of calcium and magnesium to the feed of an activated sludge.

3.4 Role of Cations in Flocculation

The cation bridging model describes how cations aid in flocculation. In the model, flocculation is accomplished by the cations bridging negative sites on exocellular EMP

(Bruus *et al*., 1992; Urbain *et al*., 1993; Higgins and Novak 1997b). Busch and Stumm (1968) suggested that divalent cations help complex bacteria to EMP. Eriksson and Alm (1991) and Bruus *et al*. (1992) found that when calcium was removed from the floc, smaller particles appeared and turbidity increased, thus indicating the relative importance of calcium to the floc matrix. Bruus *et al*. (1992) further stated that of all the calcium in the system, half is associated with EMPs. When Keiding and Nielsen (1995) removed calcium from activated sludge samples, they found an increase in dissolved EMP in solution. Urbain *et al*. (1993) cited Belcourt *et al*. (1974) and Eriksson and Alm (1991) in stating that calcium and magnesium have been shown to be involved in the chemical structure of flocs. More specifically, Higgins and Novak (1997a) reported that the addition of both calcium and magnesium improved the floc strength, sludge settling, and sludge dewatering properties.

3.5 COD and BOD Reduction of Influent Wastewater

One of the most important parameters in the treatment of wastewater is the SRT. According to Kinetic theory, the higher the SRT, the greater the removal of BOD. However, BOD is not a good indicator of increases in recalcitrant extracellular byproducts that accompany endogenous growth. A better indicator of increases in recalcitrant byproducts is the COD. Bisogni and Lawrence (1971) showed an increase in soluble effluent COD at highest SRTs; this increase could be explained by a buildup of recalcitrant cellular byproduct.

3.6 Effluent Size Distribution

In order for microorganisms to utilize substrate, it must first be of the appropriate size for passing across the cell membrane. This process typically involves the reduction of substrate size by enzymatic activity where enzymes synthesized within the cells hydrolyze sorbed molecules (Levine *et al*., 1985; Confer and Logan 1997a). Polypeptides and polysaccharides greater than 1000 daltons must be broken down by enzymatic activity before they can be assimilated by cells (Confer and Logan 1997a,b).

In a degradation study of large molecular weight proteins, Confer and Logan (1997a) showed that in pure culture, an accumulation of 2,000–10,000 daltons effluent proteins occurred. When a more diverse culture (activated sludge) was used, the accumulation of this size fraction of protein did not occur. A similar situation occurred in their polysaccharide degradation experiment (Confer and Logan, 1997b). In pure cultures 54 percent of polysaccharides accumulated were less than 1000 daltons and in diverse culture only 17 percent of the polysaccharides were in the same size fraction when large molecular weight polysaccharides were being degraded.

Manka and Rebhun (1982) found that 61 percent of the dissolved organic matter in a domestic secondary effluent was greater than 20,000 daltons. Saunders and Dick (1981) used COD to characterize their reactor effluents. They reported concentration of high molecular weight (100,000 daltons–0.45 ?) fraction of extracellular slime compounds decreased as SRT increased. Low molecular weight (5,000–100,000 daltons) compound concentration initially decreased, but increased until at the highest SRT (19.8 days) it represented almost all the 0.45 ? COD.

IV. EFFECT OF SOLIDS RETENTION TIME ON ACTIVATED SLUDGE PROPERTIES AND EFFLUENT QUALITY

Gary P. Phillips, Sudhir N. Murthy, and John T. Novak

ABSTRACT: The effect of solids retention time (SRT) or sludge age on activated sludge properties and effluent quality was investigated using laboratory scale reactors. It was found that an increase in SRT resulted in an increase in effluent solution polysaccharide, with the < 3,000 daltons (3K) size fraction contributing up to 68 percent of solution polysaccharides. The feed consisted of low molecular weight, readily degradable protein, suggesting that the observed increases in protein and polysaccharide were due to increased release of exocellular microbial product (EMP). The increase in solution protein and polysaccharide resulted in an increase in effluent chemical oxygen demand (COD). The increase in effluent COD was not accompanied by a similar increase in effluent biological oxygen demand (BOD), indicating that the EMPs released were resistant to biodegradation. At the highest SRT, the resistance to shear decreased and the capillary suction time (CST) increased. Following an initial increase, the sludge volume index (SVI) decreased at higher SRT.

KEYWORDS: Solids retention time, activated sludge, effluent, COD, BOD, protein, polysaccharide, biopolymer, exocellular microbial product, settling

The activated sludge process relies on a consortium of microorganisms to convert wastewater components into a form that can be easily removed. The conversion of organic matter to flocculating cells results in changes in size distribution and properties of

components in the effluent. Industrial wastewaters treated by the activated sludge process are characterized by limited amounts of proteins and polysaccharides in the influent, but considerable concentrations of these EMPs appear in the effluent stream (Murthy and Novak, 1998). Due to the strictly industrial origin of these wastewaters and lack of EMP in the influent, it is easy to identify that the effluent EMP is generated by the treatment process. However, municipal wastewaters typically consist of large amounts of protein and polysaccharide (Metcalf and Eddy, 1991) so it is not a simple matter to determine the source of effluent EMP.

Activated sludge flocs contain microorganisms, debris, exocellular polymers, and inorganic cations (Eriksson and Alm, 1991; Bruus *et al*., 1992; Higgins and Novak, 1997a). EMP or exocellular polymers are part of a three-dimensional matrix that holds activated sludge flocs together (Novak and Haugan, 1981; Eriksson and Alm, 1991; Bruus *et al*., 1992; Higgins and Novak, 1997a). Exocellular polymers may be part of the floc or exist as colloids in solution (Novak and Haugan, 1980). Exocellular polymers can originate from degradation products, lysis products, and organic complex formation through condensation reactions (Saunders and Dick, 1981). Urbain *et al*. (1993) further described possible origins as metabolic excretions or the leaking of exocellular constituents.

In order for microorganisms to utilize substrate, it must first be the appropriate size for passing across the cell membrane. This process typically involves the reduction of substrate size by enzymatic activity where enzymes synthesized within the cells hydrolyze sorbed molecules into units that can be transported across the cell wall (Levine *et al*., 1985; Confer and Logan 1997a). Polypeptides and polysaccharides greater than 1000

daltons must be broken down by enzymatic activity before they can be assimilated by cells (Confer and Logan 1997a,b). Typically, particle sizes less than 0.1 ? are common and those are likely to be cell fragments, macromolecules, and miscellaneous debris, with protein and polysaccharides being among the major groups of macromolecules (Levine *et al.*, 1985). Saunders and Dick (1981) stated that the assumption made by Daigger and Grady (1977) that all organic matter in the effluent was the result of EMP formed during degradation, was perhaps correct for wastewaters containing easily degradable substrate, but that may not be the case for wastewaters with complex substrate. For example, Confer and Logan (1997b) found that material resistant to degradation, in their high molecular weight protein degradation study, was probably hydrolyzed influent fragments produced during degradation. Furthermore, Haldane and Logan (1994) stated that the recalcitrant nature of polysaccharides is due to the large amount of enzymes required for their degradation. Since protein and polysaccharide are major components of domestic wastewater, the size of the molecules to be degraded is important to effluent quality and treatment efficiency.

In a degradation study of large molecular weight proteins, Confer and Logan (1997a) showed that in pure culture, an accumulation of effluent proteins (2,000–10,000 daltons) occurred. When a more diverse culture (activated sludge) was used, the accumulation of this size fraction of protein did not occur. Similar results occurred in their polysaccharide degradation experiment (Confer and Logan, 1997b). In pure cultures, 54 percent of polysaccharides accumulated were less than 1000 daltons and in diverse culture only 17 percent of the polysaccharides were in the same size fraction when large molecular weight polysaccharides were being degraded. Haldane and Logan (1994) found 54 percent

of polysaccharides accumulated were less than 10,000 daltons, in the degradation of a large molecular weight protein by pure culture.

Manka and Rebhun (1982) found that 61 percent of the dissolved organic matter in a domestic secondary effluent was greater than 20,000 daltons. Saunders and Dick (1981) used COD to characterize their reactor effluents and reported a concentration of high molecular weight (100,000 daltons–0.45 ?) fraction of extracellular slime compounds decreased as SRT increased. Low molecular weight (5,000–100,000 daltons) compound concentration initially decreased, but increased until at the highest SRT (19.8 days) it represented almost all the 0.45 ? COD.

One of the most important parameters in the treatment of wastewater is the SRT. It is common knowledge that the longer the SRT, the greater the removal of BOD. However, BOD is not a good indicator of increases in recalcitrant extracellular byproducts that accompany endogenous growth. A better indicator of increases in recalcitrant byproducts is the COD. Bisogni and Lawrence (1971) showed an increase in soluble effluent COD at highest SRTs, which could be explained by a buildup of recalcitrant cellular byproduct.

Research indicates that with endogenous growth the production of EMP increases (Bisogni and Lawrence, 1971; Pavoni *et al*., 1972; Saunders and Dick, 1981). For example, Andreadakis (1993) citing Kristensen *et al*. (1992) and Haung *et al*. (1985) stated that after a certain point, increasing the SRT will decrease the biomass active fraction. A decreasing active fraction can result from a buildup of non-degradable biomass debris, EMP, and influent material resistant to degradation. Saunders and Dick (1981) found one source of EMP to be the large amount of lysis that occurs at high SRTs.

Eriksson and Alm (1991) reported that readily extractable exocellular polymer amounts were higher with increasing SRT. Andreadakis (1993) encountered increasing sludge polysaccharide content at higher SRT, but at highest SRT found decreasing sludge polysaccharide content. This was explained by citing Postgate and Hunter (1962), Pavoni *et al*. (1972), Gaudy *et al*. (1971), Yang and Gaudy (1974), and Yang and Chen (1977) in saying that the reduction is due to acclimation to substrate conditions and production of enzymes able to hydrolyze the EMP.

Much research has been dedicated to finding out which EMP plays the most important role in bioflocculation, and the results are varied. Bruus *et al*. (1992) and Wahlberg *et al*. (1992) suggested that polysaccharides were the most important to flocculation, while others have indicated that protein is more important to flocculation (Barber and Veenstra, 1986; Eriksson and Alm, 1991; Urbain *et al*., 1993; Jorand *et al*., 1995; Higgins and Novak, 1997c). Higgins and Novak (1997c) suggested that the protein lectin is important in the flocculation of microbial cells and used enzymes to show that deflocculation occurred to a greater extent when exocellular proteins were degraded but not when exocellular polysaccharides were degraded.

A floc that is held together by a loosely bound matrix will be less resistant to shear than a floc that is more dense. Eriksson and Alm (1991) showed that flocs from relatively long SRTs were more dense than flocs from relatively short SRTs. The preceding information suggests that the flocs from longer SRTs are more resistant to shearing forces. Higgins and Novak (1997a) found that over time flocs could be strengthened by the addition of calcium and magnesium to the feed of an activated sludge process.

The cation bridging model describes how cations aid in flocculation. In the model, flocculation is accomplished by the cations bridging negative sites on EMP (Bruus *et al*., 1992; Urbain *et al*., 1993; Higgins and Novak, 1997b). Busch and Stumm (1968) suggested that divalent cations help complex bacteria to EMP. Eriksson and Alm (1991) and Bruus *et al*. (1992) found that when calcium was removed from the floc, smaller particles appeared and turbidity increased, indicating the relative importance of calcium to the floc matrix. Bruus *et al*. (1992) further stated that of all the calcium in the system, half is associated with EMP. When Keiding and Nielsen (1995) removed calcium from activated sludge samples, they found an increase in dissolved EMP in solution. Urbain *et al*. (1993) cited Belcourt *et al*. (1974) and Eriksson and Alm (1991) in stating that calcium and magnesium have been shown to be involved in the chemical structure of flocs. More specifically, Higgins and Novak (1997a) reported that the addition of both calcium and magnesium improved the floc strength, sludge settling, and sludge dewatering properties.

The purpose of this study was to investigate the role of SRT on activated sludge properties and effluent quality. Effluent quality was monitored by measuring the size fractions of protein, polysaccharide, COD, and BOD. Activated sludge properties were determined by measuring mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), CST, optimum polymer dose, shear, and SVI. By examining the preceding parameters, it was hypothesized that SRT impacts the production, release, and degradation of solution EMP. When considering the reuse of wastewater or the dewatering of biosolids, size distribution and composition resulting from treatment become very important. Under proper conditions, larger particles are easily removed with small doses of coagulant while small particles are typically removed by sweep floc (i.e.,

large coagulant doses). More specifically, when the wastewater effluent constituents are high in molecular weight and hydrophobicity, good removal by coagulation can be expected. When the wastewater effluent constituents have low molecular weight and are hydrophilic, poor removal by coagulation can be expected. Predominant EMP found in wastewater effluent are proteins and polysaccharides. Proteins are hydrophobic and polysaccharides are hydrophilic, so the amounts and the size distribution of each can influence the cost to dewater or reclaim the wastewater. Furthermore, biofouling is an important consideration when filtration is used to reclaim wastewater. An understanding of how SRT impacts particle size distribution of protein, polysaccharide, and COD could be useful to persons reclaiming or dewatering activated sludge.

Materials and Methods

Laboratory activated sludge system setup and operation. Experiments were conducted with 10 L continuous-flow, bench-scale reactors, freshly seeded from a municipal wastewater treatment facility. The reactors consisted of a complete mix zone and a settling zone, separated by a slanted baffle. An aeration stone provide both air (approximately 7 mg/L) and mixing to the system. Five reactors were operated to maintain SRTs of 5, 10, 20, 40, and 50 days. The SRT was controlled by compensating for effluent solids in the wastage rate. Steady state was usually achieved in 7–10 days. Steady state values of each parameter are presented as averages. The reactors were operated for two SRTs before sampling and analysis. The reactors were operated with a 2 day hydraulic retention time. The reactors setup is further described by Higgins and Novak (1997a). The influent COD was maintained at 600 mg/L by the addition of 400 mg/L Bactopeptone (protein source) and 200 mg/L acetate, expressed as COD.

Materials. Ca^{2+} and Mg^{2+} were added as calcium acetate, magnesium acetate, and sulfate salts. Potassium was added as a chloride salt. Ammonium phosphate was added to provide additional nitrogen and phosphorus. The influent cation analysis of the feed is presented in Table 1.

Sample preparation. To quantify the smaller size fractions, samples were ultrafiltered at 55 psi through Amicron YM30 and YM3 partly hydrophobic membranes (approximate molecular size 30,000 and 3,000 daltons respectively). Samples were taken from the effluent of laboratory reactors and filtered through a 1.5 ?, 0.45 ?, 30,000 daltons (30K), and 3,000 daltons (3K) filters. The 1.5 ? samples were given the designation of 'total' and no attempt was made to measure larger particles in the effluent. The fractionated samples were analyzed for protein, polysaccharide, BOD, and COD. Acetate and cations were measured from samples filtered through a 0.45 ? filter.

Cation analysis. Sodium, potassium, calcium, and magnesium ions were quantified using a Dionex ion chromatograph with a CS12 column and Dionex 2010I conductivity detector with self-regenerating suppression of the eluent.

COD and BOD analysis. Solution COD was analyzed using Method 5220C of *Standard Methods* (1995) and solution BOD_5 (5-day BOD test) was measured using Method 5210B of *Standard Methods* (1995).

Solids analysis and settling properties. MLSS and MLVSS were analyzed using Method 2540D and 2540E of *Standard Methods* (1995). SVI was analyzed using Method 2710D *Standard Methods* (1995). When filamentous bulking occurred (observed by microscopic and settling data) the biomass was chlorinated until the filaments decreased to an acceptable level.

Acetate analysis. Residual acetate was measured on a Hewlett-Packard 5880 gas chromatograph fitted with a flame ionization detector.

Dewatering. CST was analyzed using method 2710G of *Standard Methods* (1995). Reactor samples were thickened to approximately 2500 mg/L MLSS.

Shear determination. Mixing experiments were performed using the high energy mixer described by Novak and Lynch (1990). Reactor samples were thickened to approximately 2500 mg/L MLSS. A rotational frequency of 3,000 rpm was used resulting in a velocity gradient (G) of approximately 2,500 s^{-1}.

Solution protein and polysaccharide analysis. Solution proteins and polysaccharides samples were analyzed using the Hartee (1972) modification of the Lowry *et al*. (1951) method. Polysaccharides were analyzed using the method of Dubois *et al*. (1956). Protein standards were prepared with bovine serum albumin, and polysaccharide standards were prepared with glucose.

Results and Discussion

Effect of SRT on effluent protein and polysaccharide. The laboratory reactors were operated at SRTs of 5–50 days. The feed was Bactopeptone (400 mg/L as COD) and acetate (200 mg/L as COD). Bactopeptone (protein source) was found to contain

Table 1—Influent cations for the laboratory reactors.

Sodium (mM)	Potassium (mM)	Magnesium (mM)	Calcium (mM)
4.1	0.1	1.1	0.6

protein with 45 percent < 3K and 55 percent was in the 30K–0.45 ? size range. The feed contained no polysaccharides; therefore, all effluent polysaccharide resulted from biomass

generation and release. At all SRTs, the acetate in the effluent was less than 1 mg/L. Figure 1 shows the effect of SRT on the effluent polysaccharide. The effluent polysaccharide increased with increasing SRT. Figure 2 shows the percentage of polysaccharide for each size fraction and its relation to SRT. At all SRTs, the <3K fraction comprised the largest portion (56–68 percent) of the effluent. The other size fractions changed less than 10 percent over the course of the experiment. An increase in polysaccharide with SRT is consistent with previous findings (Bisogni and Lawrence, 1971; Andreadakis, 1993; Murthy and Novak, in press). Furthermore, Murthy and Novak (in press) found that degradation of protein in bioflocs was accompanied by a release of polysaccharide into solution. Figures 3 and 4 show the effect of SRT on the effluent

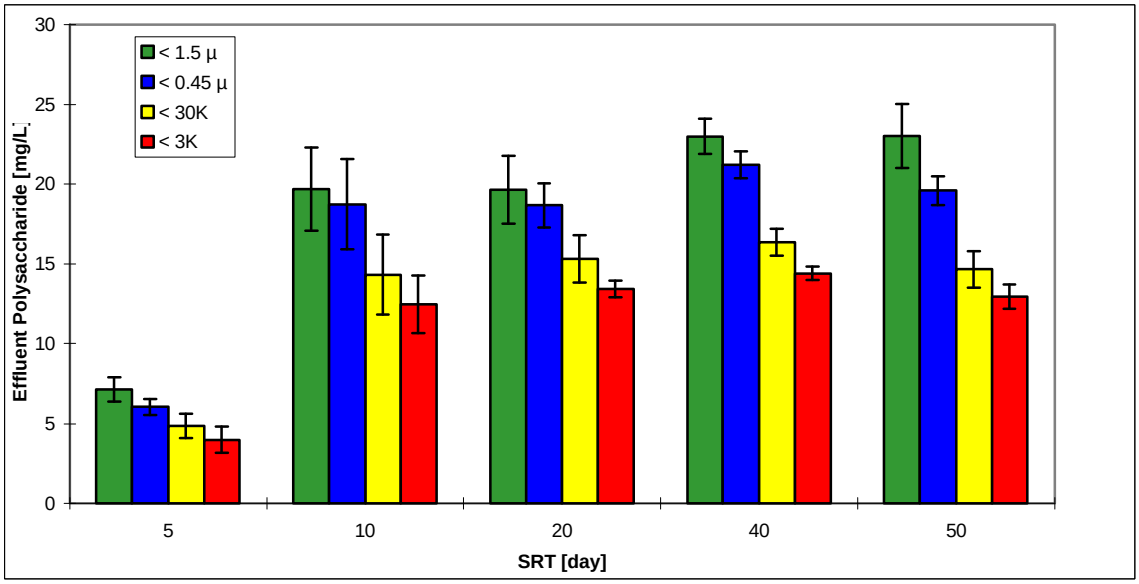


Figure 1—Effect of SRT on effluent polysaccharide.

protein. After the 20 day SRT, the <3K size fraction increased from 26 to 35 percent of the total portion. The 3K–30K size fraction decreased from 25 to 21 percent of the total during the same SRTs. This increase in small fragments and the decrease in larger fragments could be the result of protein being hydrolyzed. The largest increase with SRT,

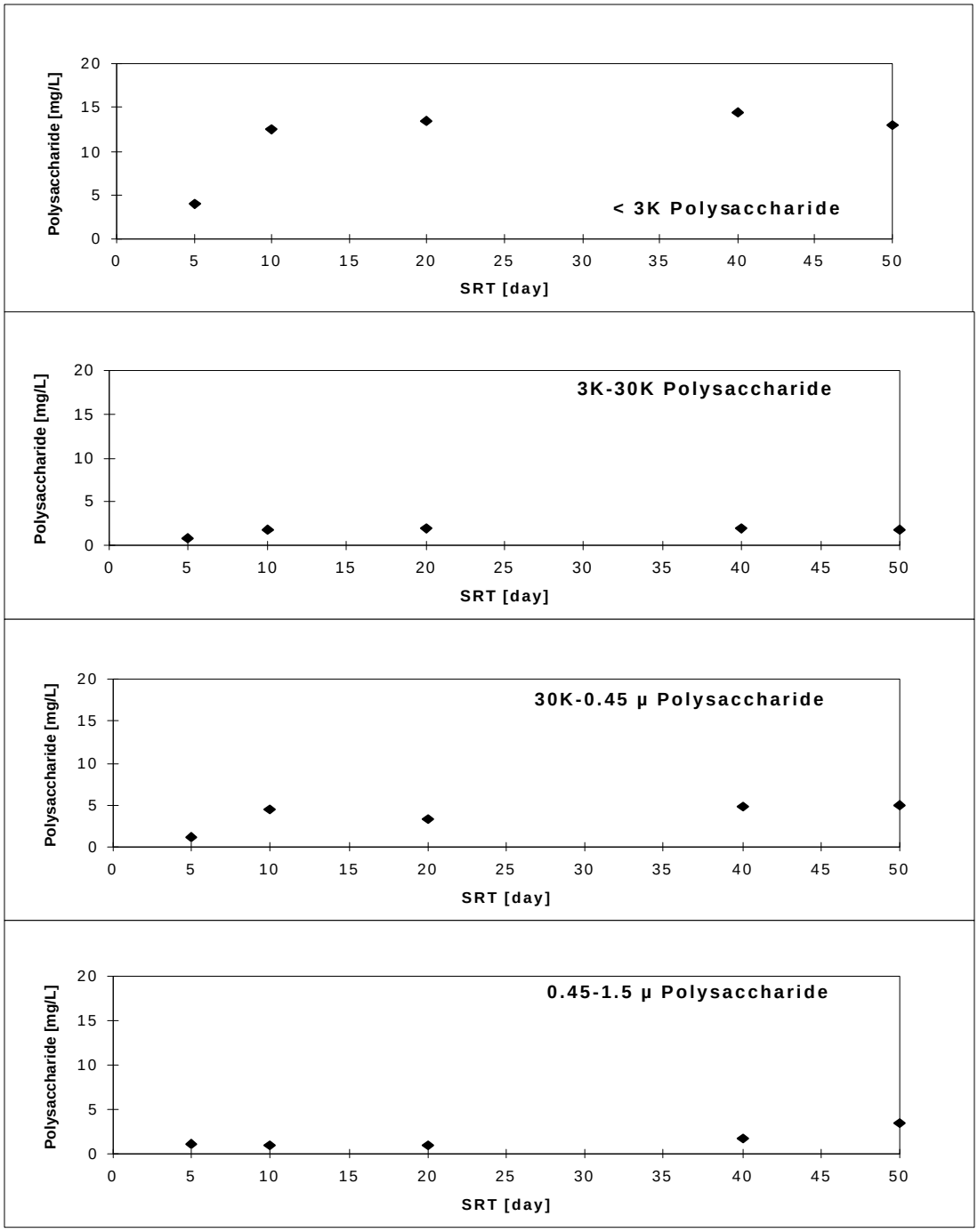


Figure 2—Effect of SRT on effluent size fraction of polysaccharide, as a percent of total (1.5 ?) portion.

after the 10 day SRT, is in the 30K–0.45 ? size fraction. The influent did not contain any proteins in this size range. Therefore, these proteins were most likely released from the activated sludge flocs. At the low SRTs (5 and 10 day), the higher protein levels in the two largest size fractions may result from measurement of individual cells as dispersed growth.

Effect of SRT on effluent COD and BOD. Figure 5 illustrates the effect of SRT on effluent COD and BOD. The effluent COD decreased from the 5 to 10 day SRT and reflects the decrease in effluent protein for the same SRTs. The lowest effluent COD occurred at the 10 day SRT. Starting at the 10 day SRT, there is an increase in effluent COD due to the buildup of recalcitrant organics, especially polysaccharides. Further illustrating the buildup of recalcitrant organics is the fact that the BOD does not

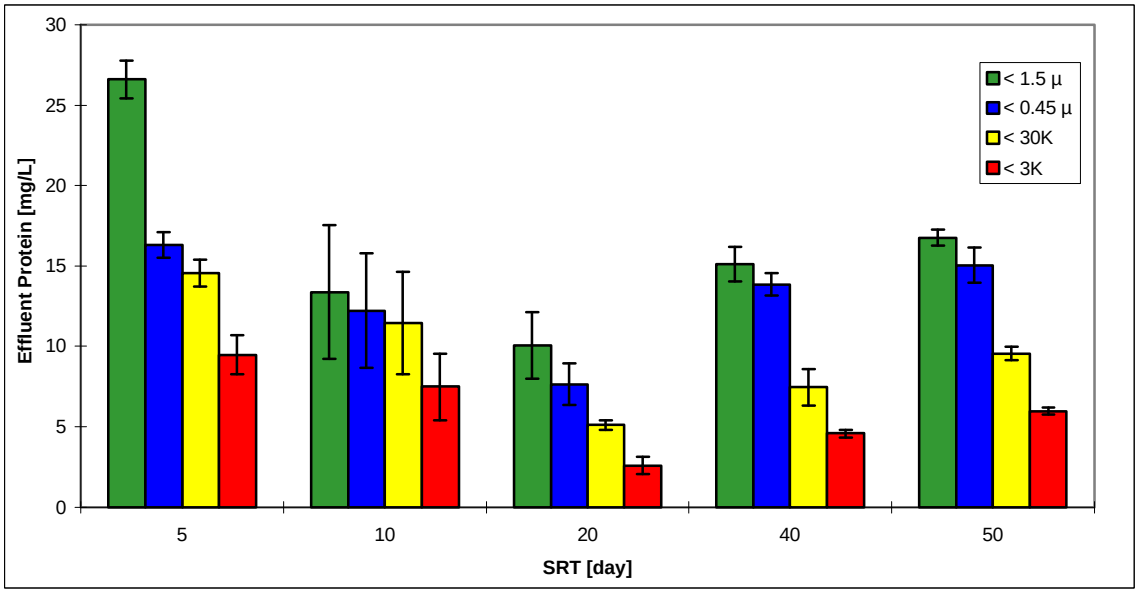


Figure 3—Effect of SRT on effluent protein.

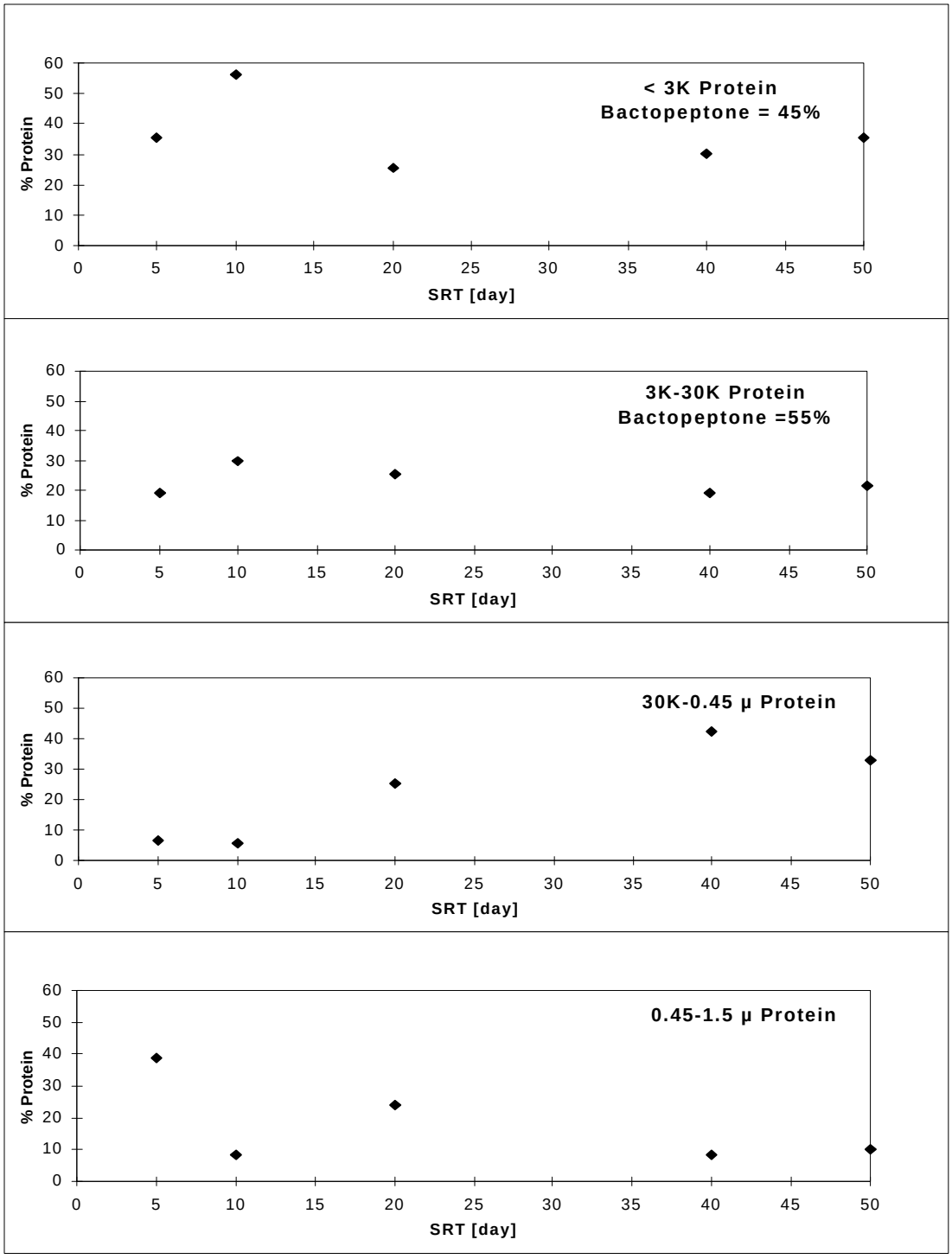
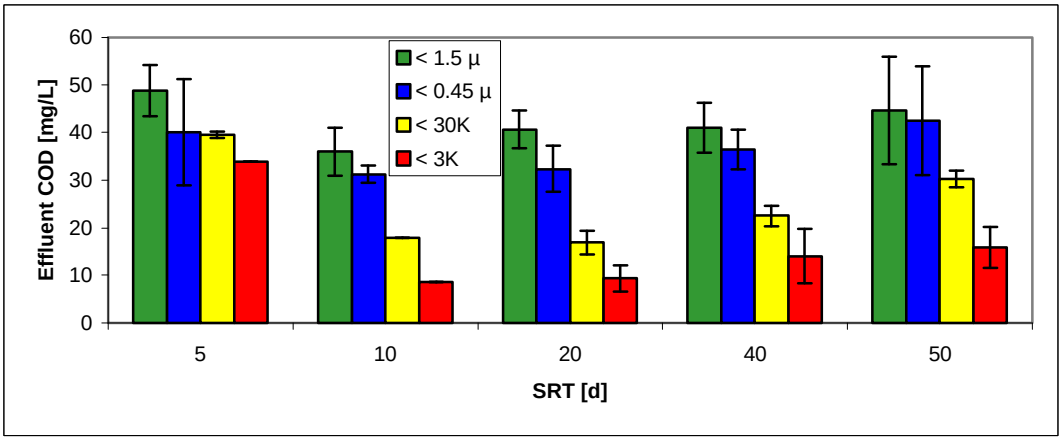
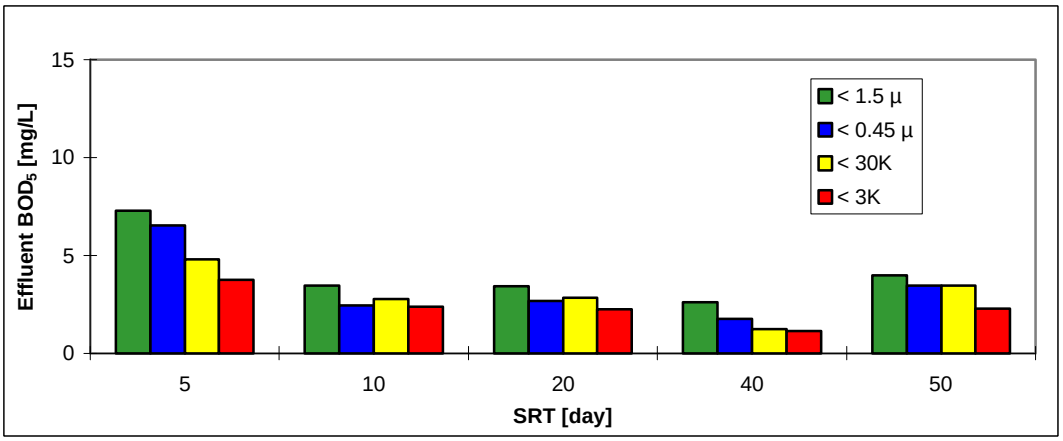


Figure 4—Effect of SRT on effluent protein as percent of total (1.5 ?).





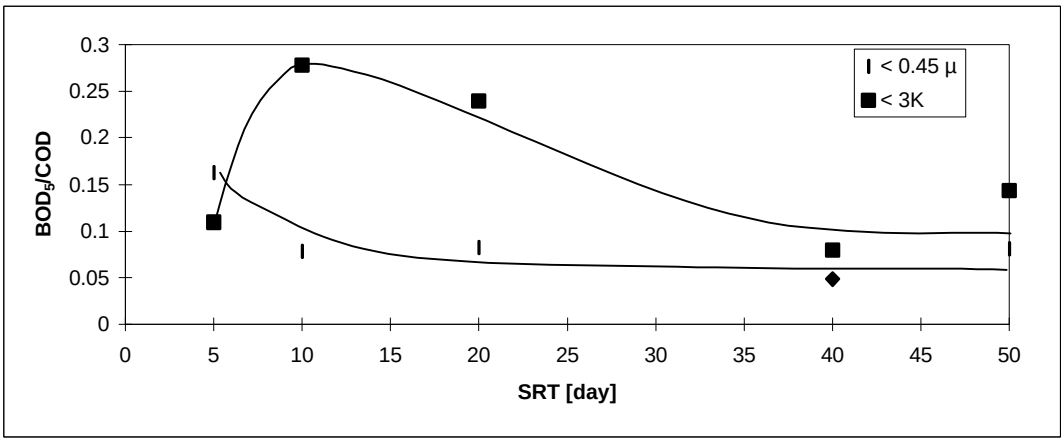


Figure 5—Effect of SRT on effluent COD and BOD.

increase with SRT as does the COD. The BOD_5/COD further illustrates the relationship between recalcitrant and degradable organics in the effluent. Figure 6 shows the change in size fraction of COD as it relates to SRT. Initially 70 percent of the COD is in the smallest

size fraction; this may be the result of residual Bactopeptone. Beginning at the 20 day SRT, the <3K COD increases from 23 to 36 percent of the total COD. This change reflects the increase of protein and polysaccharides in the <3K size fraction. At higher SRTs, there was an increase in effluent COD, polysaccharide, and protein. These increases are believed to be caused by deterioration of the floc. It was expected that the changes in floc properties would be accompanied by changes in dewatering properties.

Shear, CST, and SVI. Sludge properties were also measured over the range of SRTs. These included CST, SVI, and the effect of shear on floc properties (floc strength). Figure 7 shows the relationship between SRT and shear strength. The 40 and 50 day SRT

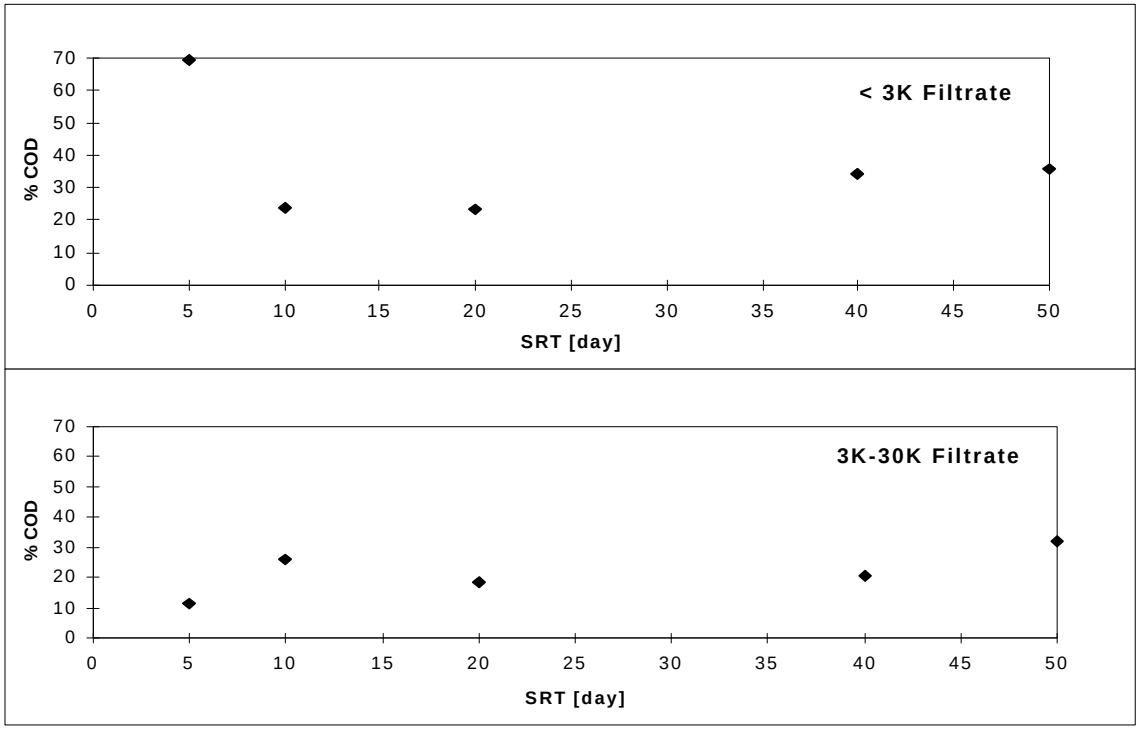


Figure 6—Effect of SRT on size fraction of effluent COD.

were less resistant to shear than those of shorter SRTs. The flocs of the 40 and 50 day

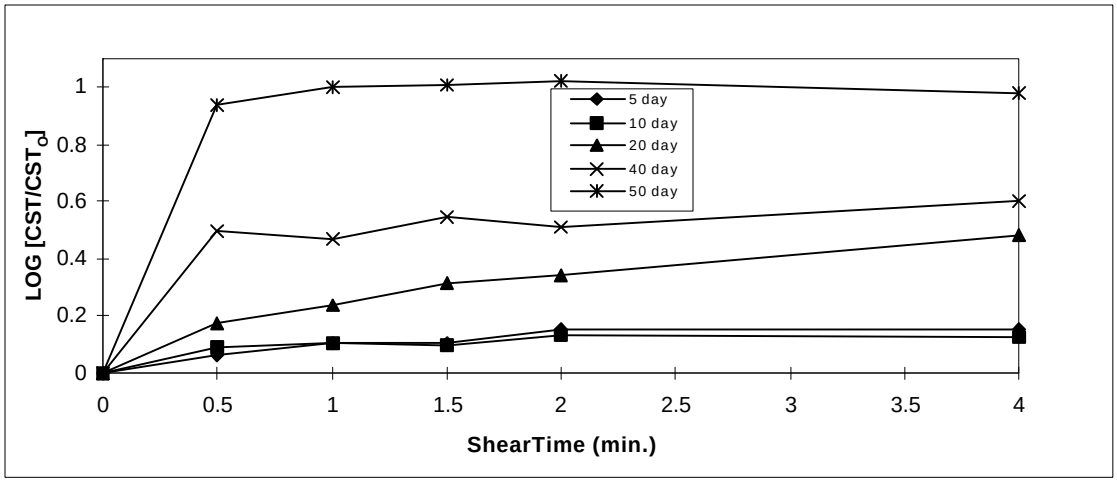


Figure 7—Effect of SRT on shear.

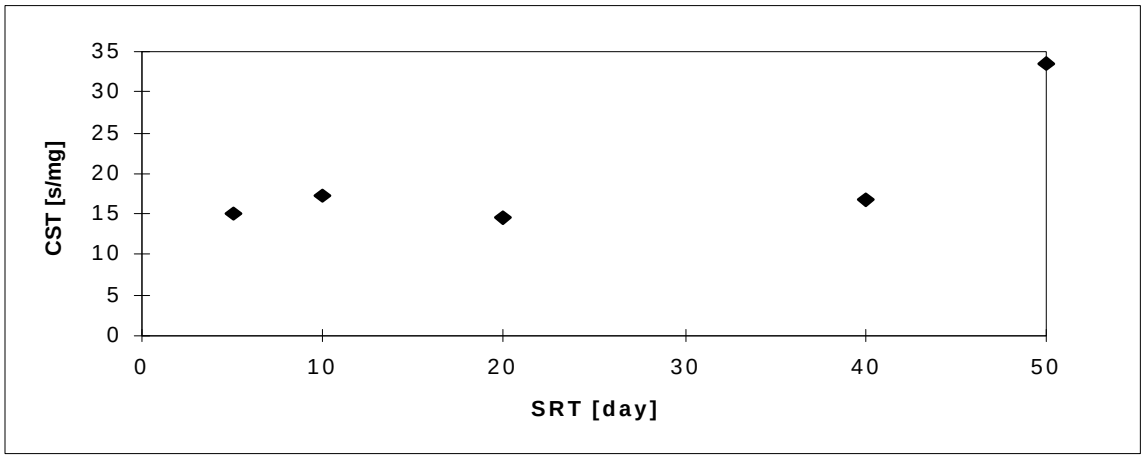


Figure 8—Effect of SRT on CST.

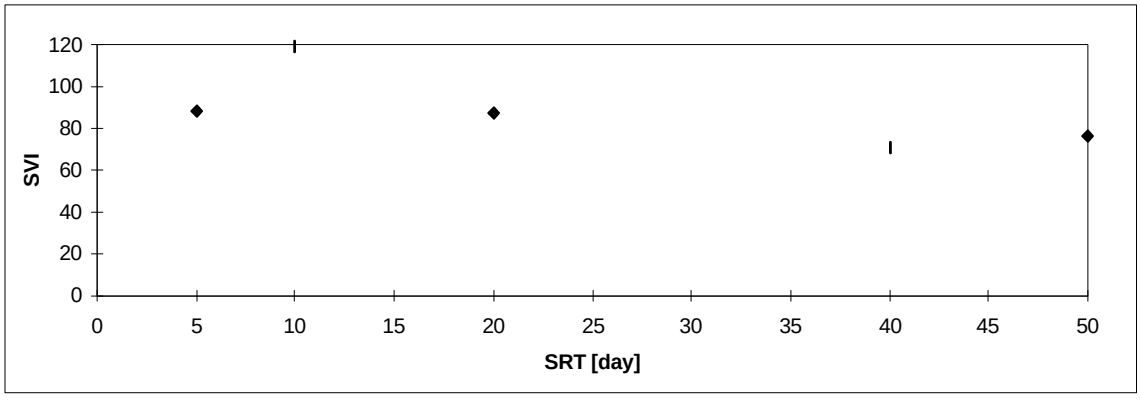


Figure 9—Effect of SRT on SVI.

SRTs were easily broken apart by the shear force. Figure 8 shows the effect of SRT on CST (normalized). The high CST values associated with the two largest SRTs show that the flocs were increasingly composed of many small particles.

Figure 9 shows the relationship between SRT and SVI. The lowest SVI values are associated with the highest SRTs. These low SVI values may be caused by large, well settling flocs. At the highest SRT, the resistance to shear decreased and the CST increased, indicating that the floc matrix and bulk solution were increasingly composed of EMP. Following an initial increase, the SVI decreased at higher SRT.

Interpretation of the data shows a relationship between the activated sludge properties, effluent quality, and SRT. At the 5 and 10 day SRTs the sludge was not easily disrupted by shear force. The relatively high amount of solution protein at these SRTs may be attributed to the presence of Bactopeptone residual and dispersed growth. As the SRTs increase above 10 days (Figure 7), the flocs were more easily disrupted by shear force. The increase in solution protein, polysaccharide, and COD with SRT coincides with a decrease in shear strength of the floc and a decrease in SVI. This suggests that as the SRT increases, the EMP becomes more loosely bound in the floc matrix, resulting in improved settling but also a greater release of EMP into solution. At high SRT, the increase in percent of the > 3K size fraction of protein may be the result of the microbial consortium's ability to hydrolyze protein and use it for substrate. These changes in activated sludge properties and effluent size distribution in relation to SRT can be monitored and subsequently manipulated to enhance amenability to further treatment.

Summary and Conclusions

An increase in SRT resulted in an increase in effluent solution polysaccharide, with the < 3,000 daltons (3K) size fraction contributing up to 68 percent. The feed consisted of readily degradable protein, indicating that the increase in protein and polysaccharide is due to increased release of EMP. The increase in solution protein and polysaccharide resulted in an increase in effluent COD. The increase in effluent COD was not accompanied by a similar increase in effluent BOD, indicating that the EMPs released were resistant to biodegradation. At the highest SRT, the resistance to shear (floc strength) decreased and the CST increased, indicating that the floc matrix was breaking apart. Following an initial increase, the SVI decreased at higher SRT.

These findings are of interest for many reasons. First, when considering reuse of wastewater, characterization of effluent quality by BOD_5 is inadequate. Of more importance is the relationship between SRT and effluent COD size distribution. The effluent COD size distribution is a better indicator of the buildup of recalcitrant organics such as polysaccharides. If the effluent of an activated sludge is to be reclaimed, careful consideration of its organic constituents and their size distribution must be made. These factors will impact the coagulation dose requirements and the formation of disinfection by-products. In high SRT membrane processes, a buildup of protein and polysaccharides can negatively impact treatment efficiency and subsequently operational costs. Previous experiments (Murthy and Novak, in press) have shown that divalent cation addition can aid in the reduction of effluent COD, protein, and polysaccharide in aerobic digestion. The concentration of divalent cations used in this study were chosen based on the work of Murthy and Novak (in press), and it is expected that a lower divalent cation concentration or a higher monovalent concentration would cause a more dramatic decline in effluent

quality and activated sludge properties. This experiment further indicates that careful selection of SRT can produce biosolids that are more easily dewatered. The decrease in resistance to shear with SRT is important to high SRT processes because dewatering costs can be reduced if the flocs are not fractured during handling.

Acknowledgments:

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V. ENGINEERING SIGNIFICANCE

The purpose of this study is to investigate the role of SRT on activated sludge properties and effluent quality. Treatment processes change the size distribution and composition of the organic material in wastewater. When considering the reuse of wastewater or the dewatering of biosolids, size distribution and composition resulting from treatment become very important. By quantifying of the organic material in wastewater effluents in terms of size distribution and studying the conversions that occur during treatment, it is possible to determine if SRT impacts further treatment processes.

Under proper conditions, larger particles are easily removed with small doses of coagulant while small particles are typically removed by sweep floc (i.e., large coagulant doses). More specifically, when the wastewater effluent constituents are high in molecular weight and hydrophobicity, good removal by coagulation can be expected. When the wastewater effluent constituents have low molecular weight and are hydrophilic, poor removal by coagulation can be expected. Predominant EMP found in wastewater effluent are proteins and polysaccharides. The size distribution of each can influence the cost to dewater or reclaim the wastewater. An understanding of how SRT impacts particle size distribution of protein, polysaccharide, and COD could be useful to persons reclaiming or dewatering activated sludge.

These findings are of interest for many reasons. First, when considering reuse of wastewater, characterization of effluent quality by BOD_5 is inadequate. Of more importance is the relationship between SRT and effluent COD size distribution. The effluent COD size distribution is a better indicator of the buildup of recalcitrant organics such as polysaccharides. If the effluent of an activated sludge is to be reclaimed, careful

consideration of its organic constituents and their size distribution must be made. These factors will impact the coagulation dose requirements and the formation of disinfection by-products. In high SRT membrane processes, a buildup of protein and polysaccharides can negatively impact treatment efficiency and subsequently operational costs. Previous experiments (Murthy and Novak, in press) have shown that adding divalent cation can aid in the reduction of effluent COD, protein, and polysaccharide in aerobic digestion. This experiment also indicates that careful selection of SRT can produce biosolids that are more easily dewatered. The decrease in resistance to shear with SRT is important to high SRT processes because dewatering costs can be reduced if the flocs are not broken apart. Murthy and Novak (in press) have further indicated the addition of divalent cations improves dewatering of aerobically digested sludge.

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VII. APPENDIX

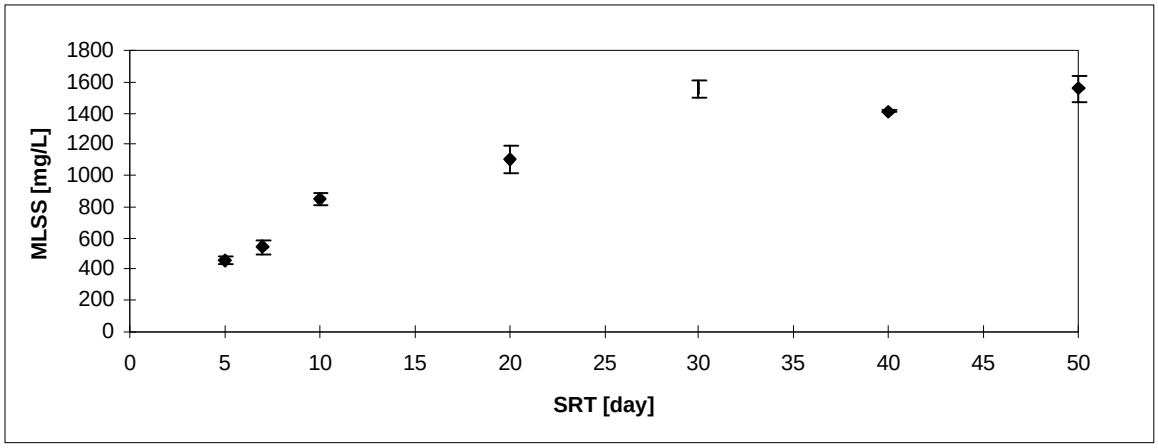

Figure 1—Effect of SRT on MLSS.

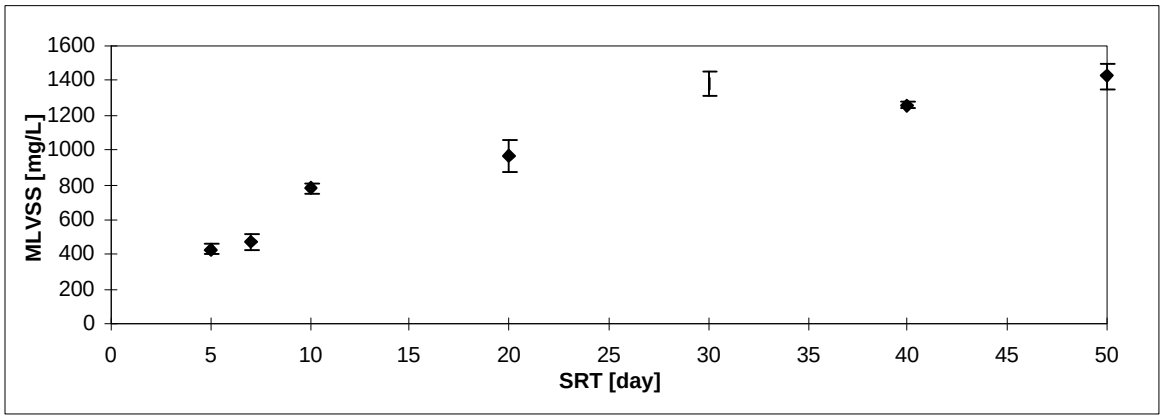

Figure 2—Effect of SRT on MLVSS.

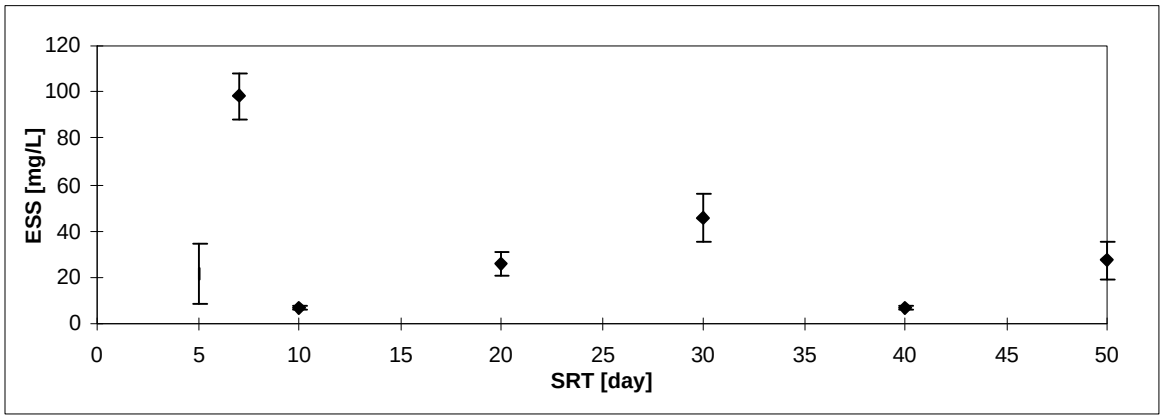

Figure 3—Effect of SRT on effluent suspended solids (ESS).

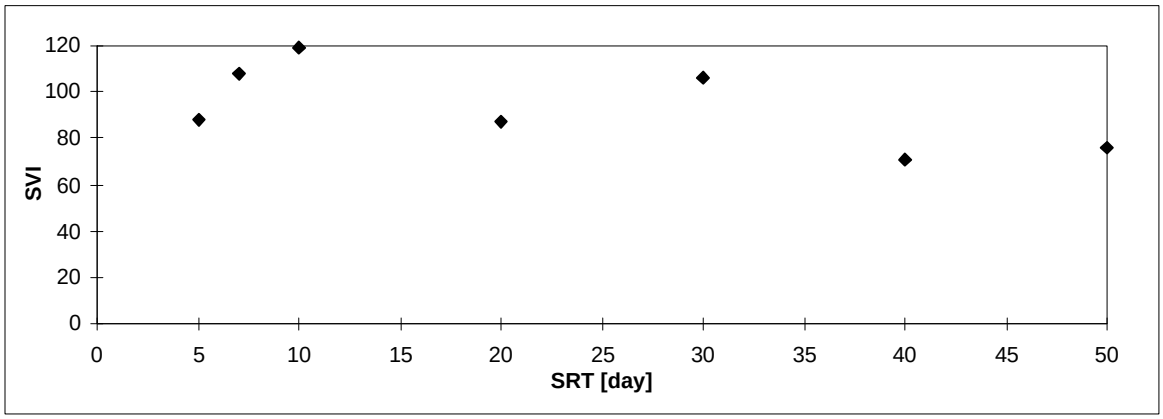

Figure 4—Effect of SRT on SVI.

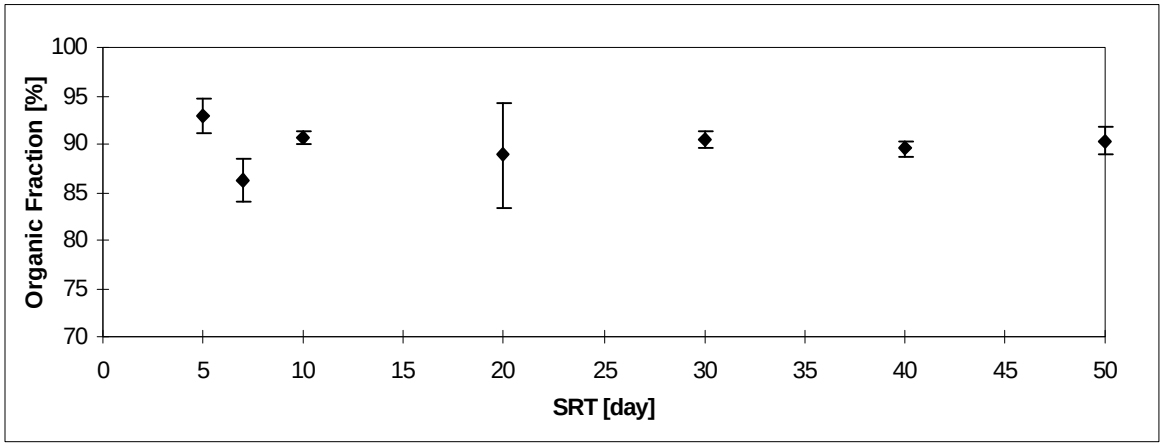

Figure 5—Effect of SRT on organic fraction (MLVSS/MLSS*100).

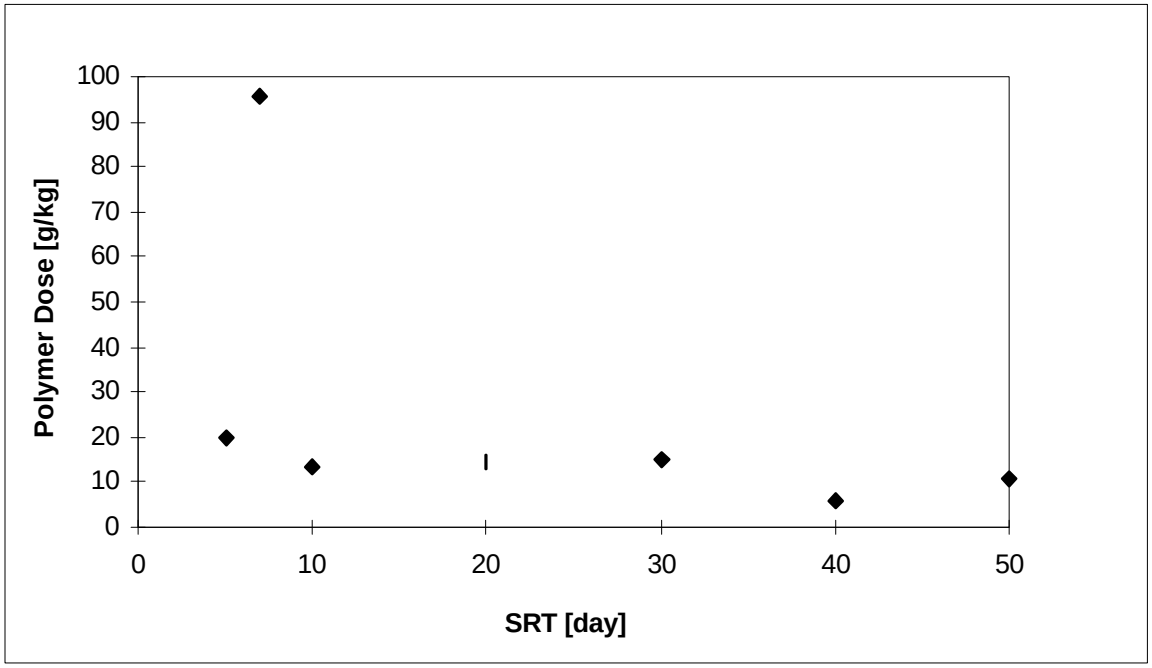

Figure 6—Effect of SRT on polymer dose.

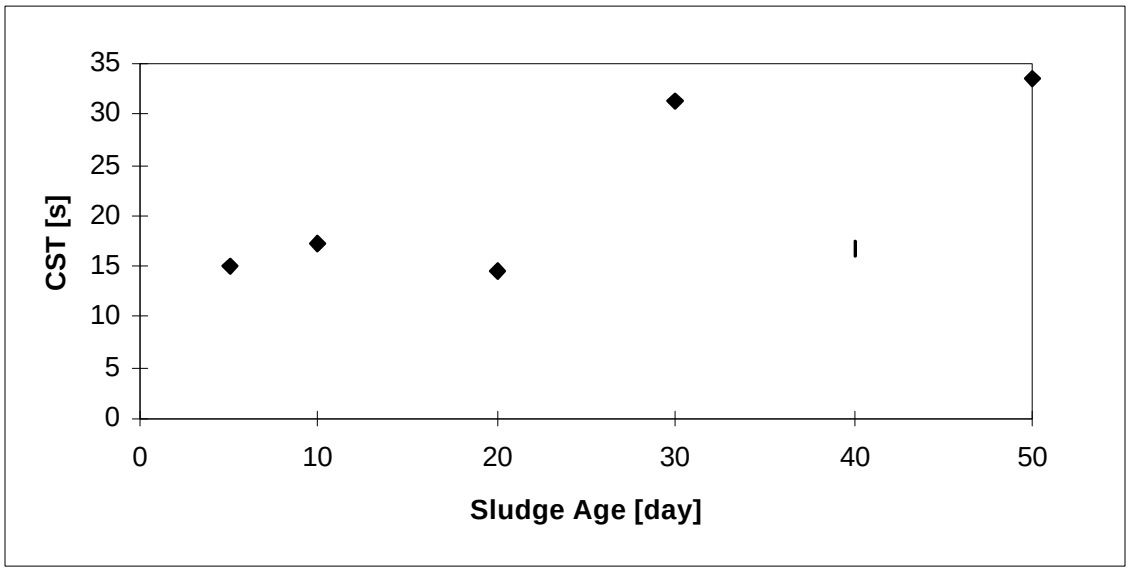

Figure 7—Effect of SRT on CST.

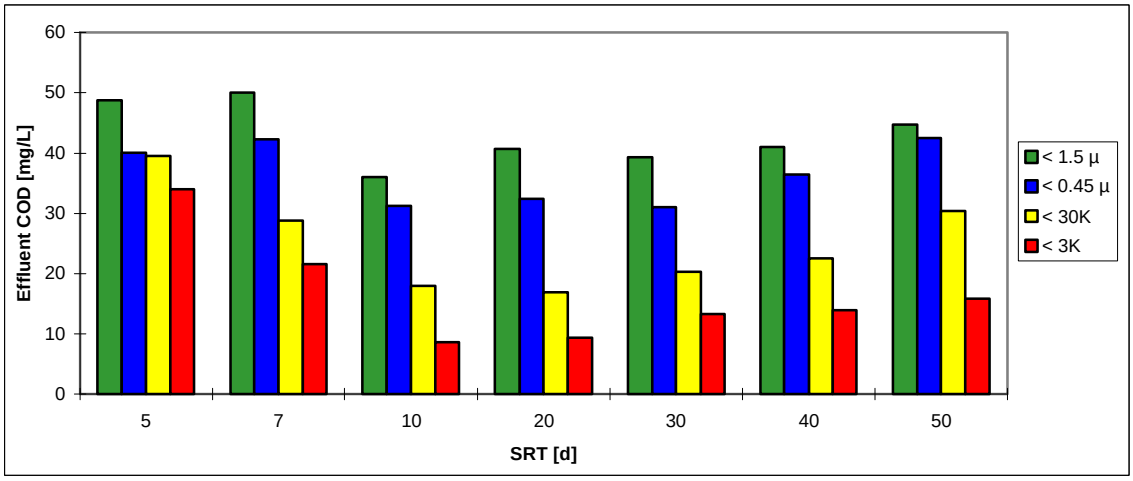

Figure 8—Effect of SRT on effluent COD size distribution.

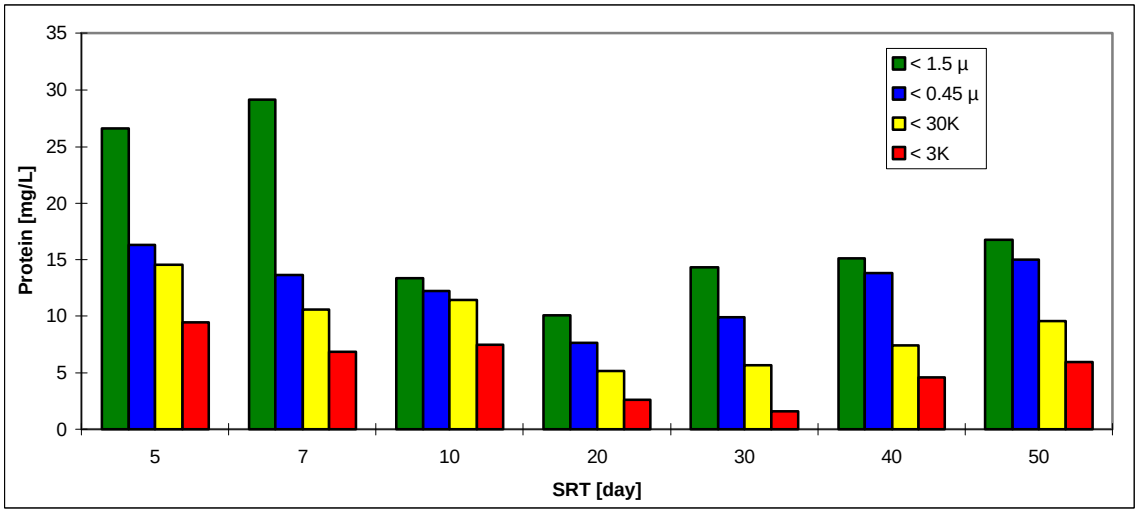

Figure 9—Effect of SRT on effluent protein size distribution.

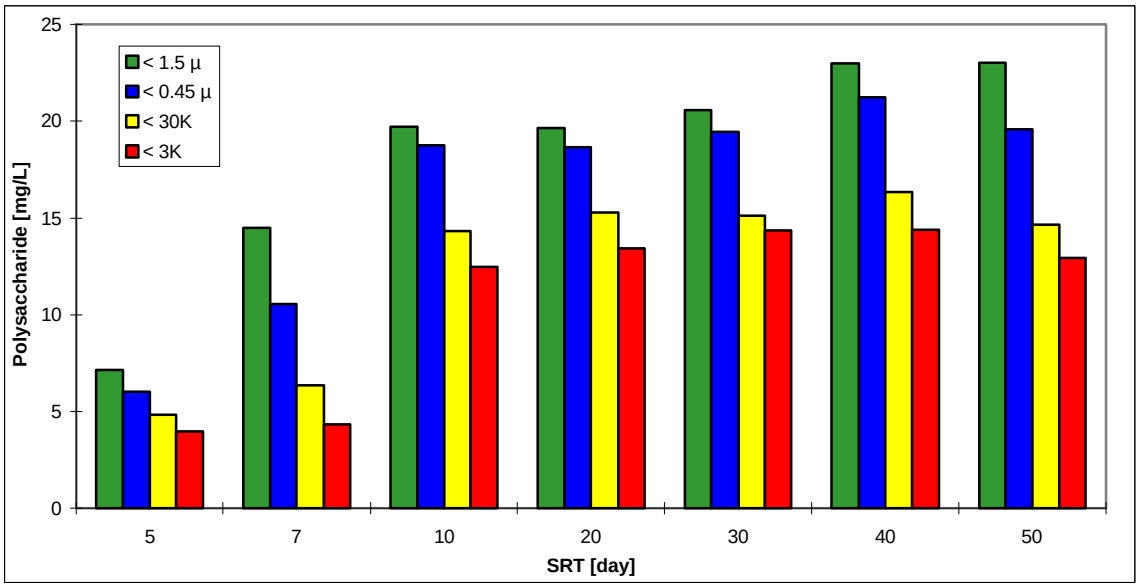

Figure 10—Effect of SRT on effluent polysaccharide size distribution.

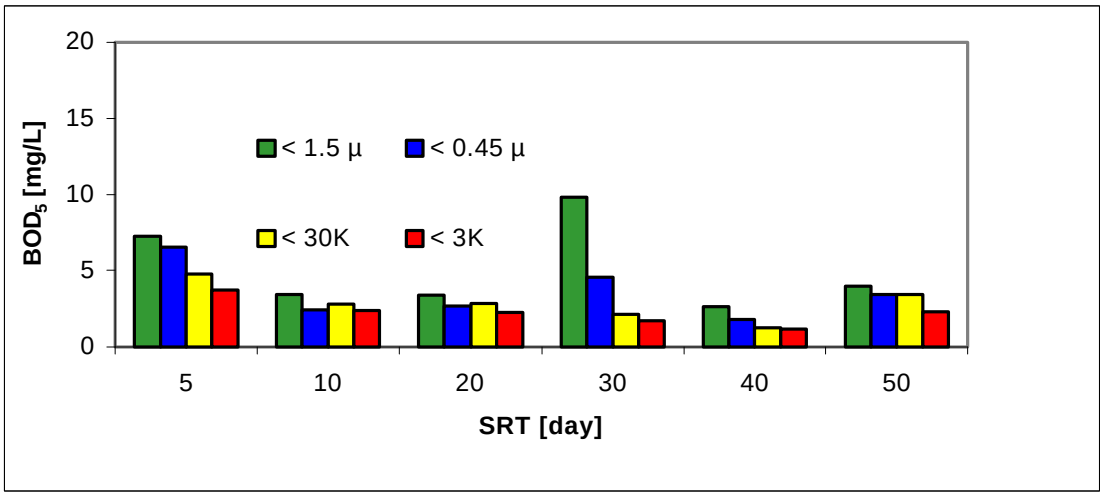

Figure 11—Effect of SRT on effluent BOD_5 size distribution.

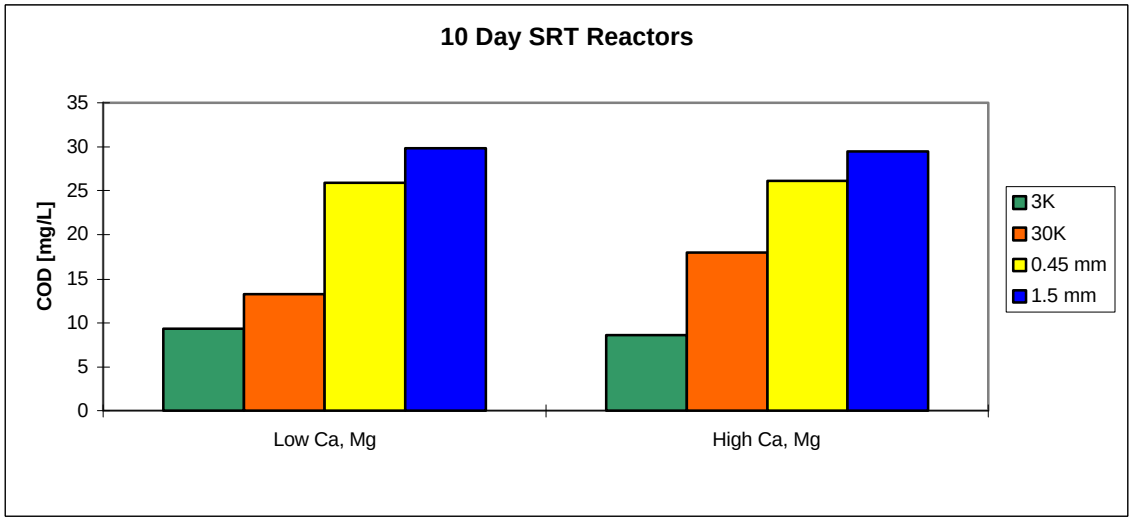

Figure 12— Effect of low calcium (7.35 mg/L) and magnesium (3.61 mg/L) concentrations versus high calcium (23.32 mg/L) and magnesium (26.57 mg/L) concentrations on steady state average effluent COD size distribution.

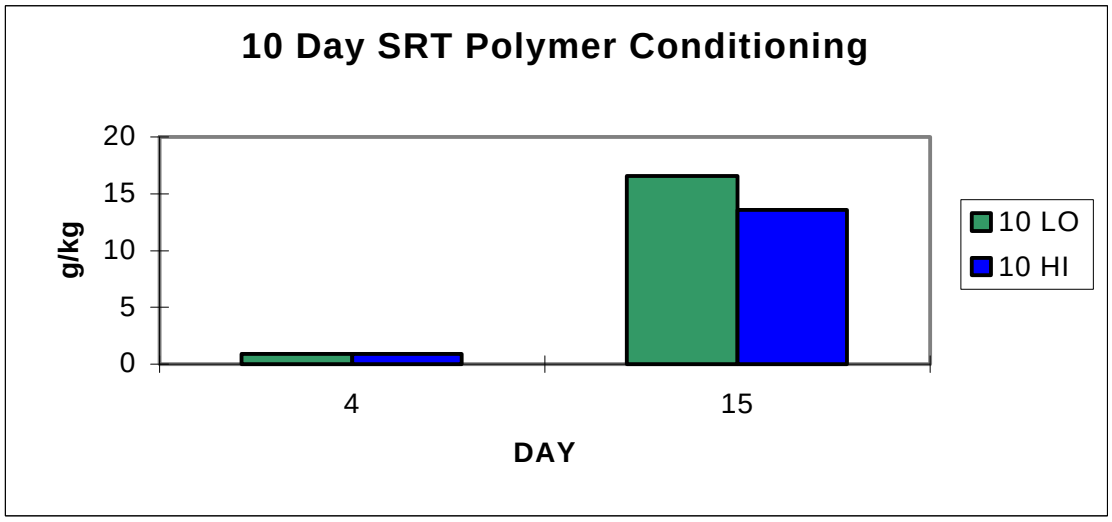

Figure 13—Effect of low and high calcium and magnesium concentrations on polymer conditioning dose.

VIII. VITA

Gary P. Phillips was born on December 30, 1967 in Newport News, Virginia. He attended Culpeper County High School in Culpeper, Virginia and graduated in June 1986. He then pursued a Bachelor of Science degree in Biology at Longwood College and graduated in December 1992. After working at in the environmental field until 1996, he enrolled in the graduate program at the Virginia Polytechnic Institute and State University to pursue a Master of Science degree in Environmental Engineering. He successfully defended his thesis on August 26, 1998.