Influence of Polymer Selection on Nutrient Phase Separation for Waste Activated Sludge Thickening at Bench Scale

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The use of polymers to condition waste activated sludge prior to thickening is a common practice at domestic wastewater treatment plants. In this study, the performance of various commercially available granular polymers was observed. Thickening by gravity belt thickener was simulated at the bench scale, and the thickened sludge and filtrate produced were examined. Laboratory analysis was used to determine the differences in nutrient chemical concentration in the thickened solids and filtrate produced by different polymers. By examining the content of nutrient chemicals such as total Kjeldahl nitrogen (TKN), ammonia nitrogen, and total phosphorous, this research showed that polymer choice could affect the chemical composition of thickened sludge and filtrate with respect to nutrients. Results showed that the total phosphorous and TKN concentrations in the thickened sludge and filtrate were affected by polymer selection, which suggested that the chemical loading on the plant due to filtrate recycle, and the nutrient content of thickened sludge delivered to the digester are affected by polymer choice. Polymer optimization studies that examine nutrient properties of filtrate and thickened sludge beyond the basic total suspended solids analysis may be advantageous to minimize recycling of these compounds into the filtrate phase.

Key words: bench-scale, digestion, nutrient, polymer, sludge, thickening

Introduction

Field research of polymer testing often focuses on the ability of a given polymer to separate solids from the liquid phase within the sludge (Severin and Grethlein 1996; Al-Muzaini and Hamoda 1998; Severin et al. 1999; Al-Mutairi et al. 2004; Olivier et al. 2004). This information, along with the cost per unit of dry solids is typically used to select a polymer for sludge thickening. In this study, the evaluation of polymers is based not only on their performance with respect to solids capture, but also on an evaluation of how different polymers direct nutrients to solid and liquid phases during thickening.

Thickening by gravity belt thickener (GBT) removes the unbound water in the sludge, typically increasing the total solids concentration from about 1% to about 5%, reducing the volume of sludge by about 5 times, and concentrating the sludge before it is introduced to a subsequent digestion process. (Kiely 1997; Dentel 2001; Olezskewicz and Mavinic 2001). Before using a GBT to thicken sludge, cationic polymers may be used to neutralize the negatively charged sludge particles to overcome electrostatic repulsion and allow aggregation into flocs (Dentel 2001; Chen et al. 2002; Metcalf and Eddy 2003). Polymers tend to be popular for use in gravity drainage systems due to their ease of use compared with alternatives such as lime and iron salts (Novak et al. 1999). Ammonia nitrogen, total Kjeldahl nitrogen (TKN), phosphorous, and total five-day biochemical oxygen demand (tBOD5) were examined in the separated thickened solids and liquid filtrate to characterize how each polymer performs with respect to the phase separation of nutrients. These nutrients may be important to either or both the digestion process and/or land application of biosolids after digestion. The importance of this process lies in the fact that the digested biosolids will be most useful and beneficial if the digested sludge is high in nutrients, since the biosolids can be used to supplement the agronomic nutrient requirements of plants.

In this study, a number of commercially supplied polymers were tested at the bench scale to characterize the waste activated sludge (WAS) thickening process using chemical parameters. Sludge samples were collected from a small domestic wastewater treatment plant (WWTP) in Crystal Beach, Ontario. The WWTP at Crystal Beach is an extended aeration facility with no primary clarification, and WAS is thickened by a GBT before anaerobic digestion. The design capacity of the plant is 9.1 ML/day, with a peak capacity of 27.3 ML/day. The average flow through the plant during the study was approximately 5.5 ML/day, which is about 60% of the design capacity.

Understanding the differences between various polymers with respect to how nutrient chemicals are directed to both solid and liquid phases during sludge thickening will also allow for tighter control of what is recycled through the WWTP. During thickening, the liquid stream (e.g., filtrate from a GBT) is incorporated into the inflow to the plant. This is an important mechanism because nutrient chemicals may be removed from
wastewater using expensive and/or sensitive processes. For example, phosphorous is often precipitated out of activated sludge using coagulants such as ferric chloride.

Phosphorous in the form of phosphates can cause imbalances in the natural aquatic ecosystem, and so regulations limit the amount of phosphorous that may be present in WWTP effluent. These negative effects have been well documented in closed systems, such as aquaculture facilities, where nutrient chemicals can quickly cause imbalances. In fact, some field research has been performed in these applications to use coagulation/flocculation and filtration to remove nutrient chemicals from recycled water (Cripps and Bergheim 2000; Ebeling et al. 2006). To ensure regulatory compliance, coagulants are mixed with activated sludge in the aeration basins. In the case of ferric chloride, the coagulation mechanism involves a reaction between iron salts and phosphates in the activated sludge, which forms insoluble phosphorous precipitates that settle to the bottom of clarifiers (Droste 1997). Therefore, if the phosphorous concentration of the activated sludge is increased by the recycling of phosphorous within GBT filtrate, the demand for coagulant chemicals will increase to maintain compliance. Understanding how polymers affect the nutrient concentration of solid and liquid streams may prevent using a polymer that offers solids capture advantages while simultaneously increasing chemical loading through the plant. Furthermore, in many localities, regulations require removal of various forms of nitrogen from plant effluent.

**Materials and Methods**

**Sludge Thickening**

*Experimental overview.* The bench-scale polymer testing process was conducted in two phases. In Phase 1 (screening), a group of eight samples were used for sludge thickening trials. In Phase 2 (dosage testing), three polymers were tested at different doses to determine relative performance over an interval of dosage levels.

**Polymer preparation for bench-scale testing.** Each type of cationic polymer was prepared in a stock solution at 0.1%, using 20°C tap water, and mixed using a jar test apparatus (Phipps and Bird PB700 Standard JarTester) at 25 rpm for 1 hour. Polymer solutions were prepared each day for testing.

**Sludge characteristics.** The raw wastewater is derived from domestic sources with no heavy industrial input. Influent wastewater is screened through bar screens, and grit is removed using centrifugal grit chambers, before entering plug flow aeration basins with fine bubble diffusers. Ferric chloride is added as a coagulant as the activated sludge flows from the aeration basins to secondary clarifiers. Sludge settles in the clarifiers, and a portion is recycled back to the aeration process. The remainder of the sludge is wasted from the system manually in batch fashion, at the discretion of operators. WAS is stored in air-mixed tanks prior to thickening on a GBT. Thickened sludge then undergoes a mesophilic anaerobic digestion process in a floating roof digester that is mixed with a recirculation pump. Digested sludge is hauled away for disposal at sludge lagoons nearby. Data from 355 daily sludge samples collected and analyzed at Crystal Beach WWTP are summarized in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1. Summary of sludge characteristics at WWTP a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Activated sludge</strong></td>
</tr>
<tr>
<td>Suspended solids (mg/L)</td>
</tr>
<tr>
<td>Avg. b</td>
</tr>
<tr>
<td>SD (±) b</td>
</tr>
</tbody>
</table>

* Crystal Beach WWTP 2006.
 b Avg. = average, SD = standard deviation.

**Phase 1 Polymer Screening**

Eight polymers were selected for testing. A bench-scale gravity thickening device was used to simulate the thickening performance of each polymer. The thickening apparatus was made from a two-litre screw-top plastic container with an open bottom. Standard GBT material (50-micron aperture size) was fitted over the container and held in place by using waterproof silicone. The belt material was allowed to dry in place for approximately 24 hours before testing was started. A custom-made funnel was screwed on top of the belt material to allow for WAS mixed with polymer to be tested.

Sludge was poured into the funnel, and thickened by the gravity belt material. The thickened solids collected on the surface of the gravity belt material while liquid filtrate passed through the porous belt material and was collected in a beaker.

Each polymer solution was added to a sample of WAS at a concentration of 36 mL of polymer (stock concentration 0.1%) per litre of sludge. This corresponds to a dosage of 4.5 g of polymer per kg of sludge solids. The dosage selection was chosen to represent the equivalent average full-scale polymer concentration used at the wastewater treatment plant where testing was conducted. The polymer and sludge were mixed using the same method outlined in Severin and Grethlein (1996), using 500-mL beakers to pour the mixture back and forth 10 times. Samples (350 mL each) were used to ensure that sufficient surface area was exposed so that water could not pool on the surface during drainage (Severin et al. 1999). Samples were poured onto the gravity thickener and allowed to drain for 10 minutes. Testing was performed as per Standard Methods (AWWA...
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on the separated solid and liquid phases. Solid and liquid phase testing included: total solids, TKN, total phosphorous, ammonia nitrogen, tBOD$_5$, total suspended solids, and turbidity.

The chemical characteristics of the polymers that were tested in this study are presented in Table 2. The charge density refers to the percentage of the polymer chain that exhibits a positive charge. This percentage may be very low (less than 10 percent), low (10 to 30 percent), medium (30 to 50 percent), high (50 to 70 percent), or very high (over 70 percent). The molecular weight refers to the average mass in grams of one mole of polymer molecules. Among the polymers tested in this study, the molecular weight ranged from medium to very high, characterized as: medium (between approximately $10^5$ and $10^6$ g/mol), medium-high (approximately $10^6$ g/mol), high (between approximately $10^6$ and $10^7$ g/mol), or very high (over $10^7$ g/mol).

Phase 2 Polymer Dosage Selection

After Phase 1 polymer testing, three polymers were selected to predict appropriate polymer dosages for subsequent full-scale thickening. The polymers were selected for Phase 2 testing based on their ability to concentrate nutrient chemicals in the solid phase and produce filtrate low in nutrient chemicals. Polymer 1 was automatically selected for dosage testing because it was the incumbent polymer in use at the Crystal Beach WWTP. The dosage range used included the following concentrations (expressed in grams of dry polymer per kilogram of sludge solids): 0, 2.75, 3.65, 4.55, 5.45, and 6.35.

The polymer was transferred by pipette to the sludge samples and rapidly mixed for 30 seconds at 300 rpm, then slowly mixed at 25 rpm for 3 minutes on the jar test apparatus. After mixing, 350 mL of flocculated sludge was poured through the gravity filter and allowed to drain for 10 minutes. The thickened solids and the collected filtrate were stored separately for testing.

A sample of filtrate was collected after 12 seconds of drainage, and tested for turbidity. The time selected approximated the contact time between the sludge and polymer mixture at full scale on the GBT at the wastewater treatment plant where testing was conducted and was considered to be representative of the industry standard.

**Results**

**Polymer Screening (Phase 1)**

Eight polymers were used for the first phase of testing. The objective of Phase 1 was to screen polymers for testing in subsequent phases. Figure 1 shows that most polymers provide thickened sludge of higher total solids content than the control sample, which contained no polymer. The notable exceptions are polymers 7 and 8, which did not improve thickening. Polymers 2 and 5 produced thickened sludge with high total solids, but with a relatively high variability in the total solids content between samples (a range of approximately half a percentage point for each polymer), which was undesirable. Polymers 1, 4, and 6 produced sludge with relatively high solids content, and were less variable in performance than the others. Polymer 1 at the bench scale is the same as the polymer used at the full-scale GBT application. It is interesting to note that the full-scale GBT results were slightly better than the bench-scale results, indicating some discrepancies with the bench-scale testing regime.

![Fig. 1. Phase 1—Average percent total solids in thickened sludge (n = 2) for each polymer. Dosage: 4.5 g polymer/kg sludge solids.](image)

**TABLE 2. Polymer characteristics**

<table>
<thead>
<tr>
<th>Polymer number</th>
<th>Polymer name</th>
<th>Charge density</th>
<th>Molecular weight</th>
<th>Comments/testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CB 4450</td>
<td>Medium</td>
<td>High</td>
<td>Incumbent Polymer at Crystal Beach WWTP</td>
</tr>
<tr>
<td>2</td>
<td>7557</td>
<td>Medium</td>
<td>Medium</td>
<td>Phase 1 testing</td>
</tr>
<tr>
<td>3</td>
<td>8160</td>
<td>Medium</td>
<td>Medium-High</td>
<td>Phase 1 testing</td>
</tr>
<tr>
<td>4</td>
<td>4290</td>
<td>Low</td>
<td>High</td>
<td>Phase 1 testing</td>
</tr>
<tr>
<td>5</td>
<td>4190</td>
<td>Low</td>
<td>High</td>
<td>Phase 1 testing</td>
</tr>
<tr>
<td>6</td>
<td>4925</td>
<td>High</td>
<td>Very High</td>
<td>Phase 1 testing</td>
</tr>
<tr>
<td>7</td>
<td>49</td>
<td>Low</td>
<td>High</td>
<td>Phase 1 testing</td>
</tr>
<tr>
<td>8</td>
<td>473</td>
<td>High</td>
<td>High</td>
<td>Phase 1 testing</td>
</tr>
</tbody>
</table>
The concentration of total phosphorous in filtrate is shown in Fig. 2. This is a particularly important parameter because chemical coagulants are used to remove phosphorous from wastewater. Thus, using a polymer that reduces the amount of total phosphorous in the recycled filtrate can decrease chemical demand and save money. The data suggested that, with the exception of polymer 7, all polymers reduced the amount of total phosphorous in the filtrate compared with control samples. This phase of testing showed a reduction in filtrate phosphorus content of up to 85% with polymers 3 and 4. In a similar study involving an aquacultural wastewater (Ebeling et al. 2006), a maximum reduction in reactive phosphorus of 41% after using polymers was achieved (supporting the finding that phosphorous may be directed into the solids phase versus the liquid filtrate).

It is important to discuss the control sample, which was untreated sludge processed through the same testing regime. As can be observed in Fig. 1, the control produced a very low thickened solids percentage, which would be expected, however the total phosphorous of this sample was relatively high compared with the treated samples, with the exception of polymer 7. This result would seem to indicate that the process of polymer thickening generally moves phosphorous into the liquid phase. Chen et al. (2006) reported a 10% decrease in filtrate phosphorous concentration with polymer addition to sludge, and this value increased upwards of 80% when aluminum chloride was used in addition to the polymer. Examination of the TKN data showed the opposite result, which may indicate that polymers generally affect these nutrients in different ways, an observation which has been established in previous literature (Westerman and Bicudo 2000). These results highlight the need for more research on the chemical interactions between polymers and nutrient chemicals.

Figure 3 shows the TKN concentration measured in thickened sludge at the bench scale. Some polymers offer an advantage in terms of concentrating TKN within the thickened sludge. For example, polymers 4, 5, and 6 concentrate approximately twice as much TKN in thickened sludge relative to polymer 1.

**Summary of bench-scale polymer screening.** The data from bench-scale polymer testing are presented in Table 3 (thickened sludge data) and Table 4 (filtrate data), along with the rank of each polymer in each test. In the case of the thickened sludge, a rank of 1 indicates the polymer that was most effective at producing sludge with the highest total solids percentage or highest nutrient concentration. In the case of the filtrate, the opposite is true; a rank of 1 indicates the polymer that was most effective at producing filtrate with the lowest solids percentage and nutrient concentration.

Polymers 1, 4, and 6 were selected for further analysis in Phase 2 testing. The polymers were selected due to their respective solids percentage and low variability in comparison with the other polymers tested. In addition, due to the opposing results found with the total phosphorus and TKN, polymer 6 was selected as it displayed the highest total phosphorus in the sludge for those polymers with positive cake solids percentage results, and polymer 4 was selected for similar reason with respect to the TKN results.

Polymer 6 seemed to be most consistent of these three, exhibiting lower variability, and producing thickened sludge with relatively high levels of total solids, TKN, and total phosphorous. Both polymer 4 and 6 were shown to be relatively effective at producing thickened sludge with consistent solids content, and were most effective at producing thickened sludge with high nutrient content relative to other polymer types. From a practical perspective, the nutrient content of the sludge may be considered a secondary objective compared with the solids percentage, because the thickened sludge must have solid content within the design expectations of full-scale thickening apparatus, usually between 4 to 6 % total solids.

**Bench-scale testing—nutrient values adjusted.** In this section, the concentration of total phosphorous and TKN in the solid phase was examined in concert with the percent total solids data by using the total solids percentage to normalize the nutrient data. In other words,
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The nutrient concentrations observed in this section are not expressed in milligram per kilogram of thickened sludge, they are listed in milligram per kilogram of dry solids. The nutrient concentration data were divided by the total solids percentage in this analysis. The formula for normalizing the nutrient concentration is shown in equation 1:

\[
C_n = \frac{C_{ts}}{\left(\frac{M_{sol}}{M_{sam}}\right)}
\]

Where:
- \(C_n\) is the normalized concentration of nutrient \(n\) in thickened sludge, expressed in mg/kg of dried solids;
- \(C_{ts}\) is the concentration of nutrient \(n\) measured in a thickened sludge sample, expressed in mg/kg of thickened sludge;
- \(M_{sol}\) is the mass of the thickened sludge solids, measured after drying for 24 hours at 105°C, expressed in kg;
- \(M_{sam}\) is the mass of the thickened sludge sample before drying, expressed in kg.

This analysis ties the nutrient concentration of the sludge to the total solids content, thereby correcting for differences in the liquid content of the sludge. In Phase 1 testing, the nutrient concentration of thickened sludge was measured by sampling the thickened sludge as it is thickened by the gravity filter. This means that the sludge samples may have different percentages of solid material. For example, sludge thickened using polymer 5 averaged over 5 percent total solids, while sludge thickened using

### TABLE 3. Summary of data from bench-scale polymer testing—solid phase

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Total *a solids</th>
<th>Total *a phosphorus</th>
<th>TKN *a</th>
<th>tBOD *a</th>
<th>Average rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>Rank</td>
<td>mg/kg</td>
<td>Rank</td>
<td>mg/kg</td>
</tr>
<tr>
<td>1</td>
<td>4.5</td>
<td>6</td>
<td>519</td>
<td>6</td>
<td>1,480</td>
</tr>
<tr>
<td>2</td>
<td>4.9</td>
<td>4</td>
<td>651</td>
<td>4</td>
<td>1,830</td>
</tr>
<tr>
<td>3</td>
<td>3.4</td>
<td>5</td>
<td>550</td>
<td>5</td>
<td>1,683</td>
</tr>
<tr>
<td>4</td>
<td>4.6</td>
<td>4</td>
<td>1,085</td>
<td>1</td>
<td>3,370</td>
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<tr>
<td>5</td>
<td>5.2</td>
<td>1</td>
<td>687</td>
<td>3</td>
<td>3,220</td>
</tr>
<tr>
<td>6</td>
<td>5.1</td>
<td>2</td>
<td>913</td>
<td>2</td>
<td>3,320</td>
</tr>
<tr>
<td>7</td>
<td>0.8</td>
<td>9</td>
<td>166</td>
<td>9</td>
<td>513</td>
</tr>
<tr>
<td>8</td>
<td>2.1</td>
<td>7</td>
<td>265</td>
<td>7</td>
<td>844</td>
</tr>
<tr>
<td>Control</td>
<td>1.3</td>
<td>8</td>
<td>250</td>
<td>8</td>
<td>744</td>
</tr>
</tbody>
</table>

* Variability in the data was as follows: Total solids SD ± 1.67; Total phosphorus SD ± 299; TKN SD ± 1,120; tBOD SD ± 3,081.
* A rank of 1 indicates the polymer that was most effective at producing sludge with the highest total solids percentage or highest nutrient concentration.
* Polymers 1, 4, and 6 were selected for further analysis in Phase 2 testing.
* N/A = not available.

### TABLE 4. Summary of data from bench-scale polymer testing—(filtrate) liquid phase

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Total *a solids</th>
<th>Ammonia *a nitrogen</th>
<th>TKN *a</th>
<th>Total *a phosphorus</th>
<th>Average rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>Rank</td>
<td>mg/L</td>
<td>Rank</td>
<td>mg/L</td>
</tr>
<tr>
<td>1</td>
<td>0.36</td>
<td>4</td>
<td>0.96</td>
<td>9</td>
<td>5.6</td>
</tr>
<tr>
<td>2</td>
<td>0.33</td>
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<td>0.68</td>
<td>8</td>
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</tr>
<tr>
<td>3</td>
<td>0.65</td>
<td>9</td>
<td>0.34</td>
<td>4</td>
<td>2.7</td>
</tr>
<tr>
<td>4</td>
<td>0.55</td>
<td>8</td>
<td>0.40</td>
<td>6</td>
<td>2.9</td>
</tr>
<tr>
<td>5</td>
<td>0.39</td>
<td>5</td>
<td>0.61</td>
<td>7</td>
<td>3.5</td>
</tr>
<tr>
<td>6</td>
<td>0.44</td>
<td>6</td>
<td>0.38</td>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td>7</td>
<td>0.35</td>
<td>3</td>
<td>0.16</td>
<td>2</td>
<td>3.9</td>
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<td>0.32</td>
<td>7</td>
<td>0.15</td>
<td>1</td>
<td>3.9</td>
</tr>
<tr>
<td>Control</td>
<td>0.32</td>
<td>7</td>
<td>0.29</td>
<td>3</td>
<td>7.9</td>
</tr>
</tbody>
</table>

* Variability in the data was as follows: Total solids SD ± 0.02; Ammonia nitrogen range ± 0.30; TKN range ± 2.09; Total phosphorus range ± 0.74.
* A rank of 1 indicates the polymer that was most effective at producing filtrate with the lowest solids percentage and nutrient concentration.
* Polymers 1, 4, and 6 were selected for further analysis in Phase 2 testing.
polymer 7 averaged under 1 percent total solids. Since the sludge solids are generally a potent source of nutrient chemicals, sludge with a higher solids percentage also has a higher concentration of nutrient chemicals (Cripps and Bergheim 2000). By dividing the nutrient chemical concentrations by the percent total solids, it is possible to characterize the chemistry of the sludge to prevent differences in solids content from affecting the results. In Fig. 4, the total phosphorus concentration of the thickened sludge is examined, while in Fig. 5, the TKN concentration of the sludge is displayed.

Fig. 4. Phase 1—Normalized average total phosphorus concentration in thickened sludge \((n = 2)\) for each polymer. Dosage: 4.5 g polymer/kg sludge solids.

Fig. 5. Phase 1—Normalized average total Kjeldahl nitrogen (TKN) concentration in thickened sludge \((n = 2)\) for each polymer. Dosage: 4.5 g polymer/kg sludge solids.

This analysis showed that there may indeed be chemical differences in the sludge produced by different polymers. For example, with the exception of polymer 4, all polymers produce sludge with lower concentrations of total phosphorous and TKN per unit weight of dried solids than the control sample, which was not dosed with polymer. In fact, polymer 1 produced sludge with the lowest levels of total phosphorous and TKN per kilogram of dried solids on average. This suggests that the polymers may act against the concentration of nutrient chemicals within the sludge to varying degrees. Perhaps polymers cause chemical reactions that alter nutrient chemicals, making them unavailable for other chemical reactions. Polymers may cause damage to organisms in the sludge, causing cell lysis and/or breakdown of organics, which could result in higher nutrient concentration in the liquid phase. In the future, a more in-depth look at the interactions between polymers and nutrient chemicals in sludge during thickening may shed some light on the effects of polymer conditioning on the availability of nutrients in thickened sludge. A similar analysis was not performed using the filtrate data due to a relatively high level of variability in the solids content of filtrate samples.

Polymer Dosage Selection (Phase 2)

The purpose of the Phase 2 testing plan was to determine the relative performance of polymers over a range of dosages (See Materials and Methods section). This testing was designed to determine the optimal dose of each polymer, and also to determine how polymers behave at doses higher or lower than the optimum dose. This analysis can also be useful for predicting the relative advantages between polymers with respect to solids capture and nutrient phase selection in a full-scale application (MacDonald and Basu 2007).

Figure 6 shows the total phosphorus concentration of thickened sludge. The data indicated that increasing the dosage past a certain point only caused a marginal improvement in lowering sludge total phosphorus, and that increasing further may actually cause thickened sludge with lower total solids. Similar effects were observed in a sludge thickening study focused on nutrient-rich sludge from an aquaculture facility (Ebeling et al. 2006). This is not surprising because as the polymer is added, the zeta potential of the solids will change and effectively decrease towards neutral and then continue to a higher positive value as more polymer is added, increasing repulsive forces and causing thickened sludge with lower total solids, and thus lower concentrations of nutrient chemicals.

At lower doses, polymers 4 and 6 produced sludge with a higher concentration of total phosphorus relative to polymer 1. The data showed that to achieve a thickened sludge, a total phosphorus concentration of approximately 800 mg/L, a dosage of about 4.375 g of dry polymer per kilogram of sludge solids was needed using polymer 1, while polymers 4 and 6 produced sludge with approximately the same total phosphorus concentration using a lower dose of 3.75 g of dry polymer per kilogram of sludge solids. Thus, the two trial polymers (i.e., polymers 4 and 6) appeared to be more effective than the incumbent polymer (i.e., polymer 1) at producing phosphorus-rich sludge at low doses.
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Figure 6. Phase 2—Average total phosphorus concentration in thickened sludge \( (n = 2) \) for different doses of polymers 1, 4, and 6.

Figure 7 shows the TKN concentration of thickened sludge. Polymers 4 and 6 produced sludge with a higher concentration of TKN relative to polymer 1. The data indicated that to achieve a TKN concentration of approximately 2,500 mg/L, a dosage of about 3.75 g of dry polymer per kilogram of sludge solids was needed using polymer 6, while a dosage of about 4.375 g of polymer per kg of sludge was used with polymer 1 to produce sludge with approximately the same TKN concentration. Polymer 4 did not produce sludge with TKN concentration above 1,800 mg/L at any dose.

Figure 8 shows the liquid phase solids percentage, and tBOD\(_5\) concentration, indicating that the dose of polymer may affect the filtrate solids concentration differently than it affects the tBOD\(_5\) concentration. Sources of tBOD\(_5\) and nutrient chemicals are present in various chemical forms which may have different responses to thickening, and thus the relationship between solids capture and nutrient phase selection is complex (Jardin and Popel 1996). Achieving a total solids percentage in the filtrate of approximately 0.05% is possible with the lowest polymer dose, (3.75 g of dry polymer per kg of sludge solids), and higher doses do not appear to result in significantly lower percent total solids. However, maximum reductions in tBOD\(_5\) concentration occur only at a much higher dose, (5 g of dry polymer per kg of sludge solids).

Conclusion

The bench-scale testing identified some distinct advantages in using some polymers to thicken sludge solids with respect to both solids capture and nutrient delivery to the solid phase. For example, Phase 1 of testing indicated that polymer 4 produced sludge solids with 40% more total phosphorous and TKN than polymer 2, with similar solids capture and filtrate with 40% less ammonia and 50% less total phosphorous. The results also indicated that most polymers used for thickening will promote the movement of total phosphorus into the liquid phase versus untreated samples; therefore, selection would inherently be based on the polymer that delivers the least amount of total phosphorus into the filtrate. Phase 2 testing indicated that polymer choice also affects nutrient delivery to thickened sludge differently than it affects solids capture at different doses. The concentration of tBOD\(_5\) in thickened sludge was shown to drop significantly only after polymer dose was increased to approximately 33% above the point when the total solids percentage of liquid filtrate levelled off. Phase 2 testing also showed that differences observed between polymers with respect to producing sludge rich in total phosphorus and TKN were significant only at certain doses. Polymers 4 and 6 produced sludge higher in total phosphorus than polymer 1 at low doses, but the advantage was diminished at higher doses. In general, this study showed that bench-scale testing can be used to optimize polymer dose and selection with respect to nutrient delivery during sludge thickening.
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