

**Optimizing Dewatering Polymer Usage and Resulting Percent Cake
Solids at the Hornsby Bend Biosolids Management Plant**

by

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CHAPTER ONE: INTRODUCTION

A city the size of Austin, TX understandably produces a substantial quantity of waste. The two major wastewater treatment plants (WWTPs) in the city, South Austin Regional (SAR) and Walnut Creek, have a total permitted capacity of 150 million gallons per day (MGD). Biological treatment -- the use of microorganisms to remove soluble pollutants from the wastewater -- is employed at both facilities to achieve acceptable levels for discharge to the Colorado River. However, these microorganisms and other solids must be separated from the clean water and disposed of prior to discharge of the clean effluent. In Austin, these microorganisms and solids, together commonly referred to as sludge, are conveyed to Hornsby Bend Biosolids Management Plant (HBBMP) for further treatment and beneficial reuse.

Like most municipalities, the City of Austin (CoA) employs anaerobic digestion at HBBMP to treat the sludge generated from upstream primary and secondary wastewater treatment. The purposes of digestion are to stabilize the sludge and to reduce the ultimate volume of solids requiring disposal while generating methane gas as a useful byproduct. Total and volatile solids content is reduced during the anaerobic digestion of sludge, but further dewatering is required to reduce the final volume of sludge requiring disposal. HBBMP applies a polymer solution to the digested sludge, and the conditioned sludge is then passed through a belt filter press for final dewatering. CoA categorizes successful dewatering of the sludge by the belt filter press as having a final total solids percentage (%TS) greater than twenty. Recent data show that the achieved %TS concentrations have regularly fallen below the targeted twenty percent. The subjects of this work are the optimization of the sludge conditioning process to maximize resultant sludge cake %TS, as well as consideration of potential magnesium precipitate formation

due to increased upstream magnesium hydroxide addition and associated disposal costs for the utility.

The governing principle behind the application of a polymer solution to digested sludge prior to dewatering is that the polymer structure creates a tighter, more cohesive floc, which allows for more water to be expelled mechanically by the belt filter press (BFP). This research was undertaken with two specific objectives: 1) to understand the impacts of polymer type, raw polymer dose, polymer solution concentration, and polymer solution age of the polymer solution added to the digested sludge on the final %TS of the sludge cake, and 2) to understand how potential magnesium precipitates resulting from upstream magnesium hydroxide addition might affect the composition, volume, and dewaterability of the sludge matrix.

The following chapters address these objectives in distinct subsections. The polymer optimization investigation involves analysis of two commonly used measures of sludge dewaterability: specific resistance to filtration (SRF) and capillary suction time (CST), as well as two additional parameters: specific CST and calculated cake %TS. SRF, CST, specific CST, and calculated cake %TS data are presented for sludges treated with different polymer solutions. The variables that were adjusted between polymer solutions are polymer type, raw polymer dose, polymer solution concentration, and polymer solution age. Conclusions are then given with respect to the optimal polymer solution to be applied to the digested sludge at HBBMP to maximize the resulting %TS of the dewatered sludge.

The investigation of precipitates involves analysis of added magnesium hydroxide data for Walnut Creek WWTP that conveys its sludge to HBBMP. Best and worst-case theoretical calculations are presented to determine the maximum and minimum daily mass of precipitates formed and (possibly) conveyed to HBBMP. These theoretical

precipitate mass data are compared with historical data for total daily mass of dewatered sludge produced by the belt filter presses. Conclusions are given with respect to disposal cost of the upstream magnesium hydroxide addition.

Chapter Two provides background information on HBBMP and context for this research with respect to the existing literature on the conditioning and dewatering of anaerobically digested sludge. Chapter Three explains the experimental methods employed in the investigations outlined above: CST, specific CST, SRF, and calculated cake %TS at two minutes. Chapter Four presents the results of both the polymer optimization and magnesium precipitate investigations, including discussion of their trends, significance, and limitations. Finally, Chapter Five summarizes the conclusions drawn from the results of both investigations, and presents recommendations for how CoA might utilize these data to improve dewatering operations at HBBMP.

CHAPTER TWO: BACKGROUND AND LITERATURE REVIEW

2.1 HORNSBY BEND BIOSOLIDS MANAGEMENT PLANT BACKGROUND

Each day, HBBMP receives approximately one million gallons of primary and secondary solids from Austin's two main WWTPs: Walnut Creek and SAR. Upon arrival, the solids are screened to remove large objects and then thickened to reduce volume. The liquid stream from thickening is sent through a sidewater treatment system, and the thickened solids are sent to an anaerobic digester. Following digestion, the remaining solids are sent to one of three belt presses for further dewatering. Filtrate from dewatering is also sent to the sidewater treatment system. The final dewatered cake is then land applied or composted (Austin Water Utility, 2017). Representative process flow diagrams for both the entire process and only the solid phase are shown in Figure 2-1 and Figure 2-2, respectively.

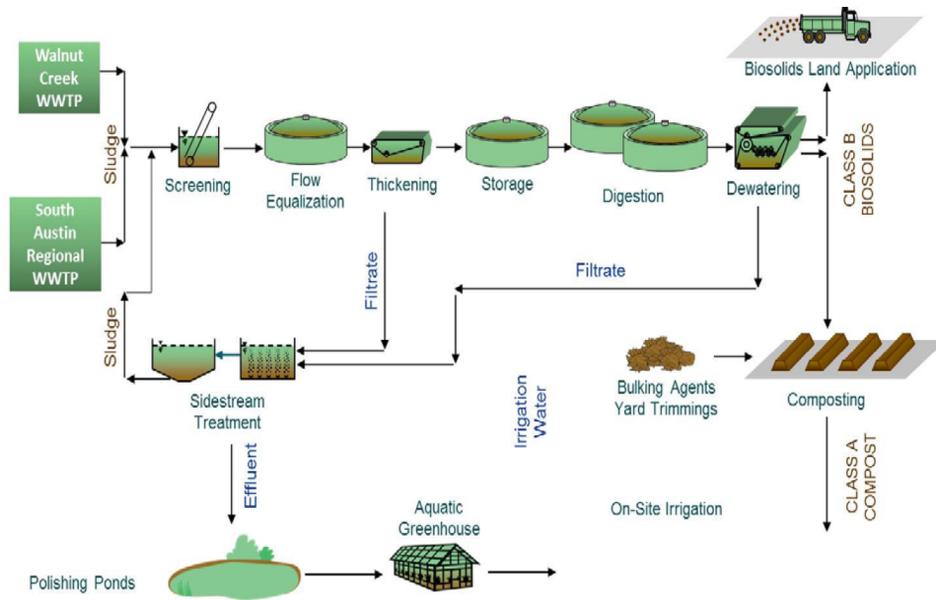
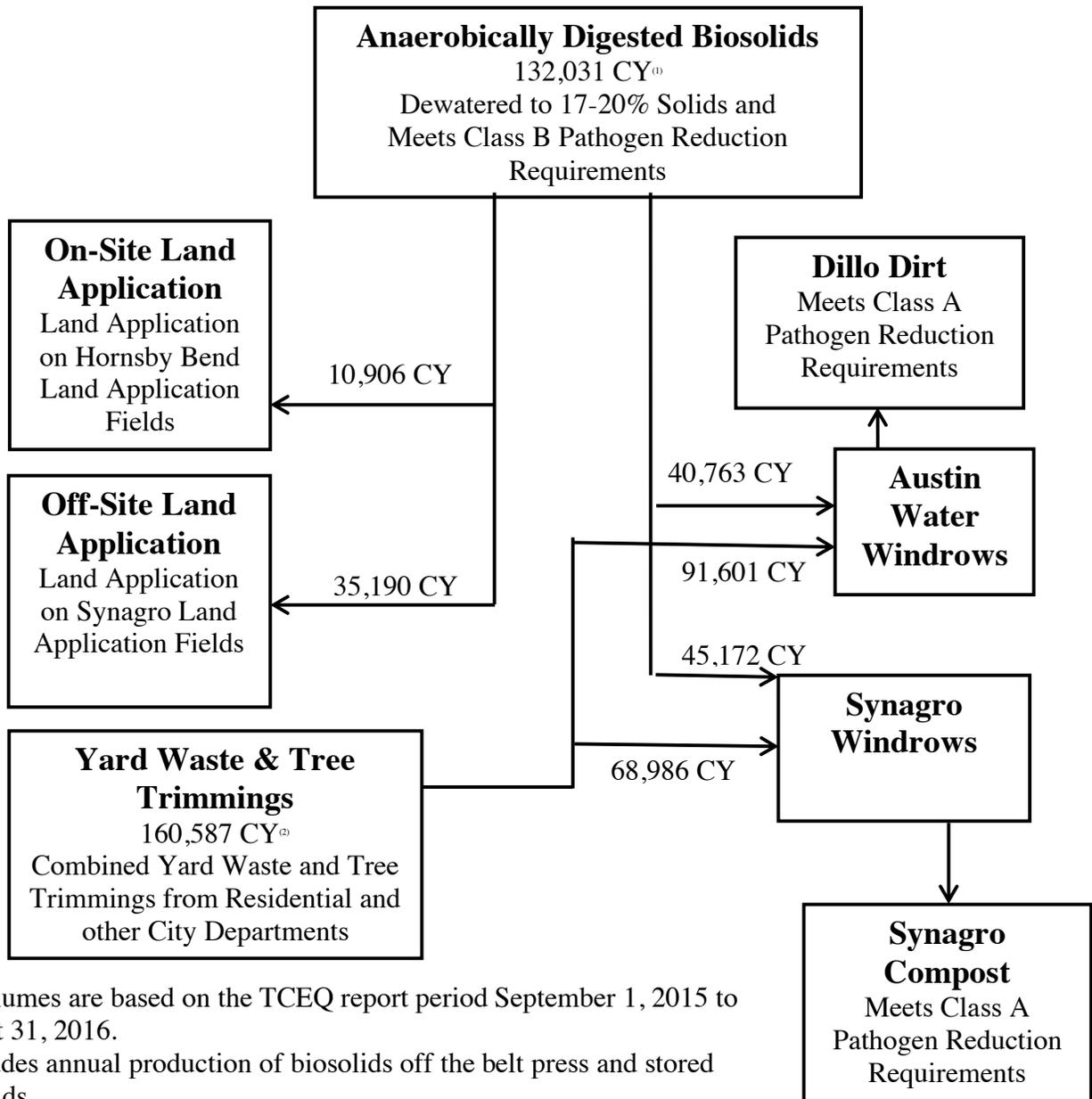


Figure 2-1: Process flow diagram for all influent sludge to HBBMP (taken from Austin Water Utility, 2017)



All volumes are based on the TCEQ report period September 1, 2015 to August 31, 2016.

⁽¹⁾ Includes annual production of biosolids off the belt press and stored biosolids.

⁽²⁾ Includes only the volume of yard waste and tree trimmings processed for biosolids reuse.

Figure 2-2 Solids process flow diagram for HBBMP (Taken from Austin Water Utility, 2017)

The focus of this research is to optimize the dewatering process at the belt presses at HBBMP. The current dewatering scheme is as follows: digested sludge is pumped from the anaerobic digesters to the dewatering building. Raw polymer is mixed with municipal reclaim water in a polymer mixing unit (PMU) to a target polymer concentration of 0.25 percent by volume. The resulting polymer solution is mixed with the influent digested sludge at a target dose of 14L added to 100L of digested sludge. This combination of a 0.25% polymer solution dosed at 14L added to 100L of digested sludge by volume yields a raw polymer dose of 0.035 L added to 100 L sludge. The conditioned sludge is then conveyed to one of the three belt presses where it is drained by gravity and mechanical pressure for approximately two minutes. The dewatered cake is then collected and sent for beneficial reuse (i.e., land application or composting). CoA targets 20% TS for the final dewatered cake.

The motivation for this project is sub-optimal dewatering of the digested sludge. As previously mentioned, the target cake solids value is 20% TS. As can be seen in Figure 2-3, excepting the period from late 2011 to late 2013, the achieved %TS has usually fallen below the 20% target.

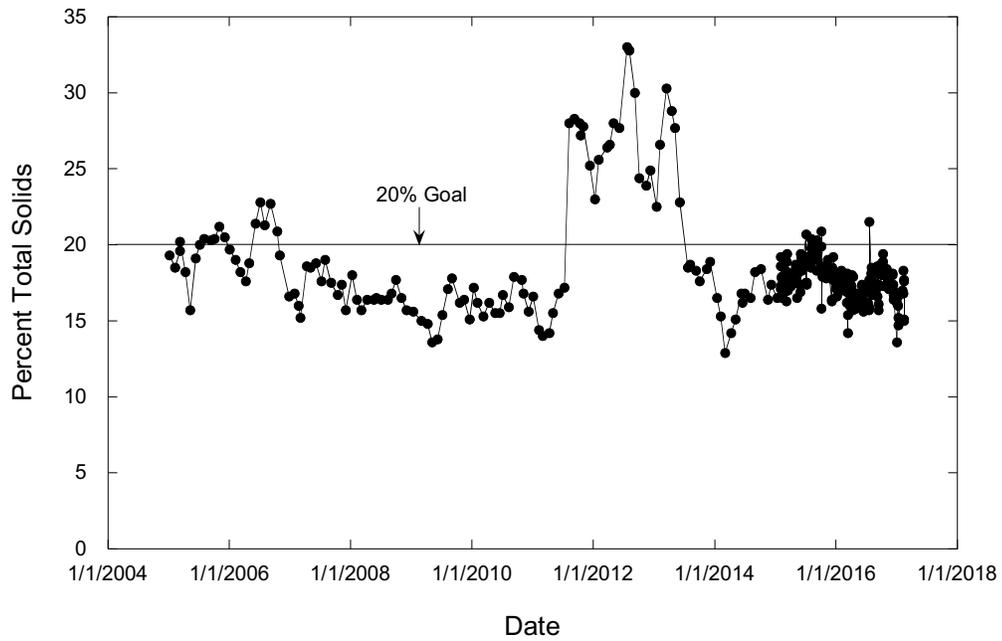


Figure 2-3: Percent total cake solids at HBBMP relative to the 20% target from 2005 through present

Figure 2-4 explains that, although high %TS values were achieved during the period from late 2011 to late 2013, those results were due to substantial lime addition at the upstream WWTPs, as evidenced by the high %TS but low percent volatile solids values. CoA terminated this lime addition after examination of various negative impacts in other treatment processes.

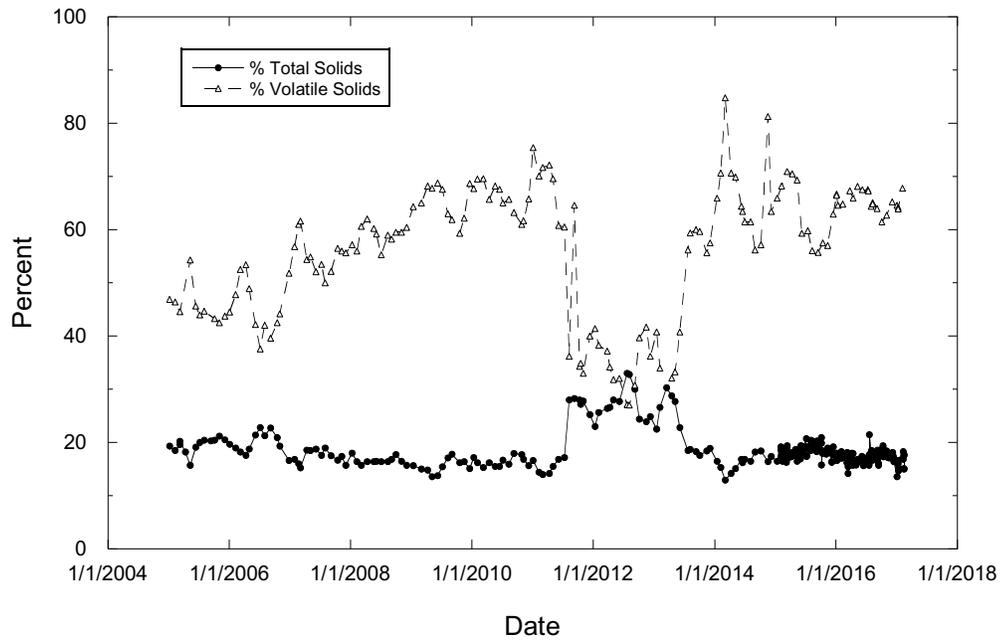


Figure 2-4: Percent total and volatile cake solids at HBBMP from 2005 through present

Figure 2-5 shows a histogram of the %TS achieved in the dewatered cake from April 19, 2014 through February 15, 2017. It is evident that %TS values in the range of 16-18% occur most frequently, followed by %TS in the range of 18%-20%. Cake %TS values in excess of 20% and below 14% occur very rarely. These data reinforce CoA’s motivation for this research.

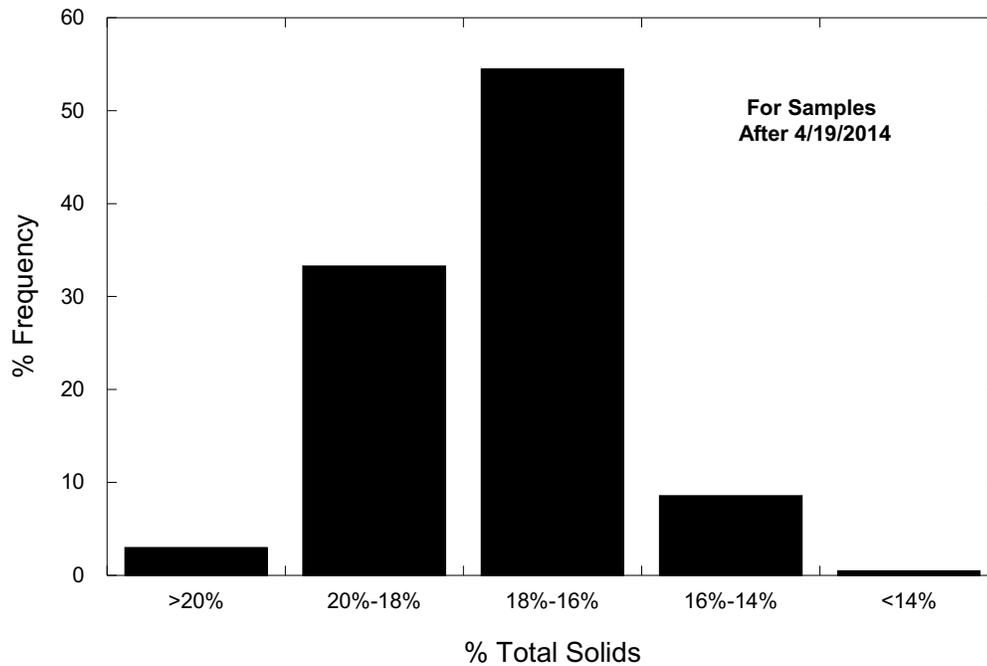


Figure 2-5: Frequency of various percent total cake solids values since 04/19/2014

This work focuses on how the sludge conditioning process can be optimized to improve sludge dewaterability and resulting cake %TS as well as the potential effects of upstream magnesium hydroxide addition on sludge cake mass and dewaterability.

2.2 SLUDGE DEWATERING

Sludge is comprised of diverse solid particles in an impure water continuum. The water within this continuum can be further categorized as free water, interstitial water, vicinal water, and water of hydration (Vesilind, 1994). Vesilind described these water types further as follows: Free water is water not associated with or influenced by solid particles. Interstitial water is trapped in the interstitial spaces between flocs and microorganisms. Vicinal water is multiple layers of water molecules held tightly to solid particles by hydrogen bonding. The force is believed to be short-ranged, but large in

magnitude. Water of hydration is water chemically bound to the particles and removable only by the expenditure of thermal energy (Vesilind, 1994).

It follows logically that the easiest water to remove from sludge is free water, which can be removed by gravity drainage, thickening, and/or mechanical dewatering. Interstitial water, however, is trapped within the floc structure and thus can only be removed by compressing or destroying the floc structure via mechanical compression or chemical conditioning. Mechanical dewatering cannot remove vicinal water or water of hydration as both types are chemically bound to the solid structure (Vesilind, 1994). It follows logically that the water remaining in a sludge cake following effective mechanical dewatering is likely vicinal or water of hydration. See Figure 2-6 for a conceptual representation of the change in water distribution as sludge is dewatered.

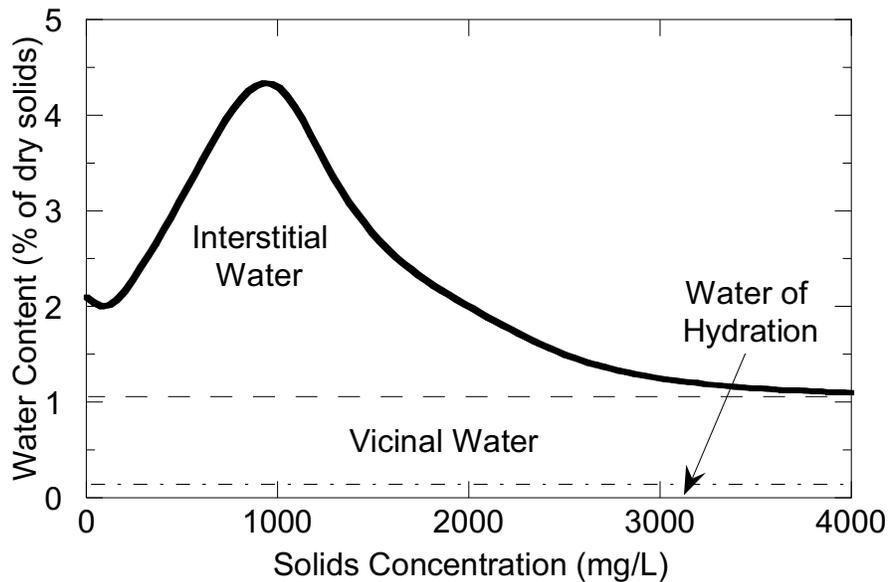


Figure 2-6: A hypothetical curve showing the change in water distribution with solids concentration (Adapted from Vesilind, 1994)

Effective mechanical dewatering is achieved when all free and interstitial water is removed from the sludge. For the operator, this entails optimizing both the mechanical

operation of the device (i.e., centrifuge, belt filter press) as well as chemical conditioning of the sludge.

2.2.1 Mechanical Dewatering

HBBMP utilizes three belt filter presses for mechanical dewatering of their digested sludge. As such, the focus of this review will be the belt filter press.

Belt filter presses (BFPs) are continuous-feed dewatering devices that use the principles of gravity drainage and mechanically applied pressure to dewater chemically conditioned sludges. A representative schematic is shown in Figure 2-7.

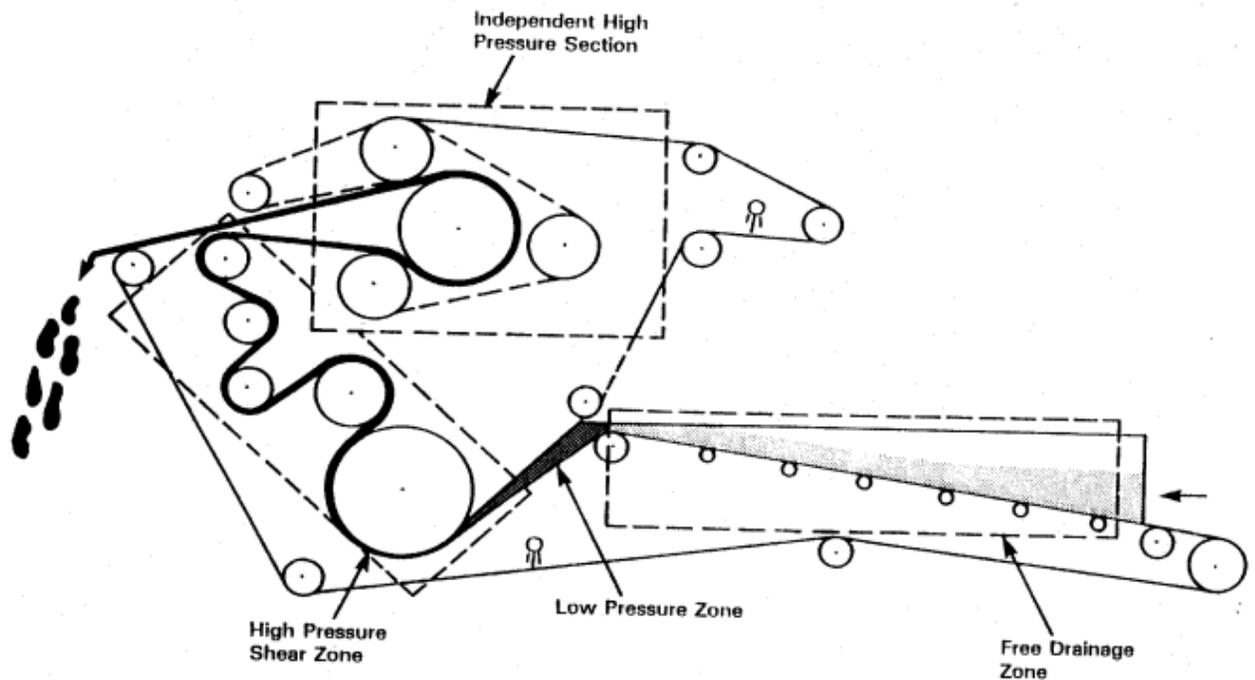


Figure 2-7: Schematic of the three basic stages of belt press dewatering (taken from US EPA, 2000)

In most BFPs, conditioned sludge is first introduced on a gravity or free drainage section of the belt. Typically, 1-2 minutes are required for gravity drainage of free water (Shammas and Wang, 2007). Following gravity drainage, pressure is applied in a low-

pressure section where sludge is squeezed between opposing porous cloth belts. In some installations, a high-pressure section follows the low-pressure section, where the sludge is subjected to shearing forces as the belts pass over a series of rollers. The final dewatered sludge cake is removed from the belts by scraper blades (Tchobanoglous et al., 2014).

BFP performance is impacted by many variables: sludge or biosolids characteristics, method and type of chemical conditioning, applied pressure, machine configuration, and belt porosity, speed, and width. Often times, a substantial tradeoff between sludge feed rate and the cake %TS achieved is observed. Allowing more time for gravity drainage and low/high pressure dewatering would improve resulting %TS, but also results in a reduction in the sludge volume that the BFP can press (Johnson et al., 1992). Regardless, belt filter press vendors have summarized the typical dewatering performance for a belt filter press receiving anaerobically digested primary and waste activated sludge (WAS) as shown in Table 2-1.

Table 2-1: Typical dewatering performance for a belt filter press receiving anaerobically digested primary and waste activated sludge (taken from Tchobanoglous et al., 2014)

Type of Feed	Dry feed solids %	Loading per meter of belt length		Cake Solids, %TS	
		<i>L/min</i>	<i>kg/h</i>	<i>Typical</i>	<i>Range</i>
Anaerobically digested Primary + WAS	2-4	150-450	320-540	24	15-28

Table 2-1 indicates that the 16-18 %TS achieved most frequently in HBBMP sludge cake falls in the low end of the expected range for belt filter press operation. Further, the 20% TS goal determined by CoA seems feasible with optimization of sludge conditioning and upstream processes.

2.3 CHEMICAL CONDITIONING

Attempts to dewater sludge without prior conditioning are typically ineffective due to sludge's inherent compressibility. Application of a vacuum or mechanical pressure to an unconditioned sludge results in a layering of the floc and microorganisms on top of each other with an overall compaction, thus nominally sealing potential paths of egress for water through the sludge. The purpose of chemical conditioning of a sludge is, therefore, to develop a more rigid and porous structure within the sludge through which water can escape. Conversely, coagulation of otherwise discrete sludge particles will result in a tightly aggregated structure which is relatively impermeable to the withdrawal of water and undesirable for sludge conditioning (Tenney et al., 1970). The chemicals chosen for sludge conditioning are typically polyvalent metal ions and/or synthetic organic polyelectrolytes (polymers), depending on the characteristics of the sludge being dewatered. At HBBMP, a cationic polymer was selected for sludge conditioning, and thus the focus of this review is cationic polymers.

Briefly, many investigators have shown that two mechanisms are necessary to condition sludge for dewatering: one is the neutralization of the surface charge, and the other is physical bridging of individual particles into a floc structure. Wastewater sludge particles commonly hold a negative surface charge, which creates an energy barrier of electrostatic repulsive forces that must be overcome if any two similar particles are to unite into a larger one (Vesilind, 1994). As a result, the addition of a cationic polymer serves to neutralize the negative surface charge of the particles, allowing for flocculation of individual particles. Further, the basic premise of interparticle bridging is that organic polymers form long molecules that attach themselves to the sludge particles and bridge the gap between particles and draw them together, creating the strong floc lattice structure necessary for efficient dewatering. The combination of charge neutralization

and interparticle bridging together explain the improved dewaterability of sludges dosed with high molecular weight cationic polymers.

Sludge characteristics, however, play a major role in both the inherent dewaterability of the sludge, as well as that sludge's polymer demand. For unconditioned, undigested sludges, it has been shown that increasing volatile suspended solids (VSS) concentrations decrease the dewaterability of the sludge. This trend is likely due to the production of extra-cellular polymeric substances (EPS) by microorganisms in the sludge; these EPS create a highly compressible layer that is resistant to mechanical dewatering as mentioned above (Skinner et al., 2015).. However, Pontoni et al. (2018) have shown that EPS up to a certain concentration are essential to the formation of sludge flocs and other microbial aggregates including biofilms and granules. EPS concentrations beyond the minimum concentration, conversely, increase the compressibility of the sludge and decrease its dewaterability, as described previously. This effect is particularly pronounced when the protein content of the EPS is high, as elevated protein levels result in an increasing amount of interstitial water (Pontoni et al., 2018). When a sludge is digested anaerobically, its VSS content is reduced, but the effect on the dewaterability of that sludge is directly related to the change in total surface area of the sludge particles.

“When digestion works well, particles of all sizes are digested and there is a preferential removal of particles of small sizes, a corresponding loss of specific surface area, and therefore increased dewaterability. When digestion does not work well, large particles are destroyed but small particles are created with a consequent gain in specific surface area and a corresponding worsening of dewaterability” (Lawler et al., 1986).

In the case where digestion is not working well, the additional specific surface area created would theoretically demand more polymer conditioning.

Additionally, the concentrations of monovalent and divalent cations in a sludge have been shown to have a substantial impact on dewaterability. An ion-bridging model has been proposed to explain the effect of cations on biological sludge properties. This model proposes that divalent cations act as a bridge between negatively charged sites on exocellular biopolymers. As a result, increasing divalent cation concentrations in a sludge should serve to improve settling and dewatering due to flocculation by this mechanism (Higgins and Novak, 1997). Experiments performed by Higgins and Novak showed that a minimum concentration of calcium and magnesium in the range of 0.72-2.0 meq/L of each are required for good settling and dewatering characteristics. Additionally, a ratio of sodium to divalent cations greater than approximately two resulted in deterioration in settling and dewatering characteristics. These facts are of particular importance when considering the implications of the increasing magnesium hydroxide feed rate upstream of HBBMP.

The selection of a cationic polymer and its corresponding dose is highly specific to the characteristics of the sludge being dewatered. Of principal importance in cationic polymer selection are the cationicity and molecular weight of the polymer. Cationicity is measured as a percent (molar or weight) and is indicative of the positive charge density of the polymer. Molecular weight is indicative of the size and weight of the polymer molecules themselves. It is somewhat intuitive that the lowest polymer doses are needed for polymers with ultra-high cationicity and ultra-high molecular weight. Higher molecular weight polymers are thought to favor a bridging interaction and thus little product is needed, whereas lower molecular weight polymers are believed to favor a charge neutralization mechanism that requires higher amounts of polymer. Similarly, for high molecular weight polymers, the impact of cationicity on the required polymer dose is minimal, as those polymers rely principally on interparticle bridging as a flocculation

mechanism (Saveyn et al., 2008). In the case of a new-plant start-up, polymers of various cationicities and molecular weights should be tested at the pilot scale to determine which polymer is most cost-effective for the sludge. However, in the case of HBBMP, a polymer, BASF Zetag 8819, has already been selected, and thus a thorough examination of polyelectrolytes is excluded from this work due to contractual commitments for CoA. An alternate polymer, Polydyne Clarifloc CE1632, is considered in this work due to previous relationships between CoA and Polydyne, and the possibility that the polymer could be changed in potential future bid opportunities.

Once a polymer has been selected, there remains considerable room for optimization of sludge conditioning. The first parameter to be optimized is polymer activation via polymer aging. BASF Zetag 8819 and Polydyne Clarifloc CE1632 are emulsion blend cationic polymers. Polymers of this type are comprised of approximately 30% hydrocarbon oil, and the remainder polymer gel is 40% polymer and 30% water. Additionally, the solution contains a stabilizing surfactant to keep the polymer gel separate from the hydrocarbon oil during storage, and an inverting or breaker surfactant to emulsify the polymer in the oil prior to mixing with sludge.

Caspar et. al (2011) and deGennes (1971) have studied the effects of polymer activation on polymer performance in dewatering applications. Both investigators developed so-called polymer activation curves, which show polymer solution viscosity as a function of polymer solution aging time. Viscosity is used as a surrogate for polymer activation because, when the polymer is re-suspended and elongated, the viscosity of the solution increases asymptotically to a maximum achievable viscosity for that polymer prior to decay. A set of typical polymer activation curves is shown in Figure 2-8.

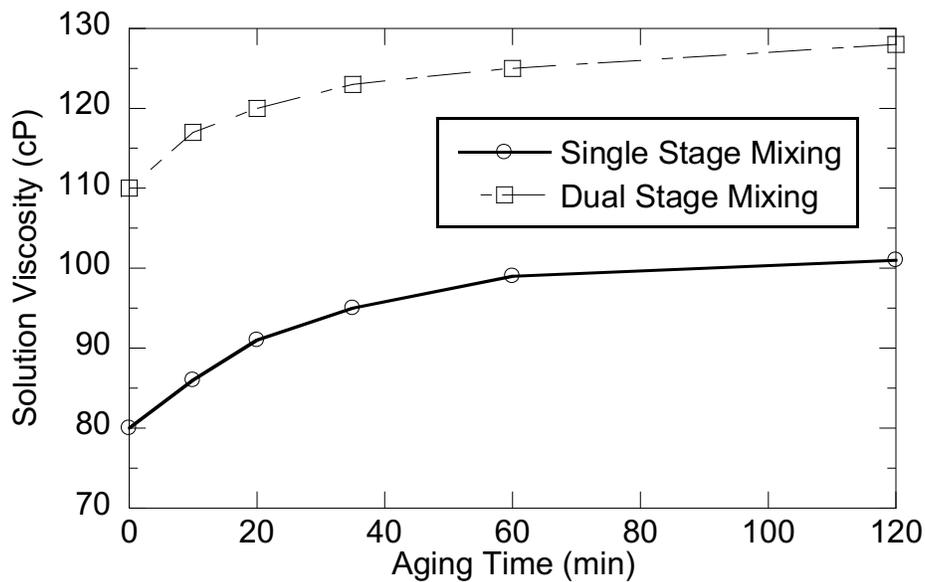


Figure 2-8: A set of typical polymer activation curves. (Adapted from Kim and Hawley, 2016)

As suggested by de Gennes (1971), Kim (2016) and Caspar et. al (2011), optimal polymer activation is achieved by two-stage mixing: an initial wetting or inversion phase, characterized by high mixing intensity ($G = 15,000 \text{ sec}^{-1}$) and short contact time, followed by a longer dissolution or aging phase, characterized by low mixing intensity and longer contact times (de Gennes, 1971). Efficacy of this two-stage mixing process is measured by the value of the maximum viscosity of the polymer activation curve, and the aging time required to achieve that maximum viscosity. Polymer solutions with a high maximum viscosity that is attained rapidly are desirable. A general precept is that a high intensity wetting or inversion phase followed by a low mixing intensity aging phase of approximately 10-30 minutes duration will increase polymer activity and thus decrease raw polymer demand. This precept is investigated for the specific polymers of interest in the work that follows. Further, this work examines how varying the polymer solution

concentration might impact the activity of the polymer solution and its impacts on sludge dewaterability.

Mixing is also important when considering the mixing of polymer solution with unconditioned sludge. Both mixing intensity and mixing time are relevant, as the conditioning process consists of flocculation of the sludge by polymer solution, breakage of sludge particles and floc due to mixing, and reflocculation effects (if residual polymer exists in solution) which together result in the final dewatering properties of the conditioned sludge (Dentel, 2001). Logically, if mixing is too intense or too long, a significant fraction of flocs formed initially are destroyed by mixing and require additional polymer for reflocculation. If mixing is too weak or short, adequate dispersion of the polymer solution into the sludge is not achieved, and flocs are not formed. It is therefore clear that mixing intensity and time is directly related to raw polymer demand. Werle et al. (1984) investigated the effect of polymer-sludge mixing intensity as characterized by the root mean square velocity gradient (G , typically reported in units of s^{-1}), polymer-sludge mixing time (t , taken here to be in s), and the dimensionless product of the two, the so-called Gt product, on the dewaterability (CST) of the conditioned activated sludge. Their results indicated that for activated sludge, a single, optimal Gt product is optimal regardless of the polymer dose (Werle et al., 1984). Note that an infinite number of combinations of G and t yield the same Gt product, but sludge dewaterability for a fixed Gt product was independent of the combination of G and t used to attain that product, so long as the $G:t$ ratio was within the range of $0.5 - 60 s^{-2}$. It appears that, for a poor Gt product, no amount of raw polymer will yield acceptable sludge dewaterability. For these reasons, it is critical to quantify both the mixing intensity and time between polymer solution and unconditioned sludge to optimize sludge dewaterability.

Perhaps the most important polymer optimization parameter from both a dewaterability and cost perspective is the raw polymer dose. The first important point to address is that, once an optimal raw polymer dose has been determined for a specific sludge sample, the required raw polymer dose appears to be linearly related to the %TS of the influent sludge (Tenney et al., 1970). Polymer feed rates should therefore be adjusted to correspond with varying influent sludge solids concentration variations.

Determining the optimal polymer dose for a sludge sample is highly specific to the sludge of interest and should be tested experimentally before full-scale operation begins. As previously discussed, both interparticle bridging and charge neutralization act to increase the cohesiveness of a floc. As such, the point of zero charge on the surface of the solid particles in the sludge may be indicative of the optimal dose of a cationic polymer. Abu-Orf and Dentel (1997) measured the surface charge of sludge particles using a streaming current detector (SCD) and found that near-zero SCD readings coincided with optimal full-scale dewatering, as indicated by solids measurements and recoveries and by minima in filtrate turbidity, filtrate viscosity, conditioned solids filterability times, and (in some cases) capillary suction time. Additionally, their experiments showed that a slight polymer underdose can cause a significant deterioration in dewatering efficiency, whereas a large overdose can bring little improvement in performance while increasing chemical costs substantially (Abu-Orf and Dentel, 1997). A simplified formula for variable treatment costs associated with chemical conditioning is given by Saveyn et al. (2008) and shown below:

$$\text{Variable Treatment Cost} = \text{Polymer Dose} * \text{Unit Polymer Cost} + \frac{\text{Wet Cake Mass}}{\text{kg Dry Cake Matter}} * \text{Unit Wet Cake Disposal Cost} \quad (2-1)$$

This equation makes it clear that the relative cost of raw polymer must be evaluated relative to the cost of wet cake disposal. For high cake disposal costs, the

polymer dose that guarantees the best dewatering results should be used, even if it has to be applied in high doses (Saveyn et al., 2008). For the sake of this research, surface charge was not measured, but rather raw polymer dose and polymer solution concentration were varied, and the resulting variations in dewatering characteristics were evaluated. The optimal dose was selected as the one that resulted in the best dewatering characteristics. Economic analyses were then performed based on the experimentally determined optimal doses.

A final objective of this research is to understand the potential impacts of magnesium precipitates on the dewaterability of the digested sludge at HBBMP. No previous research was found on this topic, but a number of the above concepts can be applied to the evaluation of the precipitates. First, since magnesium precipitates are chemical and not biological solids, they will not excrete EPS and are thus less compressible and should be more easily dewaterable than an equal volume of biological solids. However, depending on the composition of the precipitates, water of hydration could have a substantial impact on dewaterability. Magnesium precipitates with low water of hydration content like magnesium carbonate or dolomite are likely to dewater well, whereas solid-phase magnesium hydroxide, which incorporates large quantities of water, may not dewater well. These conclusions are based on the fact that water of hydration cannot be expelled without the addition of thermal energy.

CHAPTER THREE: EXPERIMENTAL METHODS

Sludge dewaterability was evaluated using four different measures: specific resistance, capillary suction time, specific capillary suction time, and calculated cake %TS after two minutes. %TS measurements for unconditioned digested sludge were made by on-site HBBMP laboratory staff per Standard Method 2540 G (Clesceri et al., 1998). The effects of polymer type, raw polymer dose, polymer solution concentration, and polymer solution age on each of these sludge-dewatering parameters were studied. The laboratory procedures used for these experiments are outlined below.

3.1 CONDITIONED SLUDGE SAMPLE PREPARATION

Conditioned sludge samples were prepared for testing by first adding 50 mL of unconditioned sludge to a clean beaker. A polymer solution was prepared in a separate beaker by adding tap water to one mL of raw polymer to yield a polymer solution of specified concentration (0.125%-0.5%). This polymer solution was mixed at 300 rpm on a five-bar stirrer for a duration of ten seconds to replicate the rapid mix phase in the PMU at HBBMP. For aged polymer solutions, the initial rapid mix was completed, and the resulting polymer solution was left to age with no additional mixing. The required volume of polymer solution, aged or unaged, as required, was added to the 50 mL of unconditioned sludge that resulted in the specified raw polymer dose. For a fixed polymer solution concentration, a larger volume of polymer solution was added to the unconditioned sludge to yield a larger raw polymer dose. The polymer solution and sludge mixture was mixed on a five-bar stirrer at 125 rpm for a duration of 30 seconds to mimic the polymer solution and sludge mixing observed at the HBBMP belt presses. After 30 seconds of mixing, the samples were taken and tested as described in the following sections.

3.2 SPECIFIC RESISTANCE

Specific resistance is a common measure of sludge dewaterability. The rate at which water drains out of the sludge under an applied vacuum is measured and expressed in terms of the resistance of the sludge to dewatering. Higher values of specific resistance indicate that the sludge is less easily dewatered (Singer and Lawler, 1982). A diagram of the apparatus used in this study is shown in Figure 3-1.

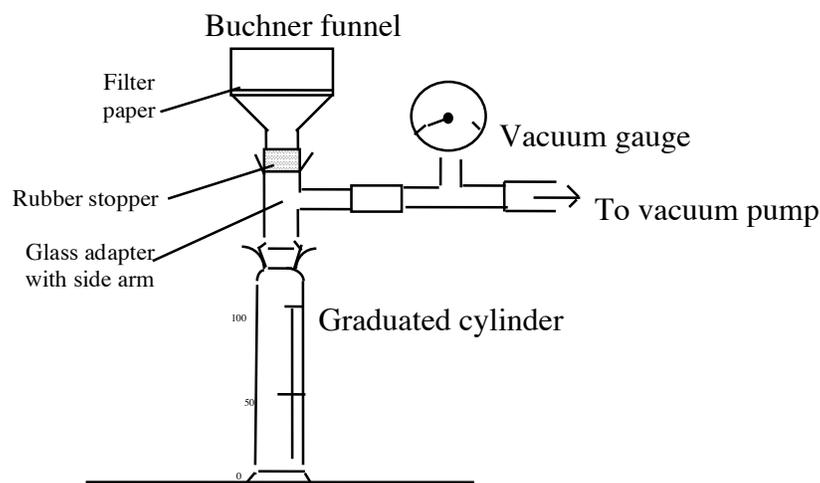


Figure 3-1: Specific resistance apparatus (Adapted from University of Waterloo Department of Civil Engineering, 2016)

A Buchner funnel with a diameter of approximately 9 cm was used. Whatman #1 filter paper was trimmed and placed in the bottom of the funnel to ensure that the filter paper sealed against the walls of the funnel to prevent short-circuiting or by-pass. Prior to the introduction of sludge, the filter was wetted with distilled water and a vacuum was applied to make the seal. The vacuum was turned off, and excess water was drained from the graduated cylinder. A suspension prepared in a beaker that contained 50 mL of sludge and the requisite volume of polymer solution was then added, a vacuum of 23 in. Hg was applied, and a stopwatch was started. The volume of filtrate collected was

recorded at various times until the flow of water was very slow. A plot of time per unit volume versus volume (t/V vs. V) was prepared, and the slope of the straight-line portion was determined. Specific resistance was calculated from the formula

$$r = \frac{2PA^2b}{\mu w} \quad (3-1)$$

where:

r is the specific resistance, in m/kg

P is the vacuum pressure, in $Newtons/m^2$

A is the area, in m^2

b is the slope of the t/V vs. V plot, in sec/m^3

μ is the viscosity, in $kg \cdot m^{-1}s^{-1}$

w is the solids concentration of the sludge, in kg/m^3

A typical t/V vs. V plot is shown in Figure 3-2. Note that the data yield a relatively straight line through the central portion of the data, but the initial and final data deviate from the line. This trend is typical for a specific resistance test. The slope of the straight-line portion of the graph is the value of “ b ” in Equation 1.

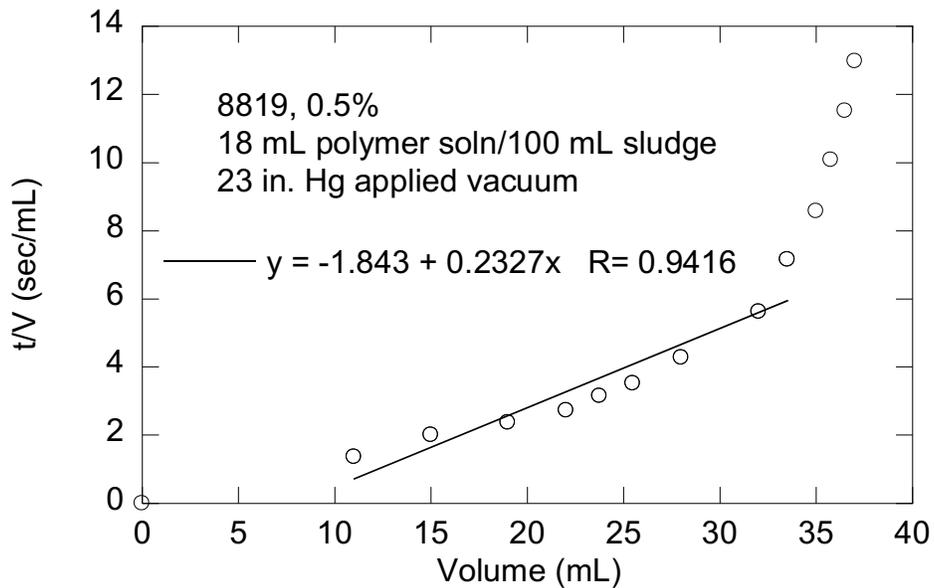


Figure 3-2: Raw data for determination of specific resistance to filtration

The main driver for variations between specific resistance measurements is variation in the slope of the t/V vs. V plot, the “b” variable in Equation 1. “b” depends on the size of the particles that make up the sludge (smaller particles lead to increased resistance), the amount of water bound to the sludge, floc structure, and surface characteristics of the sludge particles. Theoretically, at least, specific resistance is a characteristic of the sludge and is independent of the sludge concentration and the vacuum applied; nevertheless, in laboratory testing where the results of variables such as the applied polymer dose are to be compared, it is prudent to always use the same vacuum pressure and the same (or similar) solids concentration. In this experimental work, the vacuum pressure of 23 in. Hg (78,000 N/m²) was used. Sludge samples with mildly different solids concentrations were used, and were diluted with various quantities of polymer solution (as in the full-scale plant).

3.3 CAPILLARY SUCTION TIME

A second measure of sludge dewaterability is capillary suction time (CST). The device used in these experiments (Triton Electronics Ltd., Type 92) measures the amount of time, in seconds, required for water drained from a sludge sample to travel 1 cm across Whatman #17 filter paper. The device is simple to use, and operates as follows. A new filter paper is placed on the bottom filter plate, and the top plate and sample funnel are placed on top of the filter paper. The sample funnel is then filled with a sample of sludge. As water drains from the sludge by capillary action and gravity, it travels radially away from the center of the funnel on the filter paper. The top plate comprises two concentric sets of electrodes; when the water reaches the first set, a timer is activated, and when the water reaches the second electrode, one cm away, the timer stops. The travel time between the two electrodes is the CST. A schematic of the CST apparatus is shown in Figure 3-3.

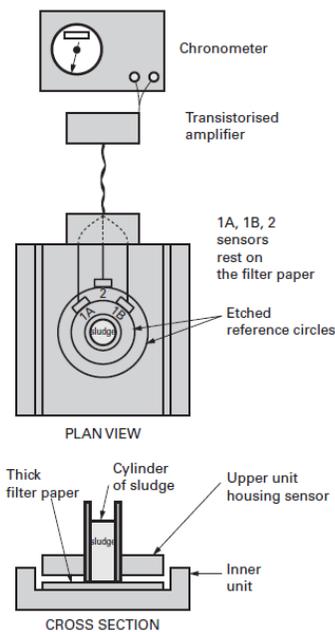


Figure 3-3: Capillary suction time device schematic. (Taken from SUEZ, 2014)

3.4 SPECIFIC CAPILLARY SUCTION TIME

Unlike specific resistance, CST does not account for differences in the solids content of the sludge. In the experiments that follow, wide-ranging volumes of polymer solution with an assumed zero suspended solids concentration were added to the sludge before CST was measured on the conditioned sludge. We hypothesize that the dilution of the sludge by the polymer solution, as well as the effect of the raw polymer itself has significant impacts on the dewaterability of the conditioned sludge. As a result, Specific CST was developed in an attempt to account for the effect of the dilution of the sludge. Specific CST is a simple calculation given by the formula

$$\text{Specific CST} = \text{CST}_{\text{measured}} * \frac{V_{\text{sludge}} + V_{\text{polymer solution}}}{V_{\text{sludge}}} \quad (3-2)$$

Therefore, for a fixed volume of sludge, increasing the volume of polymer solution added would increase the specific CST. While still imperfect, we believe that Specific CST does a better job of accounting for the dilution of the sludge by polymer solution than does traditional CST.

Many investigators have reported a good correlation between the CST and specific resistance of sludge. Regardless, we have used both parameters, as well as the calculated specific CST and cake %TS after two minutes, to study the dewaterability of the sludges in this research.

3.5 CALCULATED CAKE %TS AT TWO MINUTES

Cake %TS was calculated using filtrate volume data from specific resistance testing. The cake %TS values presented in this research are based on the volume of filtrate collected after two minutes of filtration, as two minutes is the duration that conditioned sludge is in contact with the belts at HBBMP according to operational staff. Cake %TS after two minutes was calculated as follows:

$$Cake \%TS_{two\ min} = \%TS_{initial} * \frac{V_{sludge}}{V_{sludge} + V_{polymer\ solution\ added} - V_{filtrate, two\ minutes}} \quad (3-3)$$

Calculated cake %TS after two minutes of filtration data are valuable because they closely replicate the free drainage and low-pressure dewatering zones of the belt filter press, and because they fully capture the effect of the dilution of sludge by polymer solution, unlike CST and specific CST, and don't rely in their calculation on curve fitting, unlike specific resistance. For these reasons, particular consideration is given to calculated cake %TS values in the analysis that follows. However, it must be emphasized that this calculation does not account for the high-pressure compression of sludges that occurs on belt presses, and therefore the calculated values in this research are far below the targeted value for the plant of 20% TS. Nevertheless, it is our judgment that higher values of %TS achieved at the low pressure (vacuum) of the SRF test will correspond to higher values being achieved in the filter presses at the HBBMP.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 RESPONSES OF SPECIFIC RESISTANCE AND CST TO BASF POLYMER TYPE, DILUTION AND DOSE

The effects of BASF polymer type, dilution, and dose on both dewaterability measures were determined for several samples. The polymers tested were BASF Zetag 8819 and BASF Zetag 8848, as BASF is the vendor that CoA selected during the bid process. The Zetag 8819 polymer was originally selected, but ongoing full-scale testing for beneficial use of Zetag 8848 has been occurring during the period that the research reported herein was conducted. Results for specific resistance and CST are shown in Figure 4-1 (a) and (b), respectively; the data are shown in Tables A-2 and A-3 in the Appendix. The values shown for specific resistance are for a single test, whereas the CST values are the average of three tests on the same sample. Outliers in the CST data (>10% difference) were not included in the average CST calculation. The one very high value of specific resistance in Figure 4-1 (a) and the one high value of CST in Figure 4-1 (b) might be outliers, and the interpretation that follows discounts their importance.

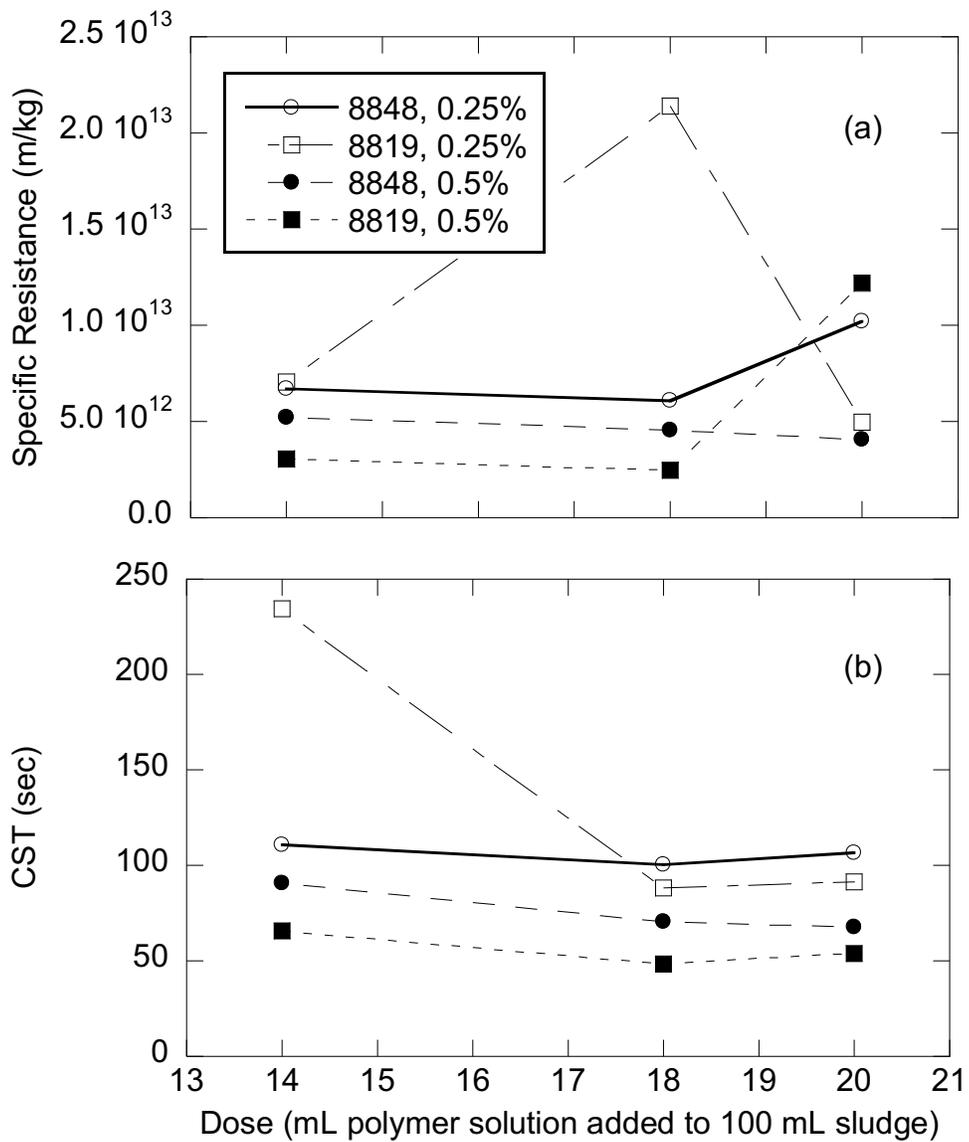


Figure 4-1: Specific resistance (a) and CST (b) as a function of polymer dose for two polymer types and dilutions

The first result that is clear from the data is that the higher polymer solution strength (0.5%) yielded lower values of both the specific resistance and the CST in virtually all cases. Note, however, that using the same dose of a stronger polymer

solution means using more raw polymer, so that achieving the lower values of these dewaterability measures is not necessarily the most cost-effective solution for the utility.

As can be seen, the specific resistance and CST decreased as the polymer dose increased from 14 mL/100 mL sludge to 18 mL/100 mL sludge for both polymers in seven of the eight cases. Conversely, when the dose was increased from 18 mL/100 mL sludge to 20 mL/100mL sludge, three of four CSTs increased, and two of four specific resistances increased. Thus, we can conclude that, among these three polymer doses, dewaterability was best at the dose of 18 mL/100 mL sludge for both types of polymer and at both polymer solution strengths.

For a fixed polymer dilution and dosage, the sludge dosed with BASF Zetag 8819 always had a lower CST than did the sludge with BASF Zetag 8848. This trend is almost always the case for SRF as well, with a few exceptions, including the one whose value might be considered an outlier. Therefore, we conclude that, for the sludge samples tested, the BASF Zetag 8819 was slightly better than the BASF Zetag 8848 for conditioning this digested sludge

A BASF representative, in conjunction with HBBMP staff, conducted a full-scale experiment in the field on April 20, 2017 to see if BASF Zetag 8848 might improve sludge dewaterability when compared to BASF Zetag 8819. Various dilutions and doses of both Zetag 8819 and Zetag 8848 were mixed with sludge and sent to the belt presses. The dewatered sludge percent total solids (%TS) was measured as an indication of how well the sludge was being dewatered. The results of the test are presented below in Table 4-1. Note that the volume of polymer solution per volume of digested sludge was generally less than in the laboratory tests, with the highest value in the field being the equivalent of the lowest value (14 mL/100 mL) of the laboratory tests.

Table 4-1: Full-scale test of Zetag 8848 and 8819: The influence of polymer concentration and dosage on dewatered sludge % TS

Time	Polymer Solution Strength	Volume Polymer Solution: Volume Sludge	Dewatered Sludge %TS
Zetag 8848			
9:00 AM	0.44%	0.108	14.8
9:30 AM	0.44%	0.108	14.9
10:00 AM	0.44%	0.108	15
10:30 AM	0.40%	0.108	13.7
11:00 AM	0.30%	0.143	13.9
11:30 AM	0.30%	0.143	14.5
12:00 PM	0.37%	0.143	15
12:30 PM	0.49%	0.108	15.2
Zetag 8819			
1:00 PM	0.49%	0.108	15.5
1:30 PM	0.28%	0.143	15.4
2:00 PM	0.28%	0.143	15.5
2:30 PM	0.28%	0.143	14.6
3:00 PM	0.28%	0.143	14.8
3:30 PM	0.28%	0.143	14.3
4:00 PM	0.28%	0.143	14.5
4:30 PM	0.28%	0.143	14.5

The results in the Table 4-1 indicate that the full-scale dewatering performance of these two polymers is not significantly different. For the Zetag 8848 polymer, the data gave some slight indication that increasing the polymer solution concentration improved dewaterability, but the testing performed on the Zetag 8819 polymer did not allow for such analysis. Similarly, the effect of increasing polymer dose was minimal on dewatering performance at full-scale. Note that polymer solution concentration and

dosage can only be adjusted coarsely in the field, so the values in Table 4-1 might not be precise.

4.2 RESPONSE OF CST TO THE DILUTION OF SLUDGE AND DEVELOPMENT OF SPECIFIC CST

Based on previous results, it was hypothesized that simply measuring the CST of a conditioned sludge did not account for the effect of dilution of the sludge by the polymer solution added. To confirm this hypothesis, CST was measured as a function of the volume of tap water added to the sludge and specific CST was calculated for the same volumes. The results of this study are presented in Figure 4-2.

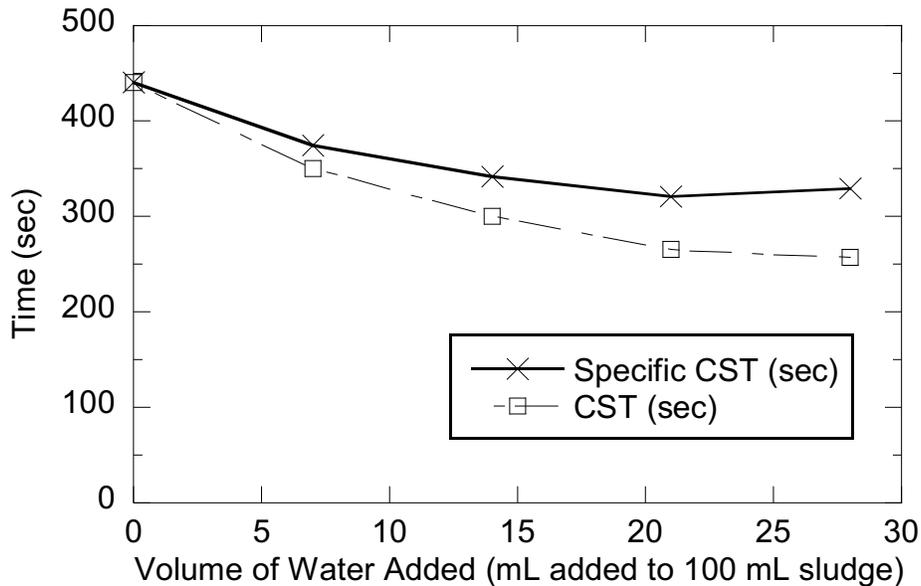


Figure 4-2: CST and Specific CST as a function of tap water added to the sludge

It is clear from this figure that diluting the sludge with water serves to substantially decrease the CST of that sludge. To better account for this effect in future studies, specific CST was developed. As mentioned in the Experimental Methods section, specific CST is a simple calculation wherein the CST is multiplied by the ratio of

the total volume of the sample, including both polymer solution and sludge, to the volume of sludge alone. If specific CST perfectly captured the effect of the dilution of the sludge by water, the specific CST values presented in Figure 4-2 would yield a horizontal line. It is obvious that this is not the case. However, the specific CST data vary less, and are closer to the undiluted sludge CST value than are the plain CST data. Further, it was determined that evaluating CST or specific CST as a function of polymer solution dose was suboptimal, as increasing polymer solution dose increases polymer costs for the utility. Rather, consideration of specific CST as a function of raw polymer dose better accounts for the effect of the dilution of sludge by the polymer solution, and intuitively allows the reader to comprehend the corresponding cost to the utility. With these new parameters in hand, the study performed in section 4.1 was repeated and plotted as specific CST as a function of raw polymer added. The results are shown in Figure 4-3.

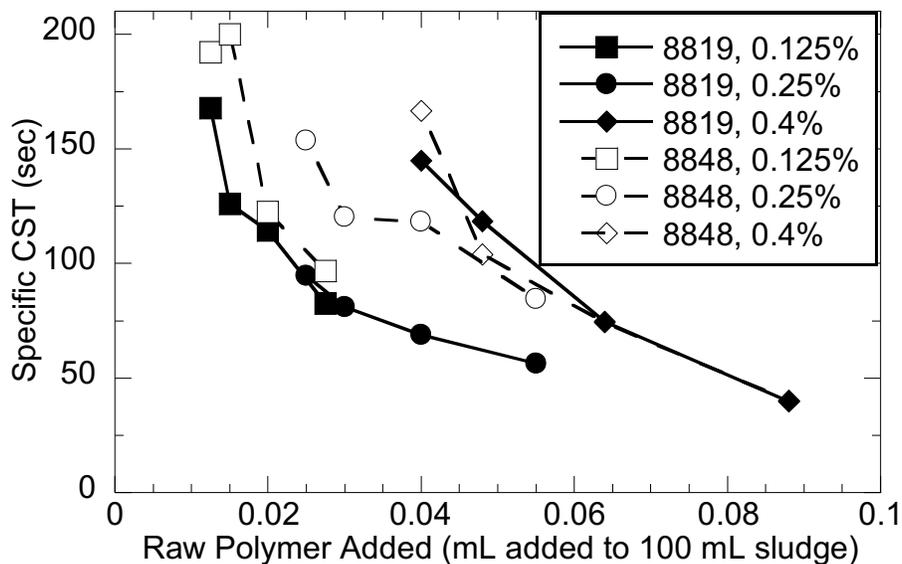


Figure 4-3: Specific CST as a function of raw polymer added for BASF Zetag 8819 and 8848

These data confirm the main conclusion from the previous study: for a fixed polymer solution concentration and raw polymer dose, Zetag 8819 improved specific CST more than Zetag 8848 for all but one measurement. However, the presentation of these data allows for further insight. First, if polymer solution concentration had no effect on dewaterability, one would expect all curves for that polymer to run together for a fixed raw polymer dose. The low polymer dose range exhibits this trend for the Zetag 8819 polymer, but it appears that polymer solution concentration has some effect on dewaterability at the moderate to high raw polymer doses. Further, it can be seen that increasing the raw polymer dose always improved specific CST for a fixed polymer solution concentration. The benefit of increasing the raw polymer dose is countered by an increasing polymer cost for the utility.

Based on these results, all investigations of dewaterability parameters (CST, specific CST, specific resistance, and cake %TS) that follow are presented as functions of raw polymer added, where appropriate.

4.3 RESPONSE OF SPECIFIC CST TO POLYMER SOLUTION AGING TIME

The BASF polymer representative suggested that the addition of a polymer solution-aging tank has improved dewatering performance in other, similar applications. This suggestion is supported broadly in the literature (de Gennes (1971), Kim (2016) and Caspar et. al, (2011)). As a result, the effect of polymer aging on specific CST was examined at the laboratory scale to determine potential benefits. First, both the BASF Zetag 8819 and 8848 were tested at the same polymer solution concentration and raw polymer dose to determine if either polymer might have preferable aging characteristics relative to the other. The results of that test are shown in Figure 4-4.

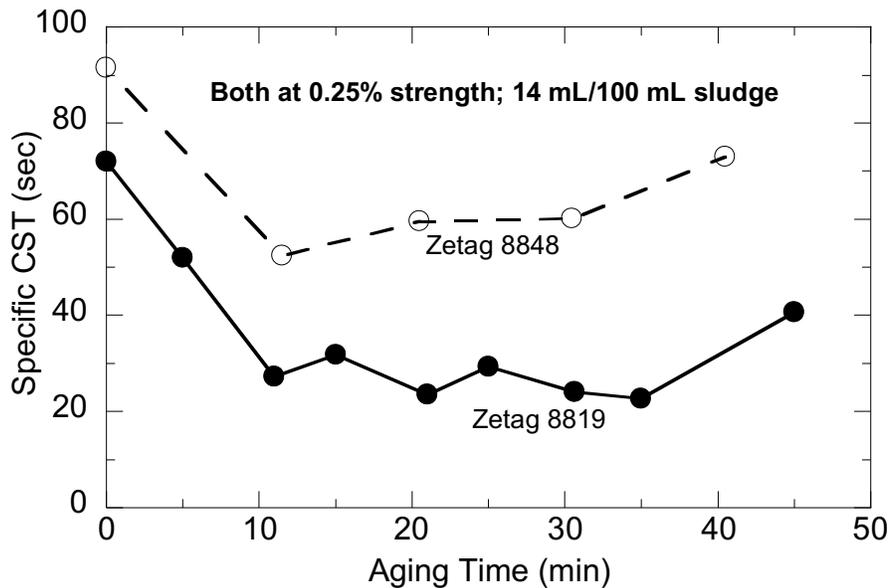


Figure 4-4: CST as a function of polymer solution aging time for BASF Zetag 8819 and 8848

These data indicate that the specific CSTs achieved by both polymers were reduced to approximately one-half the original value with an aging time of ten minutes or longer. Further, the specific CSTs measured were relatively stable with aging times ranging from 10 to 30 minutes. The specific CSTs achieved for a given aging time were always lower for the Zetag 8819 polymer than those for the Zetag 8848 polymer. These results support the results of the previous study, further indicating that the Zetag 8819 polymer is better suited for this application than the Zetag 8848 polymer. For these reasons, the studies that follow only include BASF Zetag 8819 in their analyses.

4.4 RESPONSE OF SPECIFIC CST TO THE VOLUME OF RAW POLYMER ADDED AND POLYMER SOLUTION AGING TIME

After elimination of the BASF Zetag 8848 polymer from consideration due to poor performance relative to BASF Zetag 8819, CoA staff suggested the evaluation of another polymer vendor, Polydyne, with whom CoA has had previous contractual relationships.

The Polydyne representative recommended the Clarifloc CE 1632 polymer as the most effective polymer for HBBMP, and it is thus considered in the analyses that follow.

4.4.1 BASF Zetag 8819

The applied raw BASF Zetag 8819 polymer dose was varied, and specific CST was measured as a function of polymer solution aging time for various polymer solution concentrations to determine the effect of raw polymer dose, polymer solution concentration, and polymer aging on specific CST. The results are presented in this section.

For the lowest raw polymer dose shown in Figure 4-5, all polymer solution concentrations yielded substantially lower specific CSTs when aged for ten minutes or longer. Additionally, the achieved specific CST values for a given polymer solution concentration were relatively stable for all aging times from ten to thirty-five minutes. With aging times greater than or equal to twenty minutes, the 0.125% solution achieved the lowest specific CSTs followed by the 0.4% solution, 0.25% solution, and 0.5% solution. Note that a large portion of the effect of the 0.125% polymer solution dose is likely due to dilution of the sludge by polymer solution, as that sample had 21% polymer solution added by volume. As noted above, the simple specific CST calculation does not fully account for this dilution effect.

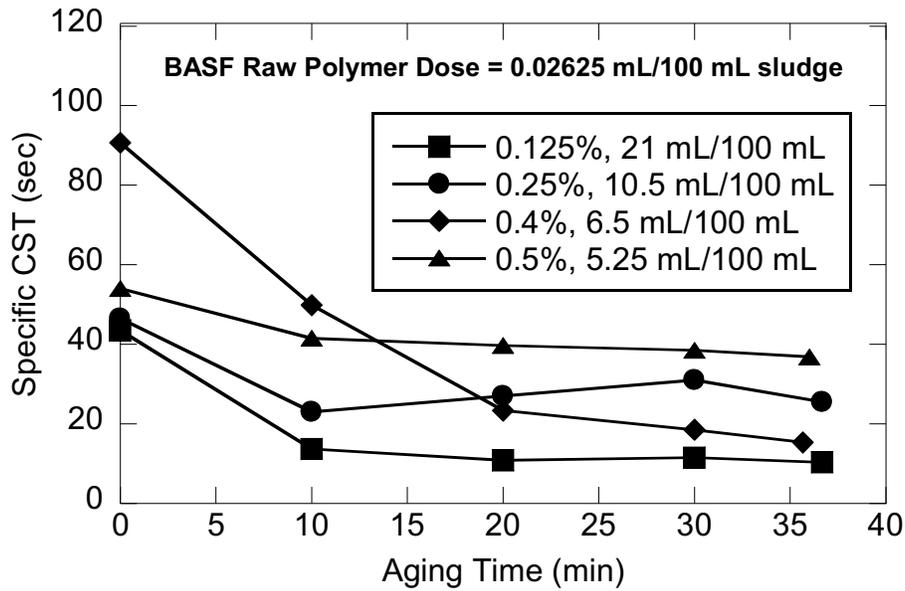


Figure 4-5: Specific CST as a function of polymer solution aging time for various polymer solution concentrations and a raw polymer dose of 0.02625 mL/100 mL sludge

Similarly, for the intermediate raw polymer dose shown below in Figure 4-6, all polymer solution concentrations yielded substantially lower specific CSTs when aged for ten minutes or longer. Like the lowest raw polymer dose, the specific CST values for a given polymer solution concentration were relatively stable for all aging times from ten to thirty-five minutes. With aging times greater than or equal to twenty minutes, the 0.4% solution achieved the lowest specific CSTs, followed by the 0.125% solution, 0.25% solution, and 0.5% solution. The same assumption regarding unaccounted for dilution of the sludge by polymer solution applies here for the 0.125% solution.

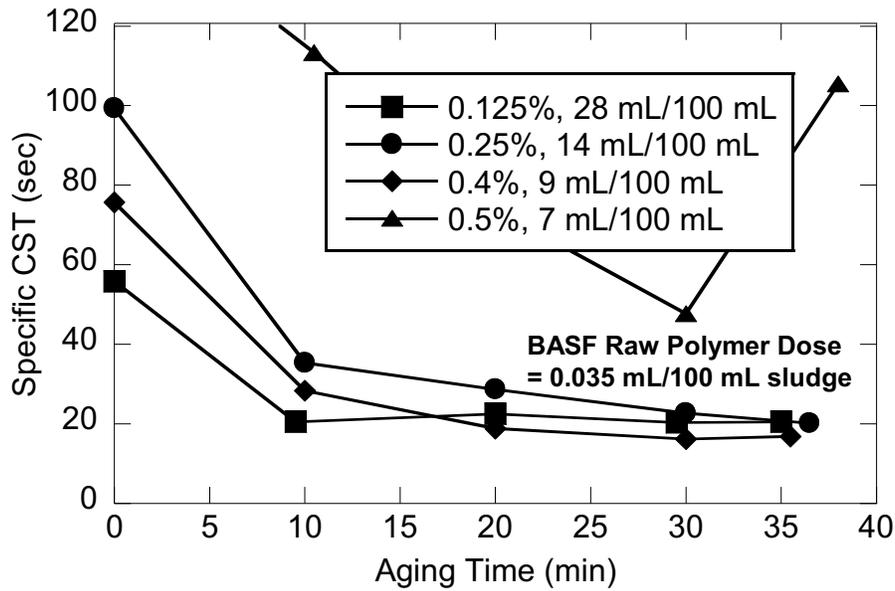


Figure 4-6: Specific CST as a function of polymer solution aging time for various polymer solution concentrations and a raw polymer dose of 0.035 mL/100 mL sludge

The highest raw polymer dose tested, shown in Figure 4-7, demonstrated substantially different characteristics than the previous two. Three of the four polymer solution concentrations tested demonstrated specific CST values that increased with ten minutes of polymer solution aging. The measured specific CST data were also relatively erratic, potentially due to the difficulty of drawing a representative aliquot from a larger, well-flocculated sample for CST testing. These results are perhaps indicative of a raw polymer overdose, where aging may not be required due to the substantial quantity of raw polymer added.

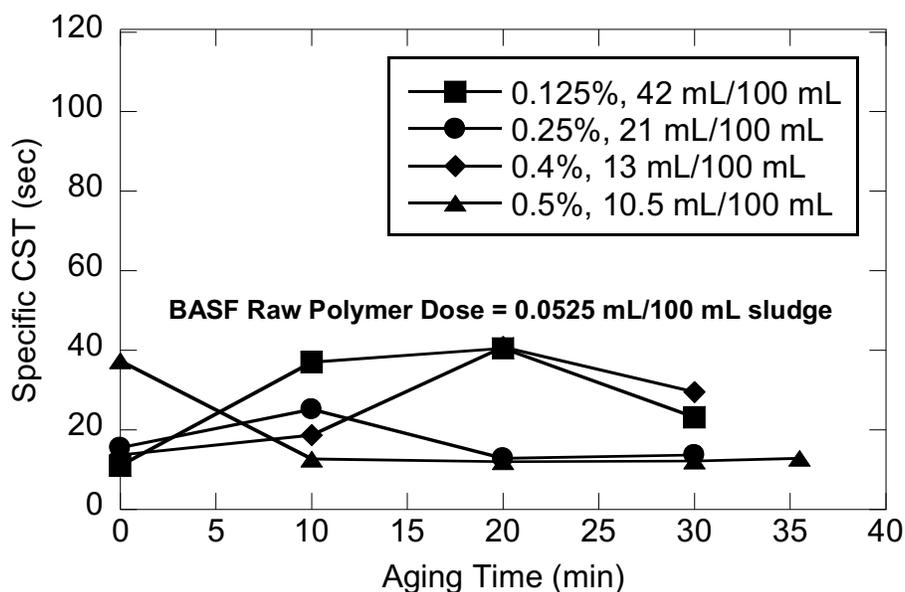


Figure 4-7: Specific CST as a function of polymer solution aging time for various polymer solution concentrations and a raw polymer dose of 0.0525 mL/100 mL sludge

When comparing all three raw polymer doses, a few key facts are evident. First, the effect of polymer solution concentration on aged specific CST appears to be reduced with increasing raw polymer dose. This trend is evidenced by the relatively tightly grouped aged specific CST values for the 0.035 mL and 0.0525 mL raw polymer doses, grouped around approximately twenty seconds in both cases, relative to the aged specific CST values for the 0.02625 mL raw polymer dose, which varies from approximately ten seconds for the 0.125% solution to nearly forty seconds for the 0.5% solution. Also, aging of both of the two lowest raw polymer doses for ten to thirty minutes reduced the measured specific CSTs by more than half. For these raw polymer volumes, the 0.125% and 0.4% solution concentrations yielded the lowest aged specific CSTs, respectively, followed by the 0.25% solution. Further, the 0.4% polymer solution achieved the lowest specific CST with an aging time of thirty minutes in both well-behaved cases.

Additionally, the 0.035 mL raw polymer dose was both less sensitive to variations in polymer solution concentration, and obtained slightly lower aged specific CSTs for the dilutions of interest. Based on this analysis, it appears that dosing 0.035 mL of polymer/100 mL sludge, creating a polymer solution ranging from 0.25%-0.4%, and aging that solution for approximately thirty minutes would yield optimal dewatering results. Choosing the more concentrated polymer solution would maximize dewaterability while minimizing sidewater production due to the addition of polymer make-down water.

4.4.2 Polydyne Clarifloc CE 1632

The same analysis as described in section 4.4.1 was performed for the Polydyne Clarifloc CE 1632 polymer, and the results are presented in this section.

For the lowest raw polymer dose shown in Figure 4-8, no significant improvement in specific CST occurred with increasing polymer solution aging time for any of the solution concentrations tested. The lowest specific CSTs were achieved for the 0.125% solution, followed by the 0.25% solution, 0.4% solution, and 0.5% solution. These results indicate that, for small raw polymer doses, the effect of polymer solution concentration on specific CST is substantial, with specific CSTs ranging from approximately twenty seconds for the 0.125% solution to approximately seventy seconds for the 0.5% solution.

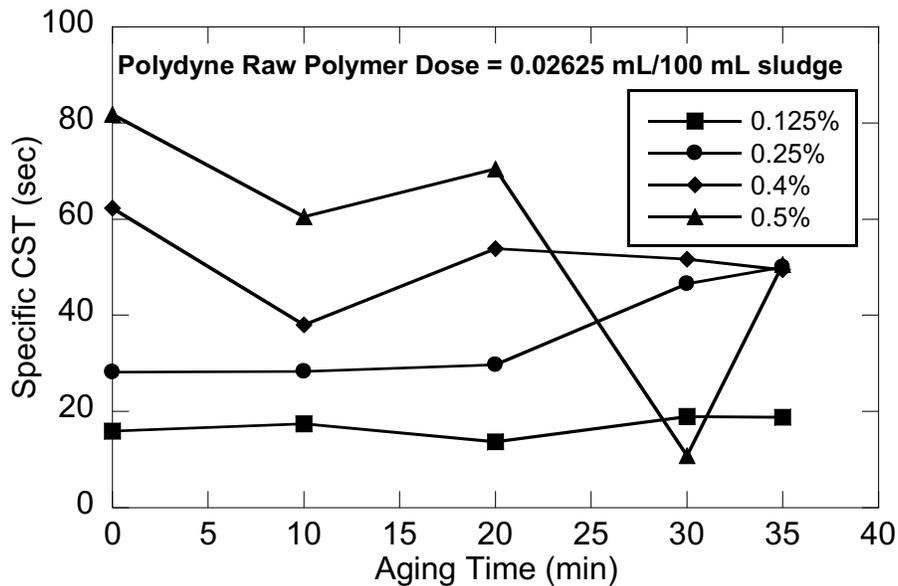


Figure 4-8: Specific CST as a function of polymer solution aging time for various polymer solution concentrations and a raw polymer dose of 0.02625 mL/100 mL sludge

For the intermediate raw polymer dose shown in Figure 4-9, no improvement in specific CST was observed with increasing polymer solution aging time for any of the polymer solution concentrations tested. The lowest specific CSTs were achieved for the 0.125% solution concentration, and specific CSTs again increased with increasing polymer solution concentration. For this higher raw polymer dose, the effect of polymer solution concentration on achieved specific CST is still evident, but substantially smaller in magnitude than the effect for the lower raw polymer dose. In this experiment, specific CSTs ranged from approximately ten seconds for the 0.125% solution to approximately twenty-five seconds for the 0.4% solution.

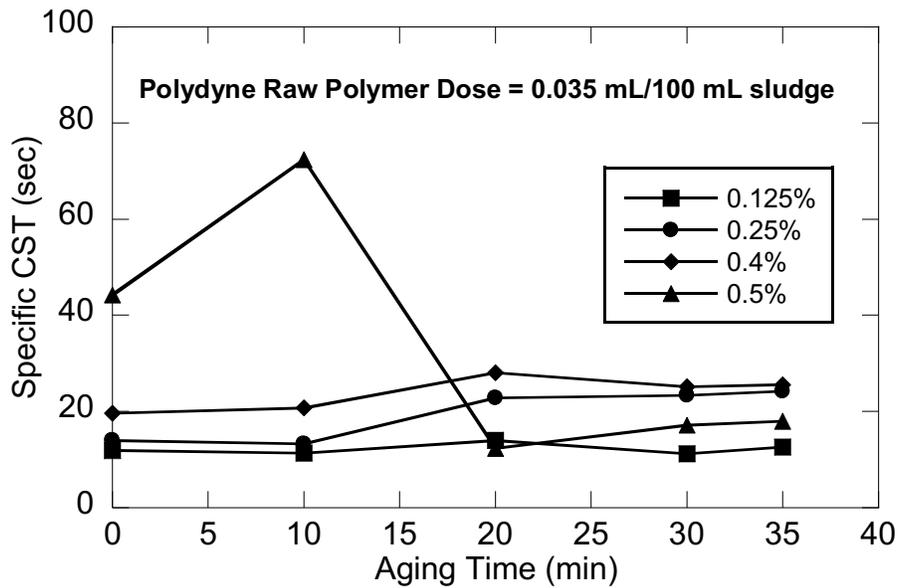


Figure 4-9: Specific CST as a function of polymer solution aging time for various polymer solution concentrations and a raw polymer dose of 0.035 mL/100 mL sludge

For the highest raw polymer dose shown in Figure 4-10, no aging effect was observed for any of the polymer solution concentrations tested. The specific CSTs for each polymer solution concentration were tightly grouped, and generally ranged from nine to thirteen seconds for all polymer solution concentrations. This result is further evidence of the decreasing impact of polymer solution concentration on specific CST with increasing raw polymer dose.

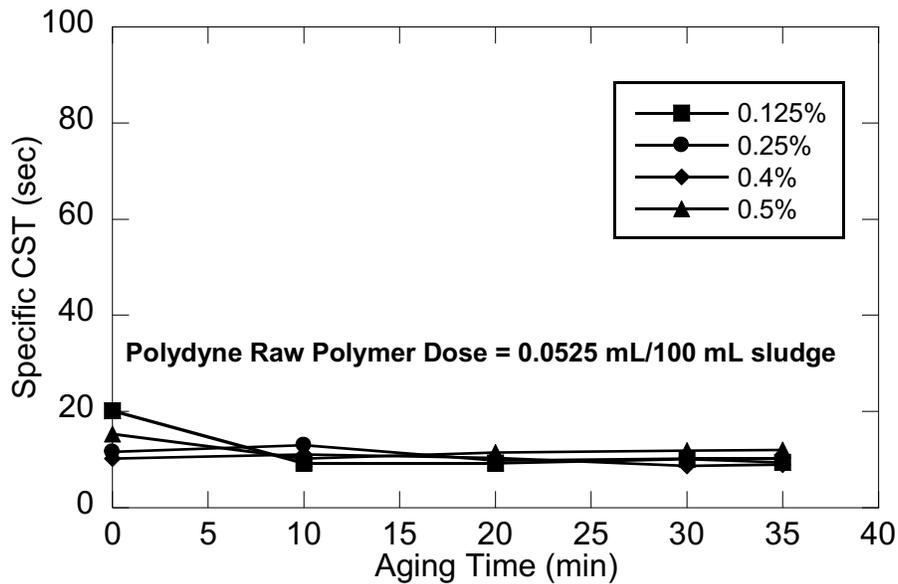


Figure 4-10: Specific CST as a function of polymer solution aging time for various polymer solution concentrations and a raw polymer dose of 0.0525 mL/100 mL sludge

When considering all three raw polymer doses together, three facts are evident. First, the Polydyne Clarifloc CE 1632 polymer does not benefit from polymer solution aging. Second, the effect of polymer solution concentration on specific CST is reduced with increasing raw polymer dose; at the highest raw polymer dose tested, 0.0525 mL/100 mL sludge, the effect of polymer solution concentration was negligible. Finally, it appears that specific CST decreases with increasing raw polymer dose, albeit by a small margin. Based on this analysis, it appears that dosing Polydyne Clarifloc CE 1632 at 0.035-0.0525 mL/100 mL sludge, adding water to create a 0.25%-0.4% polymer solution would yield the best dewatering results for that polymer.

4.5 RESPONSE OF SPECIFIC CST, SRF, AND TOTAL CAKE SOLIDS TO RAW POLYMER DOSE AND POLYMER SOLUTION CONCENTRATION

Based on the analysis in the preceding section, it was determined that all further tests using BASF Zetag 8819 should be performed after having aged the polymer solution of desired concentration for fifteen minutes, as this amount of aging yielded significantly reduced specific CSTs without increasing raw polymer demand. Conversely, polymer solutions made with Polydyne CE 1632 were not aged, as previous experiments demonstrated no reduction in specific CST with increasing polymer solution age. The volume of raw polymer added and polymer solution concentration were varied, and specific CST, SRF, and the calculated cake %TS after two minutes of filtration were measured. Two minutes was chosen as the time after which to make cake %TS measurements as that is the contact time for the sludge applied to the belt filter press at HBBMP, as reported by operational staff. Note again that these calculated %TS values are not an indication of the expected %TS that would be achieved on the belt press, as the sludges in this test are only exposed to a mild vacuum, not the substantial pressure applied on the belt press. Specific CST values presented are the average of three tests, while specific resistance and calculated cake %TS are results of a single test. The results of these tests are shown below in distinct sections for BASF Zetag 8819 and Polydyne Clarifoc CE 1632. The data are presented graphically in the sections that follow, but the exact values are presented in the Appendix.

4.5.1 BASF Zetag 8819

The specific CST data shown in 4-11 (a) indicate that, at the lowest raw polymer dose tested, the effect of polymer solution concentration was substantial. With increasing raw polymer doses, the effect of polymer solution concentration was reduced to near-

negligible levels. Except for the 0.5% polymer solution, increases in raw polymer dose beyond 0.02625 mL/100 mL sludge did not significantly reduce specific CST. Based on these results, it appears that a raw polymer dose ranging from 0.02625-0.035 mL/100 mL sludge at a solution concentration ranging from 0.25%-0.4% would yield best dewatering results. Note that choosing a raw polymer dose on the low end of that range and a polymer solution concentration on the high end of its range would yield lowest polymer costs and minimize sidewater production.

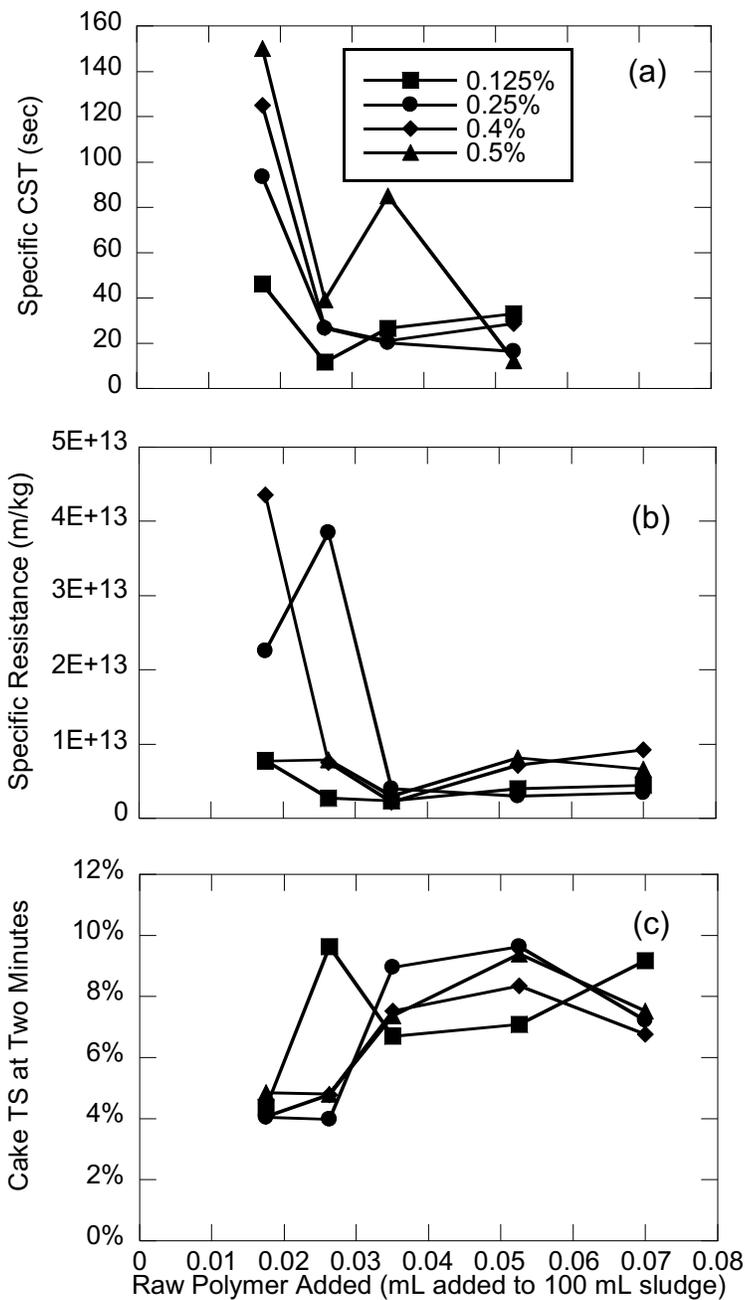


Figure 4-11: Specific CST (a), specific resistance (b), and calculated cake %TS at two minutes (c) as a function of the volume of raw BASF Zetag 8819 polymer added for various polymer solution concentrations

The specific resistance data presented in 4-11 (b) are similar to those for specific CST. First, polymer solution concentration has a decreasing effect on specific resistance with increasing raw polymer dose. Next, increasing the raw polymer dose beyond 0.035 mL/100 mL sludge did not significantly improve measured specific resistances for any of the solution concentrations tested. Note also that the two lowest raw polymer doses for the 0.25% and 0.4% solution concentrations yielded specific resistance values nearly an order of magnitude larger than those obtained from raw polymer doses greater than or equal to 0.035 mL/100 mL sludge. This result indicates that, for these intermediate solution concentrations, the specific resistance of the conditioned sludge is sensitive to raw polymer dose up to a minimum threshold, 0.035 mL/100 mL, after which specific resistance remains nearly constant. Based on these data, it appears that a raw polymer dose of 0.035-0.0525 mL/100 mL sludge at 0.25%-0.4% concentration would yield optimal dewatering performance.

The calculated cake %TS data presented in 4-11 (c) are indicative a number of important trends. First, for all but the most dilute polymer solution, the maximum cake TS achieved after two minutes of filtration occurred at a raw polymer dose of 0.0525 mL/100 mL sludge; however, in most cases, the result at the dose of 0.0525 mL/100 mL is only marginally better (approximately 0.5%) than at the dose of 0.035 mL/100 mL. For each of these three well-behaved cases, increasing the raw polymer dose beyond 0.0525 mL/100 mL sludge yielded lower cake TS values. This latter trend is likely due to the development of free polymer colloidal solids in the case of a polymer overdose. For the same three well-behaved cases, the maximum cake %TS values achieved ranged from approximately 8% for the 0.4% solution to nearly 10% for the 0.25% solution. Note that these data are not indicative of the %TS values that would be achieved on the belt press, as our test did not emulate the low and high-pressure mechanical dewatering zones of the

belt press. However, it is likely that the best dose as determined by cake %TS testing is the best dose at full-scale. These data indicate that optimum dewatering performance would be attained for a raw polymer dose of 0.0525 mL/100 mL sludge at a 0.25% solution concentration.

Considering Figure 4-11 (a) through (c) together, two principal facts are evident. First, a minimum raw polymer dose of 0.035 mL/100 mL sludge is required to yield low specific CST and SRF values, and high cake %TS values. Next, at raw polymer doses ranging from 0.035-0.0525 mL/100 mL sludge, specific CST, SRF, and cake %TS were all relatively insensitive to variations in polymer solution concentration for all but the most concentrated polymer solution. Thus, it appears that, as long as the raw polymer feed-rate is chosen correctly, operational error in the make-down of the polymer solution is unlikely to affect sludge dewaterability.

4.5.2 Polydyne Clarifloc CE 1632

The specific CST data presented in 4-12 (a) indicate that, for all polymer solution concentrations, specific CST decreased with increasing raw polymer dose beyond the 0.02625 mL/100 mL sludge dose. It is also evident that with increasing raw polymer dose, the effect of polymer solution concentration on achieved specific CST decreases. The lowest specific CSTs were always achieved by the 0.125% solution, which is likely due to the effect of the dilution of sludge by the polymer solution that is not adequately captured in the calculation of specific CST. These results indicate the optimal dewatering performance would be achieved for a raw polymer dose of 0.0525 mL/100 mL sludge with a polymer solution concentration of 0.4%-0.5%.

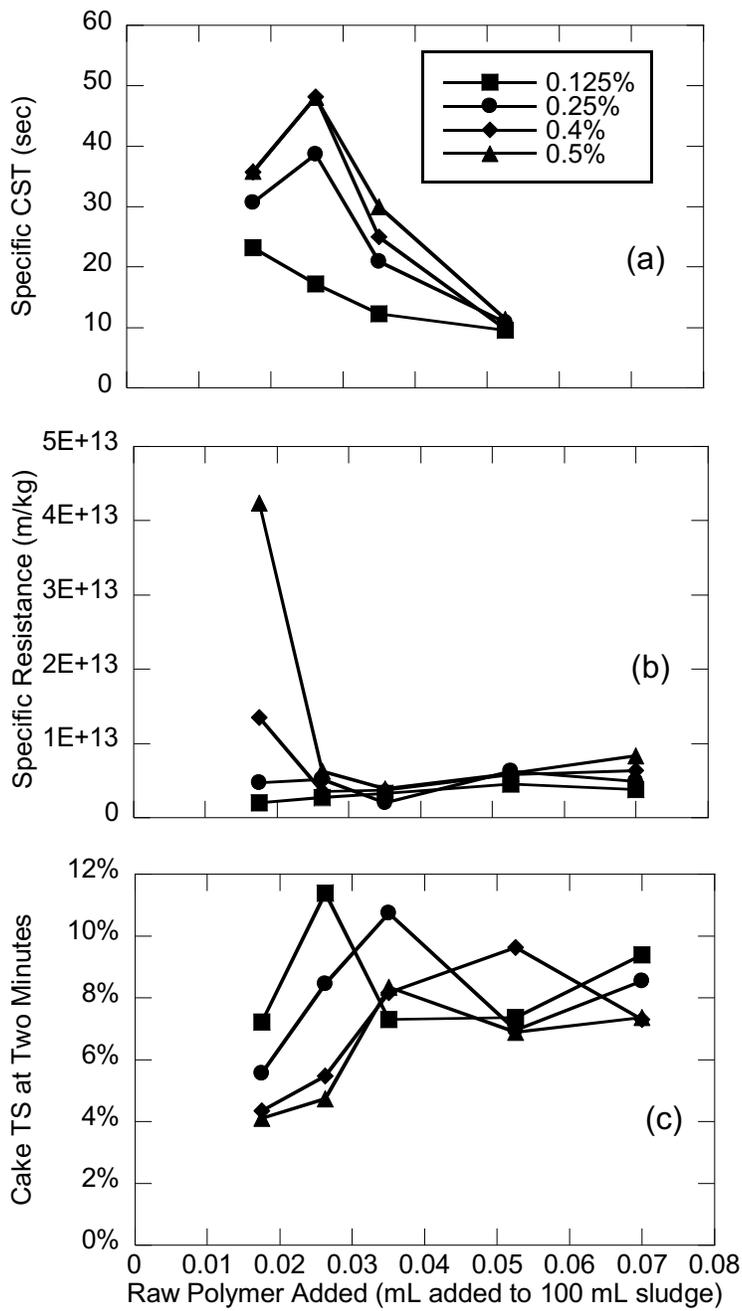


Figure 4-12: Specific CST (a), specific resistance (b), and calculated cake %TS at two minutes (c) as a function of the volume of raw Polydyne Clarifloc CE 1632 polymer added for various polymer solution concentrations

The specific resistance data presented in 4-12 (b) are similar to those for specific CST in that the effect of polymer solution concentration is negligible for raw polymer doses greater than or equal to 0.02625 mL/100 mL sludge. However, increasing the raw polymer dose beyond 0.02625 mL/100 mL sludge did not significantly improve achieved specific resistances for any polymer solution concentration tested. Three of the four polymer solution concentrations tested yielded minima in their specific resistances for the 0.035 mL raw polymer dose. As a result, it appears that a raw polymer dose of 0.035 mL/100 mL sludge at 0.25%-0.5% solution would yield optimal dewatering results, albeit by a small margin relative to other raw polymer doses in the 0.02625-0.07 mL range.

The calculated cake %TS data presented in 4-12 (c) show that three of the four polymer solution concentrations tested yielded maximum cake TS values at different raw polymer doses. Further, the maximum cake %TS values are substantially higher than the next highest value for the same polymer solution concentration. On average, the difference is approximately 2%. Polymer solution concentration also appears to have a significant impact on the maximum cake %TS achieved, ranging from nearly 12% for 0.125% solution to approximately 8.5% for the 0.5% solution. Ruling out the 0.125% solution due to the sheer volume of water that would need to be added to the sludge, it appears that a raw polymer dose of 0.035 mL/100 mL sludge at 0.25% concentration would yield optimal dewatering results. Variations from this optimal dose and/or concentration appear to significantly affect the achieved cake %TS.

Considering 4-12 (a) through (c) together, a few inconsistencies of concern are evident. First, while the specific CST and SRF data show a decreasing impact of polymer solution concentration with increasing raw polymer dose, the calculated cake %TS data were highly dependent on polymer solution concentration for all raw polymer doses tested. Next while SRF values were relatively stable for a raw polymer dose in

excess of 0.02625 mL/100 mL sludge, specific CSTs were reduced substantially for raw polymer doses greater than 0.02625 mL, and cake %TS values were erratic for the same doses. However, for each of the three dewatering parameters measured, 0.035 mL of raw polymer/100 mL sludge at 0.25% solution concentration appeared to yield optimal dewatering results. Small variations from this dose and solution concentration may have a significant impact on dewatering performance based on this analysis.

4.6 ECONOMIC ANALYSIS

The results presented in the preceding sections indicate that, for both polymers tested, the optimal raw polymer dose appears to be in the range of 0.035 mL – 0.0525mL/100 mL sludge. Note that CoA is currently targeting a raw polymer dose of 0.035 mL/100 mL sludge for conditioning of the digested sludge prior to dewatering at the belt press. In the economic analysis that follows, it is assumed that the current raw polymer dose would need to be increased to 0.0525 mL/100 mL sludge to demonstrate the relative economic value of increased cake %TS compared with increasing polymer costs. The disposal costs were calculated using sludge and cake volume data for the period from September 1, 2015 to August 31, 2016. We assume here that the relative proportions of sludge composted and land applied will remain constant, as will the costs associated with each type of beneficial re-use. The abscissa in Figure 4-13 represents theoretical increases in cake TS beyond 17%, the value HBBMP achieved most frequently in recent history. Note that this analysis assumes that these cake %TS increases would be sustained, on average, for the entire year. The ordinate axis shows net savings for corresponding increases in cake %TS beyond 17%. These savings are calculated as savings from reduced disposal costs minus the associated cost of increasing

the raw polymer dose from 0.035 mL to 0.0525 mL/100 mL sludge for both polymers, respectively.

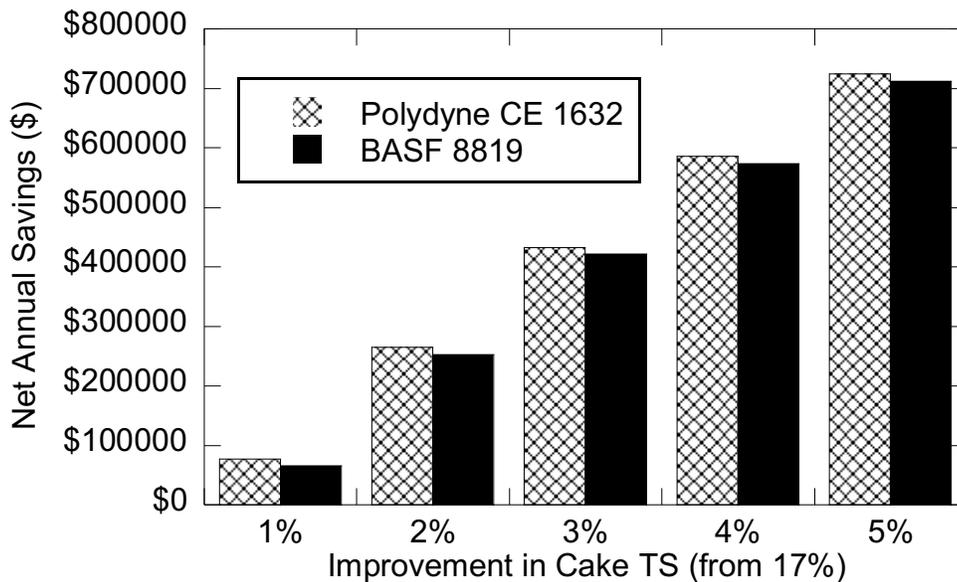


Figure 4-13: The effect of increasing cake TS on total dewatering costs for CoA considering two polymer manufacturers

Figure 4-13 demonstrates that, even for the minimum cake TS increase from 17% to 18%, CoA would save approximately \$75,000/year despite increasing the raw polymer dose by 150% for both polymers. Although the Polydyne polymer is slightly less expensive per pound, the overall effect of the price difference is negligible assuming that both polymers improved cake %TS values the same amount. Additional improvement in cake %TS beyond 18% yield savings up to approximately \$700,000/year for a cake TS of 22%. As suggested by Saveyn et al. (2008), these results indicate that the high cake disposal costs at HBBMP necessitate that the optimal polymer dose be used, even if that optimal dose is high. Although a 50% increase in raw polymer dose was assumed for this analysis, note that an increase in raw polymer dose from 0.035 mL/100 mL sludge may

not substantially improve cake %TS. Previous results indicate that aging a BASF Zetag 8819 polymer dose of 0.035 mL – 0.0525 mL/100 mL sludge at 0.25% - 0.4% solution for 10-30 minutes reduced specific CST by approximately half and thus dewaterability of the sludge would be expected to increase. As a result, HBBMP could apparently hold constant the current raw polymer dose, add a polymer aging tank, and improve their achieved cake %TS. By holding constant the raw polymer dose and simply including polymer solution aging, the utility could save even more per percent cake TS than shown in Figure 4-13 above, which assumes a 50% increase in raw polymer use. These savings are substantial, totaling \$143,276.87, annually. The only additional expenses incurred by the utility in implementing a polymer aging tank are the capital expenses associated with purchasing, procuring, and installing a tank of adequate volume. If we assume that the 0.035 mL raw polymer dose is achieved by making a 0.4% polymer solution, and dosing that solution at 9L added to 100L digested sludge, and we assume the average digested sludge flow is 130 gpm, we can estimate the tank volume required for 30 minutes of aging to be 350 gallons; a lesser aging time, which seems reasonable based on the results shown in Section 4.4.1, would allow for a smaller volume tank. A three-foot diameter tank would need to be approximately 6' 8" tall to accommodate such a volume, which is very reasonable in the space available at HBBMP. Note that with a fixed aging tank volume, the achieved aging time is directly proportional to the achieved polymer dilution. If, for example, raw polymer and make-up water flows were not correctly balanced and the polymer solution were only 0.25% concentration, the aging time would be reduced to less than 19 minutes. However, the specific CST data indicate that for the BASF Zetag 8819 polymer at a raw polymer dose of 0.035 mL/100 mL and 0.25% concentration, 19 minutes of polymer aging appears to substantially reduce specific CST and thus improve

dewaterability. It appears, then, that a 350 gallon aging tank is likely to provide robust dewatering improvements at minimal cost to the utility.

4.7 EFFECT OF POTENTIAL MAGNESIUM PRECIPITATES ON VOLUME OF SLUDGE DEWATERED AND SLUDGE DEWATERABILITY

As previously mentioned, one of the two upstream wastewater treatment plants that conveys its sludge to HBBMP has been substantially increasing its magnesium hydroxide feed rate in response to an increasing alkalinity demand for nitrification. CoA staff has expressed concern over formation of potential magnesium precipitates and their effect on the dewaterability of the digested sludge, as well as the mass of sludge cake produced requiring disposal.

In the analysis that follows, two principal assumptions were made: all added magnesium hydroxide ends up in the solid phase and is conveyed to HBBMP, and the most likely precipitates formed are magnesium hydroxide (Mg(OH)₂), dolomite (MgCa(CO₃)₂), magnesium carbonate (MgCO₃), and magnesium sulfide (MgS). The concentration of the precipitate formed is based on the mass ratio of the precipitate to magnesium hydroxide. Those values are presented in Table 4-2.

Table 4-2: Mass ratio of various magnesium precipitates to magnesium hydroxide

Solid Species Formed	Molecular Weight (g/mol)	Mass Ratio (mass solid species/mass Mg(OH)₂)
Mg(OH) ₂	58.32	1
MgCa(CO ₃) ₂	184.4	3.16
MgCO ₃	84.31	1.45
MgS	56.38	0.97

The above data indicate that the formation of only dolomite would yield the largest mass of magnesium precipitates, while formation of only magnesium sulfide would produce the smallest mass. In reality, the precipitates formed are likely a

combination of those listed above; digesters contain high concentrations of carbonate and sulfide and simple equilibrium calculations suggest that solid species containing these could precipitate in Austin’s digested sludge under the assumed conditions. To simplify things, theoretical minimum (all magnesium sulfide) and maximum (all dolomite) magnesium precipitate masses were calculated based on daily magnesium hydroxide feed data. A twenty-five day moving average was calculated to eliminate some of the inherent variation of the data. These theoretical minima and maxima running averages were plotted against the mass of sludge cake produced in Figure 4-14.

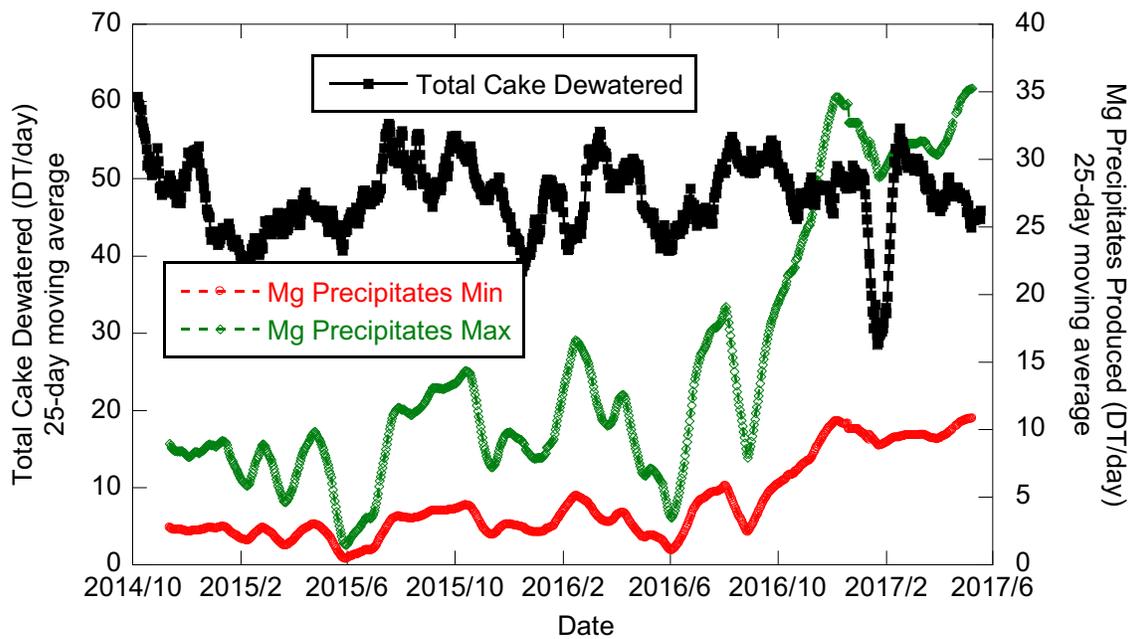


Figure 4-14: 25-day moving average of minimum and maximum theoretical magnesium precipitates and total mass of sludge cake dewatered

Figure 4-14 shows that the mass of sludge cake dewatered remained relatively constant over time, despite significant increases in potential magnesium precipitates formed. This result is somewhat surprising, especially given that the most recent data

indicates potential magnesium precipitate formation of approximately 10-35 DT/day relative to the total of approximately 50 DT of cake produced each day.

The stability of the mass of sludge cake produced relative to the increasing potential magnesium precipitate mass indicates that one of the assumptions made in this analysis must be incorrect. At least one of the following must be true: some of the magnesium hydroxide added at the upstream plant remains as soluble magnesium, or all of the precipitates formed are not collected and conveyed to the HBBMP belt presses.

It appears, then, that the precipitated solids compose a small enough fraction of the overall solids load that they are lost in the noise of the cake dewatered data. Therefore, based on the data analyzed in this section, no measurable increase in sludge cake disposal cost for the utility due to upstream magnesium hydroxide addition was observed.

4.8 EFFECT OF DIGESTER PERFORMANCE ON SLUDGE DEWATERABILITY

One of the main purposes of anaerobic digestion is to stabilize the sludge by converting volatile solids into carbon dioxide and methane. It is logical, then, that a high volatile solids content in the effluent of an anaerobic digester is indicative of poor digester performance. Further, Lawler et al. (1986) showed that when digestion is working well, particles of all sizes are removed, but small particles are preferentially removed, decreasing specific surface area and improving dewaterability of the digested sludge. Conversely, when digestion is not working well, large particles are preferentially removed, and more, smaller particles are created, increasing specific surface area and hindering dewaterability. Combining these two ideas, it follows that digester effluent that has a high volatile solids concentration is likely to not dewater well.

Revisiting Figure 2-4, it is evident that there is an increasing trend in the volatile solids content of the sludge cake over time. Increasing volatile solids concentration in the sludge cake is indicative of a decrease in digester performance. The same data as shown in Figure 2-4 are plotted in Figure 4-15, but they are visualized as the total solids concentration of the sludge cake as a function of the volatile solids concentration; data from the period when the calcium carbonate sludge from the water treatment plants was being disposed of through the wastewater plants are omitted.

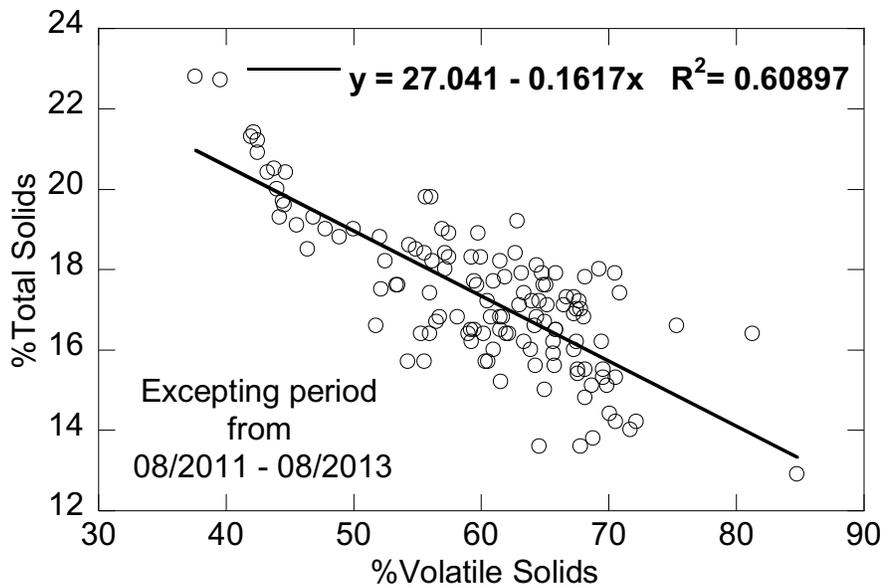


Figure 4-15: Sludge cake total solids as a function of sludge cake volatile solids

It is clear from Figure 4-15 that there is a strong negative correlation between percent volatile solids and percent total solids. These data support the idea that, when digestion is working well and digester effluent volatile solids concentrations are low, the sludge is more easily dewatered. Conversely, when digestion is not working well and digester effluent volatile solids concentrations are high, the sludge is more difficult to

dewater. Irrespective of the sludge conditioning process, the performance of the digester is inextricably tied to dewatering performance.

CHAPTER FIVE: CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

5.1 CONCLUSIONS

The objectives of this work were to optimize the sludge conditioning process to maximize the sludge cake %TS achieved by the belt presses at HBBMP as well as to quantify the effects of upstream magnesium hydroxide addition on the dewaterability of the digested sludge and the mass of sludge cake produced. CST, specific resistance, specific CST, and calculated %TS data were analyzed as a function of raw polymer dose and polymer solution concentration to determine the optimal bench scale raw polymer dose and polymer solution concentration combination. Note that the calculated %TS values determined at the bench scale are not indicative of the values that would be achieved after full-scale belt press dewatering, as the bench-scale experimental procedures did not replicate the low and high-pressure zones of the BFP where significantly quantities of water are expelled. However, the raw polymer dose and solution concentration that yielded the highest cake %TS at the bench scale would likely do the same at full-scale. Maximum and minimum daily magnesium precipitate masses were calculated based on the mass ratio of various magnesium solids to magnesium hydroxide. These theoretical data were compared against the daily mass of sludge cake produced from April 2005 through February 2017 to determine the disposal cost of the increased magnesium hydroxide addition at Walnut Creek WWTP. The following conclusions can be made based on the preceding results:

1. BASF Zetag 8819 polymer solutions must be aged for 10-30 minutes to obtain optimal dewatering results; all of the data presented in Section 4.5 is for BASF polymer solutions aged for fifteen minutes. Specific CSTs were reduced by more than half in all well-behaved cases for polymer

solutions aged for more than 10 minutes. While it is difficult to extrapolate these specific CST reductions to theoretical increases in cake %TS, the result is indicative of a substantial and consistent increase in dewaterability that can be realized at scale in a cost-effective manner. For the raw polymer dose currently applied, 0.035 mL/100 mL sludge, a 350-gallon aging tank is required to age a 0.4% polymer solution for 30 minutes. This small required volume minimizes capital expenses and footprint, and yet is expected to improve sludge dewaterability.

2. For BASF Zetag 8819 polymer solutions aged 10-30 minutes, 0.035 mL – 0.0525 mL of raw polymer added per 100 mL sludge at a polymer solution concentration of 0.25%-0.4% appears to be the optimal raw polymer dose range and solution concentration range, respectively.
 - a. Specific CSTs for these combinations of raw polymer dose and solution concentration ranged from 16-29 sec. Specific CST appeared relatively stable in the raw polymer dose and polymer solution concentration ranges of interest.
 - b. Specific resistances for these combinations of raw polymer dose and solution concentration ranged from 2.22e+12 to 3.98e+12 m/kg, with the exception of one combination, which appears to be an outlier. Specific resistance appeared relatively stable in the raw polymer dose and polymer solution concentration ranges of interest.
 - c. Cake %TS concentrations achieved for these combinations of raw polymer dose and solution concentration ranged from 7.52% to 9.64%. Maximum cake %TS values were achieved for the 0.0525

mL/100 mL raw polymer dose for both the 0.25% and 0.4% solutions, and the next highest values were achieved for the 0.035 mL/100 mL dose. These maximum values were 8.36% and 9.64%, respectively. Cake %TS results should be assigned particular weight in analyzing the optimal raw polymer dose and solution concentration, as the calculation fully captures the dilution of sludge by polymer solution, unlike specific CST, and does not rely in its calculation on fitting parameters, unlike specific resistance.

3. Polydyne Clarifloc CE 1632 did not yield consistently and substantially better dewaterability metrics for a fixed raw polymer dose and polymer solution concentration than did BASF Zetag 8819 when aged with no mixing for 10-30 minutes. Optimal specific CST values achieved for both polymers were in the range of 10-30 seconds for all polymer solution concentrations. Optimal specific resistance values for both polymers were centered around approximately $5e+12$ m/kg for both polymers at all polymer solution concentrations. The maximum calculated cake %TS ranged from 8%-12% for the Polydyne polymer and 7%-10% for the BASF polymer, but the required raw Polydyne polymer dose to achieve maximum cake %TS was highly variable depending on the polymer solution concentration. Conversely, excepting the most dilute polymer solution, the BASF polymer always attained maximum cake %TS values for a raw polymer dose of 0.0525 mL/100 mL sludge, and its next highest value at 0.035 mL/100 mL sludge. These results are indicative of a more robust solution at full-scale. Although the BASF polymer is slightly more expensive per pound and requires polymer solution aging to maximize

sludge dewaterability, the additional cost relative to potential savings in disposal costs is negligible. For these reasons, coupled with existing contractual obligations between CoA and BASF, HBBMP staff should continue to use BASF Zetag 8819 as the polymer of choice at the belt presses.

4. The effect of magnesium precipitate formation due to increased magnesium hydroxide addition upstream of HBBMP has had no tangible impact on the mass of cake dewatered, or the dewaterability characteristics of the sludge. Further, the literature suggests that the addition of divalent cations, like magnesium, to an activated sludge increases the dewaterability of that sludge due to double layer compression. It is also likely that unless the precipitates formed are magnesium hydroxide solids (which is unlikely at the pH of digested sludges), the waters of hydration for the precipitates are substantially lower than for biosolids. Together, these facts suggest that, in the hypothetical future event that significant volumes of magnesium precipitates were reaching the belt presses, the dewaterability of the sludge may be improved.

5.2 RECOMMENDATIONS

Based on the preceding results and the above conclusions, we recommend the following to HBBMP staff:

1. Conduct full-scale testing at the belt press to confirm the optimal raw polymer dose and solution concentration determined at the bench scale for aged BASF Zetag 8819 polymer solutions.

- a. Begin by adding a polymer solution aging tank of sufficient volume (350 gallons), and maintaining the current raw polymer dose, 0.035 mL/100 mL sludge, at the current polymer solution concentration, 0.25%. Measure achieved cake %TS twice daily for a duration of two (2) weeks to determine improvements in sludge dewaterability.
- b. After the impact of aging alone has been determined, increase the raw polymer dose 50% from 0.035 mL/100 mL sludge to 0.0525 mL/100 mL sludge. Measure achieved cake %TS twice daily for a duration of two (2) weeks to determine improvements in sludge dewaterability. Although this test protocol increases the raw polymer cost for the utility by 50%, our calculations show that a one-percent annual increase in cake %TS covers the additional raw polymer cost of \$143,276, and saves an additional \$75,000 in disposal costs.
- c. If the increased raw polymer dose from (b) has negligible or negative impact on cake %TS, return the raw polymer dose to 0.035 mL/100 mL sludge.
- d. After determining the effect of aging and raw polymer dose, increase the polymer solution concentration from 0.25% to 0.4%. Bench scale testing indicated that increasing the polymer solution concentration for the two raw polymer doses of interest increased specific CSTs and decreased calculated cake %TS, albeit by a small margin; both of these outcomes are undesirable. Regardless, it is worthwhile to confirm these bench scale results at scale

because increasing polymer solution concentration yields reduced volumes of sidewater produced by dewatering. Measure achieved cake %TS twice daily for a duration of two (2) weeks to determine improvements, if any, in sludge dewaterability.

- e. Select the combination of raw polymer dose and polymer solution concentration that yields the highest achieved cake %TS values, and resume normal operation.
2. Revise specification for “Liquid Emulsion Cationic Polymer for Sludge Thickening and Dewatering” to ensure future bidding contractors are required to perform consistent tests that allow for selection of the most cost-effective polymer for the application.
 - a. Revise section 4.1 of the specification to require a gravity drainage test in evaluating potential polymers. The general procedure for a gravity drainage test is as follows:
 - i. Measure 200 mL of well-mixed, fresh sludge into a 400 or 500 mL beaker.
 - ii. Add the desired volume of polymer solution all at once.
 - iii. Mix the treated sludge by pouring from one beaker to another 16 times.
 - iv. Rapidly transfer the conditioned sludge to a 10 cm Buchner Funnel equipped with the belt-press filter fabric held in place with a section of 2.5” o.d. stainless steel pipe and supported over a 250 mL graduate.
 - v. Start timing filtration when liquid is first observed falling from the funnel tip.

- vi. Record on Drainage Test Data Sheet the volume of filtrate collected at 5, 10, 15, 20 30 and 60, 90, and 120 sec
 - vii. Carefully clean beakers, funnel, ring and cylinder, and especially the filter fabric.
 - viii. Repeat Steps i-vii as necessary with additional raw polymer dosages (until performance has leveled off) to generate a performance (filtrate volume vs. raw polymer dosage) curve.
 - ix. Repeat steps i-viii with different polymer solution concentrations to generate performance curves for relevant polymer solution concentrations.
- b. Further revise section 4.1 to specify a mixing intensity, characterized by the root mean square velocity gradient (G), and mixing time (t), for both the mixing of raw polymer with water and polymer solution with sludge prior to the gravity drainage test. G and t values specified should replicate those applied at the polymer mixing unit and mixing valve where sludge and polymer solution meet, respectively. If exact values cannot be obtained, best-estimate G and t values should be specified to ensure consistency across vendor tests.
- c. Revise sections 4.4 and 4.5 to require the two lowest bidders to provide sufficient raw polymer for a full-scale test of one weeks' duration. For each of the two lowest bidders, operate the belt presses for a duration of one week with the manufacturer-determined optimal raw polymer dose and solution concentration,

measuring achieved cake %TS twice per day for the duration of the test.

- d. Revise section 4.6 to award the contract to the manufacturer with the lowest total dewatering cost, including the cost of raw polymer and the cost of disposal based on the average cake %TS achieved over the course of the one-week, full-scale test. Note that an improvement of one percent in cake %TS yields significant savings for the utility relative to the cost of polymer.
3. Evaluate digester performance and make requisite changes to optimize methane production and minimize effluent volatile solids concentration. Data from HBMMP exhibit a strong negative correlation between sludge cake volatile solids concentration and sludge cake total solids concentration; this trend is consistent with studies in the literature. Thus, improving the digestion process, and thereby reducing the volatile solids concentration in the digested sludge, is likely to improve sludge dewaterability.

5.3 FUTURE WORK

1. Perform full-scale testing to determine the effect of mixing intensity and mixing time between polymer solution and unconditioned sludge on conditioned sludge dewaterability. Dentel (2001) suggests that overly intense and long mixing can result in breakage of sludge particles and floc, which then require residual polymer in solution to reflocculate. As a result, raw polymer demand increases. Conversely a lack of mixing intensity and time can inhibit the dispersion of polymer throughout the

sludge matrix and therefore inhibit dewaterability. Further, Werle et al. (1984) demonstrated that, for an activated sludge, a single, optimal dimensionless Gt product exists for polymer-sludge mixing that is independent of the raw polymer dose. Together, these facts indicate that the mixing of polymer solution with unconditioned sludge is a crucial step in the conditioning process. The effect of polymer-sludge mixing should be investigated for HBBMP as follows:

- a. Characterize the current mixing intensity (G) and time (t) in the pipe section between the point of mixing of sludge with polymer solution and application of conditioned sludge to the belt. If such characterization is impractical, consider the application of a well-characterized mixing apparatus (e.g.: tank with static mixer or in-line mixer) to better understand the effects of mixing on dewaterability.
- b. Vary the product of G and t within a reasonable range of G to t ratios ($0.5\text{-}60 \text{ sec}^{-2}$) for a fixed raw polymer dose and measure the achieved cake %TS to determine the optimal (dimensionless) Gt product for that raw polymer dose.
- c. Vary the raw polymer dose and polymer solution concentration and find the optimal Gt product for each raw polymer dose and solution concentration combination.
- d. Select the raw polymer dose, polymer solution concentration, and Gt product that together yield highest achieved cake %TS values.

APPENDIX

Table A-1: Sludge sample date and solids content for sludges tested in the following Appendix Tables

Sludge Sample #	Sample Date	TS (mg/L)	VS (mg/L)
<i>1</i>	4/25/17	37600	25600
<i>2</i>	7/26/17	36800	22500
<i>3</i>	8/22/17	38400	23200
<i>4</i>	9/22/17	38000	23600
<i>5</i>	9/25/17	38400	23600

Table A-2: The influence of polymer type, dilution, and dose on specific resistance (Sludge Sample 1)

Polymer Name and Dilution	Specific Resistance (m/kg)		
	14 mL/100 mL sludge	18 mL/100 mL sludge	20 mL/100 mL sludge
<i>BASF 8848, 0.25% solution</i>	6.72E+12	6.07E+12	1.02E+13
<i>BASF 8819, 0.25% solution</i>	7.07E+12	2.14E+13	4.97E+12
<i>BASF 8848, 0.5% solution</i>	5.21E+12	4.55E+12	4.05E+12
<i>BASF 8819, 0.5% solution</i>	3.07E+12	2.47E+12	1.22E+13

Table A-3: The influence of polymer type, dilution and dose on CST (Sludge Sample 1)

Polymer Name and Dilution	CST (seconds)		
	14 mL/100 mL sludge	18 mL/100 mL sludge	20 mL/100 mL sludge
<i>BASF 8848, 0.25% solution</i>	110.70	100.29	106.53
<i>BASF 8819, 0.25% solution</i>	234.53	88.13	91.43
<i>BASF 8848, 0.5% solution</i>	90.57	70.57	67.63
<i>BASF 8819, 0.5% solution</i>	65.57	48.47	54.00

Table A-4: The influence of raw polymer added and polymer solution concentration on specific CST (sec) for BASF Zetag 8819 (Sludge Sample 3)

Polymer Solution Concentration (%)	Raw Polymer Added (mL/100 mL sludge)			
	0.0175	0.02625	0.035	0.0525
<i>0.125</i>	46.11	11.59	26.72	32.97
<i>0.25</i>	93.46	26.67	20.08	16.32
<i>0.4</i>	124.86	26.74	21.05	28.65
<i>0.5</i>	150.20	39.19	85.11	12.45

Table A-5: The influence of raw polymer added and polymer solution concentration on specific resistance (m/kg) for BASF Zetag 8819 (Sludge Sample 5)

Polymer Solution Concentration (%)	Raw Polymer Added (mL/100 mL sludge)				
	0.0175	0.02625	0.035	0.0525	0.07
<i>0.125</i>	6.02E+12	4.13E+11	7.25E+11	2.46E+11	1.16E+11
<i>0.25</i>	1.31E+13	1.83E+13	4.82E+11	3.17E+11	3.77E+11
<i>0.4</i>	1.86E+13	5.51E+12	1.30E+12	3.70E+11	4.56E+11
<i>0.5</i>	8.50E+12	6.34E+12	1.89E+12	3.86E+11	3.86E+11

Table A-6: The influence of raw polymer added and polymer solution concentration on cake TS (%) for BASF Zetag 8819 (Sludge Sample 5)

Polymer Solution Concentration (%)	Raw Polymer Added (mL/100 mL sludge)				
	0.0175	0.02625	0.035	0.0525	0.07
0.125	4.37	9.64	6.71	7.09	9.17
0.25	4.04	3.98	8.95	9.64	7.23
0.4	4.06	4.79	7.52	8.36	6.77
0.5	4.85	4.81	7.37	9.40	7.52

Table A-7: The influence of raw polymer added and polymer solution concentration on specific CST (sec) for Polydyne Clarifloc CE 1632 (Sludge Sample 2)

Polymer Solution Concentration (%)	Raw Polymer Added (mL/100 mL sludge)			
	0.0175	0.02625	0.035	0.0525
0.125	23.23	17.21	12.27	9.50
0.25	30.63	38.63	20.90	10.83
0.4	35.74	48.23	24.93	9.80
0.5	35.80	48.03	29.96	11.41

Table A-8: The influence of raw polymer added and polymer solution concentration on specific resistance (m/kg) for Polydyne Clarifloc CE 1632 (Sludge Sample 4)

Polymer Solution Concentration (%)	Raw Polymer Added (mL/100 mL sludge)				
	0.0175	0.02625	0.035	0.0525	0.07
0.125	7.71E+11	1.88E+11	1.59E+11	1.20E+11	9.82E+10
0.25	2.13E+12	4.94E+11	1.91E+11	2.65E+11	2.25E+11
0.4	1.13E+13	3.06E+12	1.05E+12	2.71E+11	3.53E+11
0.5	2.20E+13	6.41E+12	1.05E+12	6.99E+11	4.73E+11

Table A-9: The influence of raw polymer added and polymer solution concentration on cake TS (%) for Polydyne Clarifloc CE 1632 (Sludge Sample 4)

Polymer Solution Concentration (%)	Raw Polymer Added (mL)				
	0.0175	0.02625	0.035	0.0525	0.07
<i>0.125</i>	7.23	11.39	7.30	7.37	9.40
<i>0.25</i>	5.57	8.45	10.74	6.96	8.55
<i>0.4</i>	4.35	5.49	8.17	9.64	7.30
<i>0.5</i>	4.11	4.74	8.36	6.90	7.37

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