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Optimization of a full-scale dewatering operation based on the rheological characteristics of wastewater sludge

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ABSTRACT

Rheology is the science that deals with the flow and deformation of materials, and it has become an important tool in optimizing sludge dewatering. This study presents torque rheology data to illustrate two different methods for polymer optimization. The methods can be used to optimize the polymer dose and mixing intensity, as well as to select the best performing product among a number of candidate polymers. The first method is used for unconditioned sludges, and utilizes the peaks observed after the polymer injection. The second method is used for conditioned sludges and utilizes the entire torque-time rheograms. Both methods were tested at the lab- and full-scale at the Plum Island Water Reclamation Facility (Charleston, SC) using three different polymers. The methods were able to optimize the polymer dose and full-scale mixing, and reduce the polymer consumption by 50% at the treatment plant. This translates into major savings for the utility. Furthermore, the results indicate that the total shear intensity imparted to sludge during full-scale conditioning can be determined using torque rheology, and the jar-tester shear can be matched to the total shear based on the rheological characteristics of sludge. This information is essential to be able to simulate the full-scale mixing using a jar-tester and to precisely determine the optimum polymer dose. The results of this study indicate that well-defined rheological properties of sludge provide a reliable tool for the optimization of conditioning and dewatering operations at wastewater treatment plants.

1. Introduction

Rheology is the science that deals with the flow and deformation of materials, and it has become an important tool in characterizing wastewater sludge (Campbell and Crescuolo, 1982; Langer et al., 1994; Slatter, 1997; Abu-Orf and Dentel, 1999; Yen et al., 2002; Örmeci and Abu-Orf, 2005; Abu-Orf and Örmeci, 2005). An understanding of the rheological properties of sludge is important in the design and operation of solids treatment and dewatering processes. Torque rheology can be used to describe the effects of chemical conditioning on the physical characteristics of sludge, to predict the optimum polymer dose, and to compare the performance of polymers (Örmeci and Abu-Orf, 2006).

Several researchers have previously reported that rheograms obtained from conditioned sludges are different than those obtained from unconditioned sludges (Campbell and Crescuolo, 1982; Langer et al., 1994; Abu-Orf and Dentel, 1999; Örmeci et al., 2004; Abu-Orf and Örmeci, 2005). Conditioned

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sludges exhibit an initial peak, which increases as the polymer dose is increased (Campbell and Crescuolo, 1982). The observed peak can be explained by the existence of an elastic floc network based on the research of Michaels and Bolger (1962), Firth and Hunter (1976), and Otsubo and Umeya (1984). The elastic network increases the resistance of sludge to shear, and the peak indicates the point where the network bonds rupture (Langer et al., 1994). The higher the peak, the more energy is needed to break up the flocs (Abu-Orf and Dentel, 1999). At higher polymer doses the flocs are more stable, and more energy is necessary to destroy them.

Problems associated with the reproducibility of measurements with concentric-cylinder rheometers limited the use of peaks in the optimization of polymer dose and dewatering applications. Unconditioned sludge produces shear stress-shear rate rheograms with very good reproducibility, however as the polymer dose is increased rheograms start to diverge into separate curves. This is attributed to the difficulties of taking representative sub-samples from well-flocculated sludges with two distinct phases of water and flocculated solids (Campbell and Crescuolo, 1982; Abu-Orf and Dentel, 1999; Örmeci et al., 2004). Abu-Orf and Dentel (1997) reported that if the peak heights of shear stress-shear rate rheograms are used as a control parameter during conditioning, inaccurate control will be experienced. Similarly Campbell and Crescuolo (1982) stated that the use of rheological data from concentric-cylinder rheometers is extremely risky unless complete details of the test procedure are also available. Torque rheometers, on the other hand, use much larger sample volumes (e.g. 200–500 mL) compared to concentric-cylinder rheometers (e.g. 20–40 mL), and offer an advantage of injecting the polymer directly into the sample and eliminating the need for taking sub-samples from conditioned sludges (Örmeci and Abu-Orf, 2004). The high reproducibility of torque-time rheograms of conditioned sludge samples enables the use of torque rheology as a reliable tool for sludge characterization and optimum dose determination (Örmeci et al., 2004; Abu-Orf and Örmeci, 2005).

Torque rheometers measure the viscosity-related torque caused by the resistance of the material to the applied shear. The area under a torque-time rheogram is termed “totalized torque” which is defined as the energy required to process a certain material for that period of time (Chung, 1986). Örmeci and Abu-Orf (2004) and Abu-Orf and Örmeci (2005) reported a local decrease in the torque and totalized torque values at the optimum polymer dose during polymer conditioning tests.

The goal of this study was to investigate whether torque rheology can be used as a reliable control parameter for the optimization of dewatering operations. The study presents torque rheology data to illustrate two different methods for polymer optimization. The presented methods can be used to optimize the polymer dose and mixing intensity, to select the best performing product among a number of candidate polymers, and to determine the shear intensity that sludge is exposed to during full-scale conditioning. Both methods were tested at the lab- and full-scale. The technology provides not only an innovative way to optimize the polymer dose and mixing conditions, but also provides a valuable tool to the treatment plant operators to keep their dewatering operations at the optimum level on a daily basis.

2. Materials and methods

2.1. *Treatment plant*

The full-scale testing was conducted at the Plum Island Wastewater Treatment Plant Facility in Charleston, South Carolina. The treatment plant co-thickens primary and secondary sludge, holds it in an aerated holding tank, and dewaters using rotary press technology (Les Industries Fournier Inc., Quebec, Canada). During rotary press dewatering, sludge is rotated between two parallel revolving stainless steel screens and dewatered as the filtrate passes through the screens. The dewatered cake is sent to a landfill for final disposal. There is no aerobic or anaerobic digestion.

2.2. *Polymers*

The plant currently uses Clarifloc C-311 polymer (SNF Polydyne Inc.) to condition and dewater sludge. The polymer is a Mannich polymer of a liquid cationic polyacrylamide derivative. During the study, in addition to the performance of the Mannich polymer, two emulsion polymers (Clarifloc C-9545 and SE-914, SNF Polydyne Inc.) were tested at the lab- and full-scale. The two emulsion polymers were

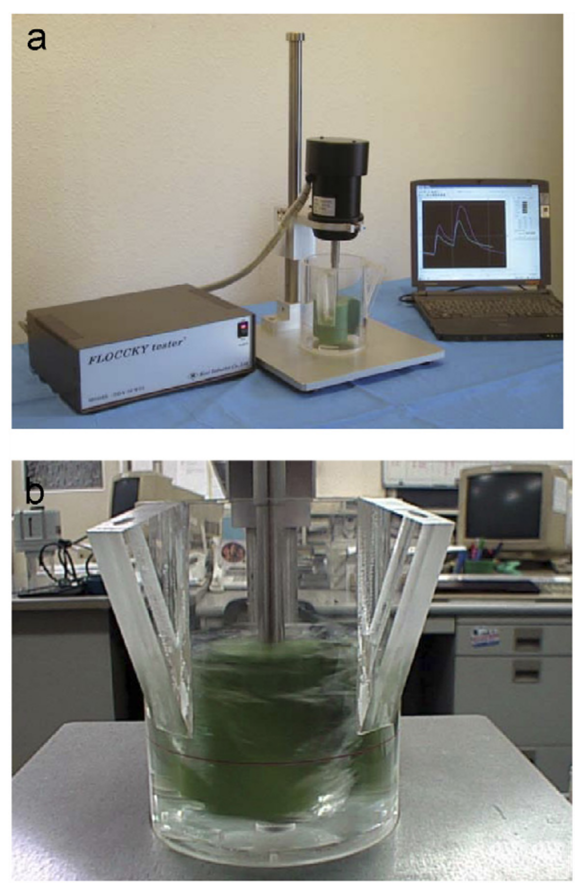

Fig. 1 – (a) Main components of the Floccky Tester and (b) Floccky beaker has build-in ports for direct polymer injection.

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recommended by the polymer supplier based on the characteristics of sludge and their experience with the treatment plant. Both are high charge cationic polyacrylamide polymers in emulsion form. The polymers were diluted to 0.25% before use. The polymer doses are reported as percentages of polymer-to-sludge ratios as typically used at treatment plants. Where necessary, polymer doses are also reported as g/kg DS (dry solids) in this study.

2.3. *Rheometer*

Floccky Tester, a torque rheometer manufactured by Koei Industry Co., Ltd (Japan), was used in the experiments (Fig. 1a). The instrument was developed to study flocculants and flocculation characteristics of municipal and industrial sludges. The rheometer uses a 200 mL reservoir, and the impeller speed can be varied from 30 to 420 rpm. The rotating impeller is equipped with a load cell that measures the resistance of sludge to shear created by the impeller. The resistance to shear is reported in terms of torque (mNm).

The software included with the rheometer reports the area under the rheograms (totalized torque) in addition to the peak torque values. The reservoir of the rheometer contains two ports, which allow direct polymer injection into the samples (Fig. 1b). This feature enables studying both flocculation and deflocculation phases of sludge.

2.4. *Reproducibility of rheograms*

The reproducibility of the rheograms obtained by the Floccky Tester has been reported to be very good (Örmeci et al., 2004). The standard deviations of the rheological measurements were within 5% of the arithmetic mean in this study. Rheological measurements were conducted in duplicate using two separate sludge samples that belonged to the same batch. After each measurement, the sample was discarded due to the thixotropic nature of sludge.

2.5. *Procedures*

In order to determine the optimum impeller speed for this sludge, the following impeller speeds were tested: 250, 300, 350 and 400 RPM. At the optimum impeller speed, the instrument is most sensitive to the changes in sample characteristics, which can be measured by the magnitude of the torque readings (Örmeci et al., 2004). The optimum impeller speed was determined as 300 RPM for this sludge, and unless otherwise stated 300 RPM was used for the rheological measurements.

Two different rheological methods were employed in this study.

Method 1: This method uses unconditioned sludge, and utilizes only the peaks observed after polymer injection. The method is useful in identifying the optimum polymer dose, comparing the performance of different polymers, and how polymers react with the raw (unconditioned) sludge. The reservoir of the Floccky Tester enables direct injection of the polymers into the sludge during the rheological measurement. The method consists of three steps. In Step 1, sludge is mixed at 420 RPM for 10 s. This step is necessary to suspend the settled solids, and to uniformly mix the sludge. In Step 2, sludge is mixed at 300 RPM for 40 s. This step provides a baseline reading for the unconditioned sludge. At the beginning of Step 3, polymer is injected into the sludge through the ports of the reservoir, and sludge is mixed at 300 RPM for 120 s. A peak is observed right after polymer injection, which indicates the extent of flocculation caused by the polymer (Floccky Tester Manual, 2006). The formation and deformation of the peaks typically take less than 60 s, so 120 s provide enough time to observe the peaks. Prolonged mixing during rheological measurements should be avoided, as it will impact the dewatering characteristics of the samples. Fig. 2 illustrates typical results obtained using Method 1.

Method 2: This method uses conditioned sludge and utilizes the entire torque-time rheograms (Örmeci and Abu-Orf, 2005;

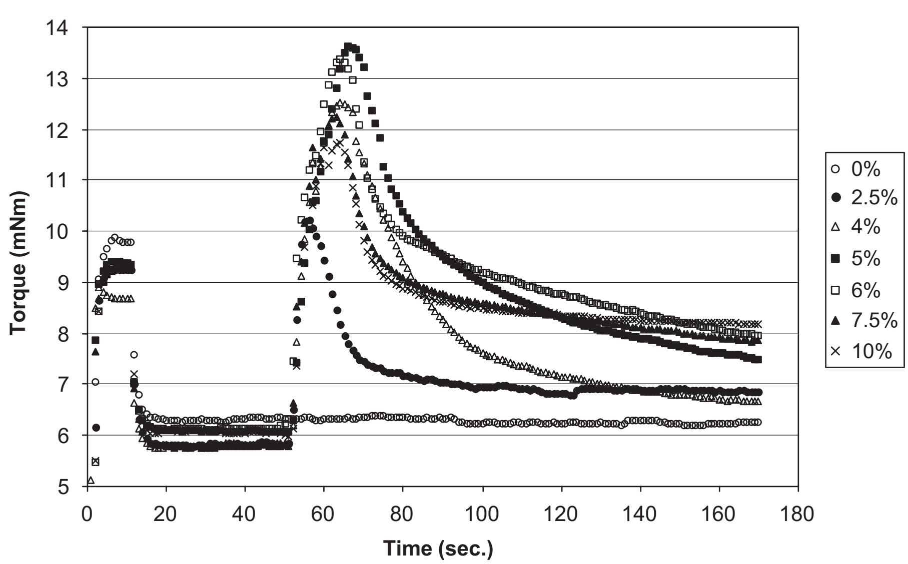

Fig. 2 – Torque–time rheograms obtained from sludge samples conditioned with the Clarifloc C-311 polymer. The rheological measurements were conducted according to Method 1.

Abu-Orf and Örmeci, 2005). The method involves one step, and rheological characteristics of samples are measured at 300 RPM for 120 s after conditioning. The conditioning can be achieved using a jar-tester or a full-scale flocculator. The method is useful in comparing the rheological and dewatering characteristics of already conditioned samples. Fig. 4 illustrates typical results obtained using Method 2.

2.6. Dewaterability measurements

Dewaterability of sludge samples was characterized using capillary suction time (CST) and gravity drainage tests. CST tests were conducted according to the Standard Methods (APHA, 1995). For the gravity drainage tests, 200 mL sludge samples were gravity-drained from an 11-μm Whatman paper for 10 min using a filtration unit (Millipore Sterifil Aseptic System, 47 mm), and the filtrate volume was measured. Cake solids retained on the filter were measured using a microwave moisture/solids analyzer (Denver Instrument Company, Model M2) at the treatment plant. CST and filtration tests were conducted in duplicate.

3. Results and discussion

At the time of the study, the treatment plant was dosing a Mannich polymer (Clarifloc C-311) at 10% polymer-to-sludge ratio (10 g/kg DS) before dewatering. Torque-time rheograms from conditioned samples at increasing polymer doses are illustrated in Fig. 2. These rheograms were obtained using Method 1 and show the average of two rheograms. The standard deviations were within 5% of the arithmetic means, and error bars are not illustrated to keep the rheograms readable. In Step 1, sludge is mixed at 420 RPM for 10 s. to resuspend the settled material. The first peaks seen on the rheograms are influenced by the impeller speed and the initial turbulence created in the reservoir by the switched-on impeller, and may not accurately indicate the sludge characteristics, degree of flocculation or optimum polymer dose (Örmeci et al., 2004). Step 2 provides 40 s of stabilization time for the torque measurements (from 10 to 50 s) and serves as a baseline reading for the unconditioned sludge samples. At the end of Step 2, polymer is injected into the sludge through the ports of the Floccky reservoir (Fig. 1b), which provides an opportunity to observe both the flocculation and the deflocculation phases. Concentric-cylinder rheometers allow the observation of the deflocculation phase only. Right after polymer injection, a steep peak is observed in torque readings, which is due to the formation of flocs and the increased resistance of the sludge network to shear. Unlike the first peak, this second peak is not affected by the initial turbulence and exhibits good reproducibility. Michaels and Bolger (1962) attributed the energy dissipated within a flocculated suspension to three separate processes. Energy is required to (1). Deform and stretch the network structures, (2). Break up the bonds between flocs, and (3). Dissipate viscous energy. Based on the work of Michaels and Bolger (1962), Langer et al. (1994) explained the formation of peaks by the existence of an elastic network, where the high energy dissipation after polymer addition is due to the deformation of the network while the top of the peaks indicate the points where the network bonds rupture. Thus, the second half (decay phase) of the peaks, where the torque values start decreasing, can be attributed to the deflocculation process and the decreased resistance to shear. After the flocs break up, the interaction between them continuously decreases resulting in a decrease in energy dissipation (Langer et al., 1994).

The rheograms illustrated in Fig. 2 can be analyzed in several different ways using the height of the peaks, width of the peaks, the area under the peaks, the difference between the stabilized torque readings before and after the polymer injection, or the area under the entire rheograms. This study investigates a possible relationship between the height and the size of the peaks and the optimum polymer dose. The rheograms in Fig. 2 indicate that in the underdose region the torque values increase in magnitude and the peaks increase in size when polymer dose is increased. This is because the strength of the network bonds and the resistance of sludge to shear are higher after polymer addition. Fig. 3a shows results from CST and filtration tests. The lowest CST and the highest filtrate volume were measured at 5% polymer-to-sludge ratio, which indicate that the optimum polymer dose is 5% (5 g/kg DS) for this sludge. After the optimum dose was reached, the torque values started to decrease in magnitude and the peaks started to decrease in size (Fig. 2). The peak height and the area under the peaks are illustrated in Fig. 3b. The area under a torque-time rheogram, or a peak in this case, has been shown to be proportional to the total energy dissipation (Örmeci and Abu-Orf, 2005). The results indicate that the peaks increase in height and size in the underdose region, and reach their maximum values at the optimum dose. Beyond the optimum dose, a decrease in the height of the peaks and measured torque values was observed. It should also be noted that the peaks eventually disappear due to extended shear application, however the torque values measured at the end of the peaks (eg. 160–170 s) are still higher than those measured before the polymer addition (eg. 20–40 s) (Fig. 2). This indicates polymer addition increases the overall strength or resistance of sludge to shear even after flocs are destroyed.

The treatment plant was dosing polymer at 10% polymer-to-sludge ratio (10 g/kg DS) before dewatering. The cake solids concentration at this polymer dose was 18%. After the lab-scale testing illustrated in Figs. 2 and 3, it was clear that the plant was overdosing sludge. The polymer dose was decreased to 5% (5 g/kg DS) at the full-scale, and 18% cake solids content was maintained at this dose. The treatment plant now can achieve the same cake solids concentration and good centrate quality only by using half of the polymer dose that it used to use. This resulted in 50% reduction in polymer consumption, and major savings for the treatment plant.

Once the optimum dose was determined and confirmed with the full-scale testing, the next step was to optimize the operational parameters of the full-scale flocculant. The flocculant was operated at 200 RPM when the polymer was dosed at 10%, however no full-scale testing of the optimum flocculant speed was previously conducted. During the full-scale testing, the polymer dose was set at 5% and the flocculant speed was increased in 50 RPM increments. Conditioned sludge samples were collected right after the sludge

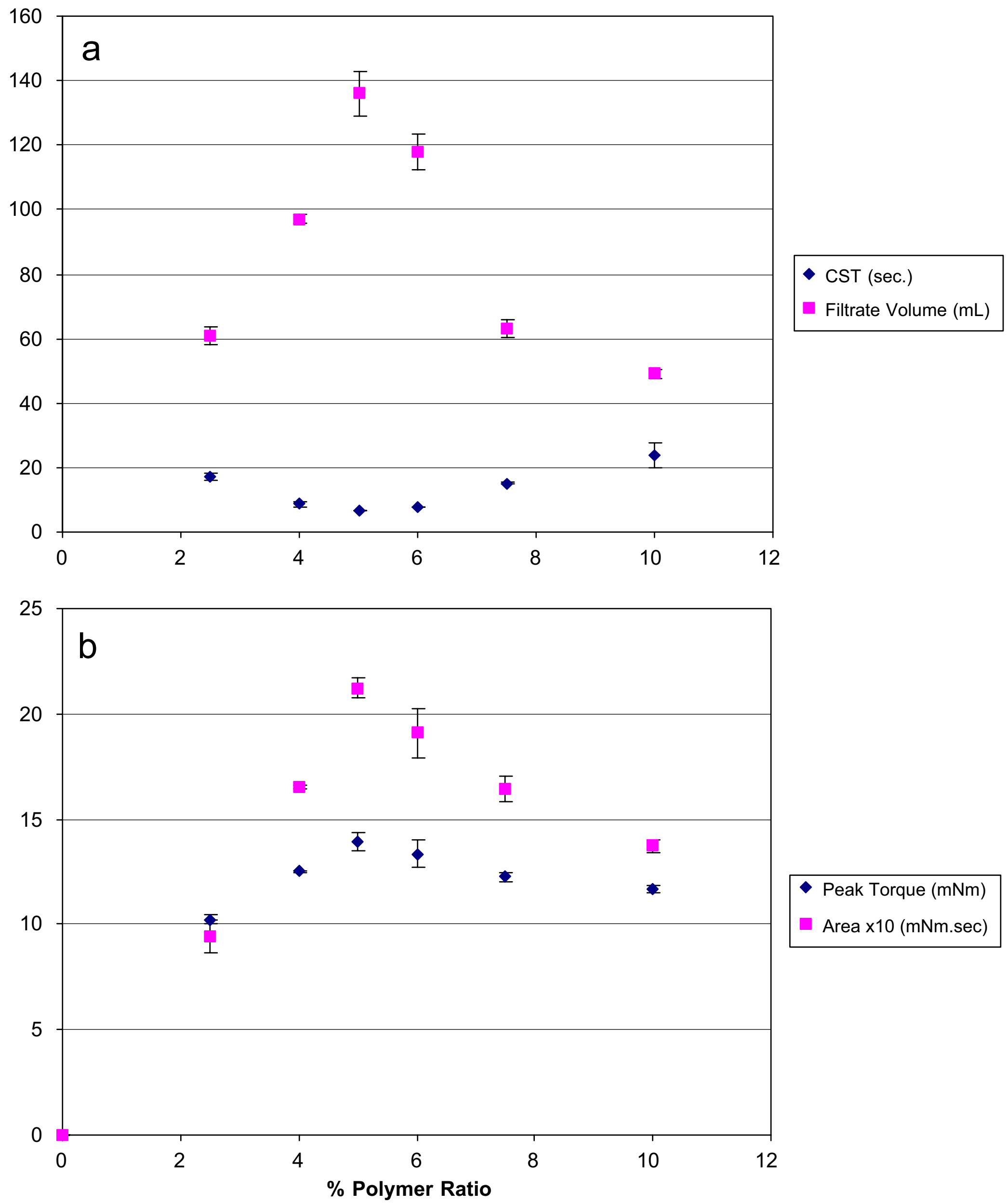

Fig. 3 – (a) Results from the CST and filtration tests indicate that the optimum polymer dose is at 5% (5 g/kg DS). (b) The height of the peaks and the area under the peaks are maximum at the optimum polymer dose.

stream left the flocculant, and rheological measurements were conducted according to Method 2. Cake solids concentration and supernatant quality were monitored. Results from the rheological measurements and dewaterability tests are illustrated in Fig. 4 and Table 1. The measured torque values were lowest for the unconditioned sludge samples as expected. At 250 RPM, the torque values were around 7.4 mN m, but decreased to around 6.8 mN m when mixing speed was increased to 300 RPM. When the flocculant speed was increased to 350 and 400 RPM, measured torque values continued to increase to 7.8 and 8.4 mN m respectively. Sludge conditioned at 300 RPM dewatered best compared to the other samples (Table 1). The lowest CST, highest filtrate volume and cake solids were measured at 300 RPM. The observed decrease in the measured torque values at 300 RPM, supported by the results from the dewaterability tests, indicates that 300 RPM is the optimum flocculant speed and sludge is conditioned best at this flocculant speed when polymer dose is 5%. Örmeci and Abu-Orf (2004) and Abu-Orf and Örmeci (2005) reported a local decrease in the measured torque and totalized torque values at the optimum polymer dose during polymer conditioning tests. The decrease in the measured torque values was attributed to the release of free water at the optimum dose and the decrease in the drag force due to the flocculation of particles, which in turn would decrease the resistance of sludge to the applied shear and result in lower torque values

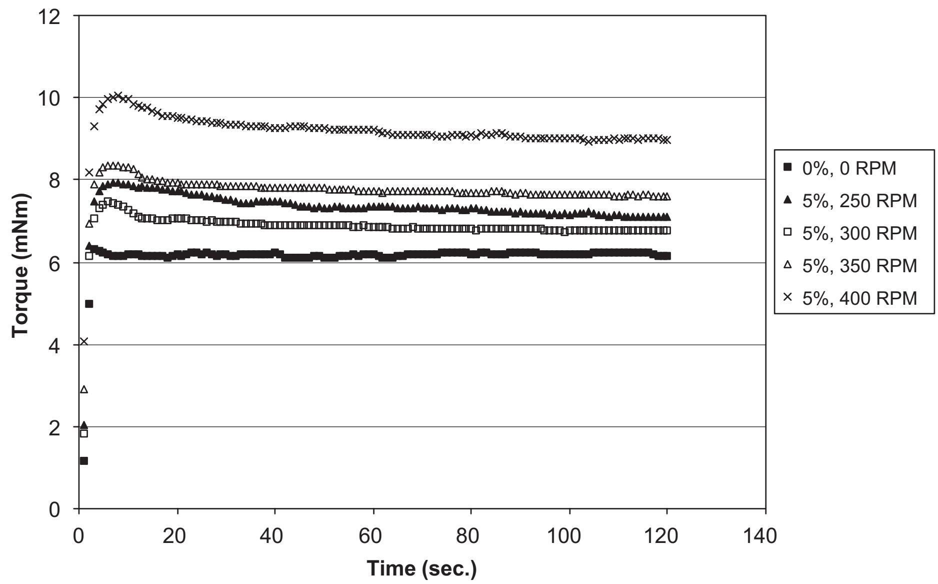

Fig. 4 – Rheograms from sludge samples conditioned at different mixing speeds using the full-scale flocculant. The rheological measurements were conducted according to Method 2. The polymer was Clarifloc C-311, and the polymer dose was 5% (5 g/kg DS).

Table 1 – CST, filtrate volume and cake solids data from samples conditioned at 5% (5 g/kg DS) polymer dose and mixed at different speeds with the full-scale flocculant

Flocculant speed	250 RPM	300 RPM	350 RPM	400 RPM
CST (s)	7.6 ± 0.14	6.5 ± 0.42	10.25 ± 1.06	9.55 ± 2.47
Filtrate (mL)	126 ± 7.07	132 ± 4.24	110 ± 5.66	92.5 ± 6.36
Cake solids	17.66	18.39	18.25	18.35

(Örmeci and Abu-Orf, 2006). Thus, it appears that a local decrease in the torque values may be used not only to determine the optimum polymer dose, but also to identify the optimum mixing conditions at the optimum dose.

Fig. 5 illustrates rheograms obtained using emulsion polymer C-9545 according to Method 1. Similar to the results obtained with the Mannich polymer (Fig. 2), the peaks increase in height and size as the polymer dose is increased. The largest peaks were observed at 5% and 6% polymer, beyond which the peaks decreased in height and size. The peak height and area measured at 6% polymer were slightly higher than those at 5% (Fig. 6b). CST and filtration test results indicated that both 5% and 6% polymer doses resulted in good dewaterability, but 6% (6 g/kg DS) corresponded to the highest filtrate volume, lowest CST, and the largest peak (Fig. 6a and b). Thus, the optimum dose was determined to be 6% (6 g/kg DS), and different combinations of polymer doses and flocculant speeds were tested at the full-scale. Previously, 300 RPM was determined as the optimum flocculant speed for the Mannich polymer C-311 (Fig. 4), so higher flocculant speeds were tested with polymer C-9545 since emulsion polymers typically require a higher mixing intensity compared to Mannich polymers. The results from full-scale testing are illustrated in Table 2. CST, filtrate volume, and cake solids tests indicate that best dewaterability was attained at 6% and 400 RPM. The effect of mixing on the optimum polymer dose has been previously well-documented (Werle et al., 1984; Novak et al., 1988; Novak, 1990; Abu-Orf and Dentel, 1997). As the mixing intensity increases, polymer requirement also increases (for example compare 350 and 400 RPM at 5% in Table 2). Extended mixing leads to floc breakage, exposes more negative surfaces, and thus more polymer is required to achieve charge neutralization (Abu-Orf and Dentel, 1997). Thus, "optimum dose" for a given sludge is not a fixed number, and strongly depends on the mixing intensity. This means the same level of dewaterability might be achieved at a lower polymer dose mixed at lower intensity as well as at a much higher polymer dose mixed at higher intensity. If the lower polymer dose and mixing intensity are used at the treatment plant, this will result in substantial savings in polymer costs.

A second emulsion polymer (SE914) was also tested at the lab- and full-scale. Results from the lab-scale testing are illustrated in Fig. 7. Similar to the results obtained from the Mannich and C-9545 polymers, in the underdose region rheograms moved up and the peaks increased in height and size as the polymer dose was increased (eg., 3% and 4%). After the optimum polymer dose was reached, rheograms started moving down again and exhibited smaller peaks (6% and 7%). Optimum dose was determined to be at 5% based on the results from the dewaterability tests (CST = 9.35 s, filtrate volume = 136 mL).

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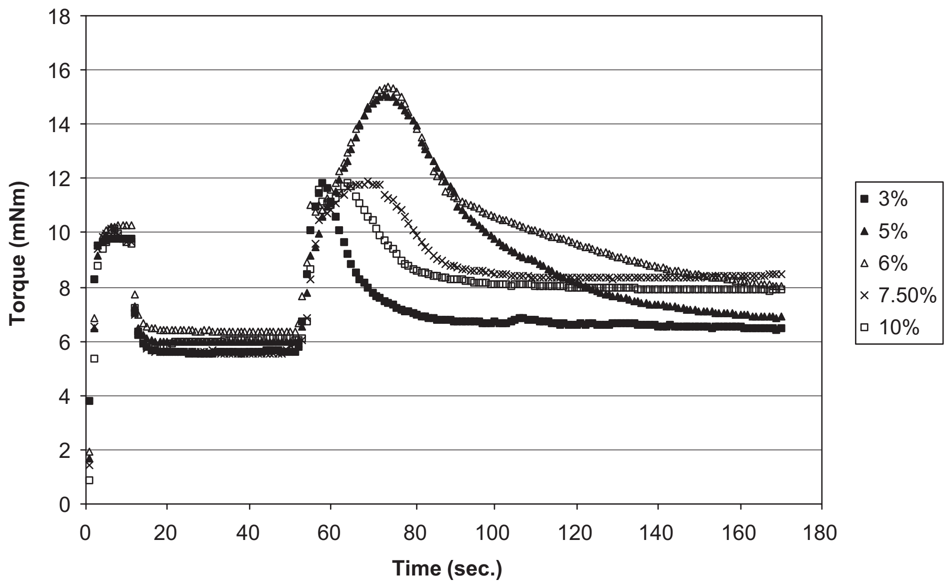

Fig. 5 – Torque–time rheograms obtained from sludge samples conditioned with the Clarifloc C-9545 polymer. The rheological measurements were conducted according to Method 1.

Results from the three polymers (C-311, C-9545 and SE-914) tested indicated that all three polymers performed well with this sludge and produced good dewaterability. The emulsion polymers (C-9545 and SE-914) were preselected by the polymer manufacturer based on the chemistry of the products and their long-term experience with the dewatering operation at this treatment plant. Even though the emulsion polymers performed well, they did not provide a significantly higher performance compared to the Mannich polymer (C-311), and the treatment plant decided to continue using the Mannich polymer in their dewatering operations.

The final task was to provide a tool to the treatment plant operators to keep their dewatering operations at the optimum on a daily basis. Sludge characteristics change over time, which requires readjustment of the polymer dose. Conventional jar tests are typically used for the determination of optimum dose at the lab-scale, however the mixing conditions used in a jar test experiment are very different from those experienced in the full-scale flocculants. In fact, as reported by Novak (1990) when polymer conditioning tests were conducted using a conventional jar-test apparatus, required doses were almost always unpredicted. In order to accurately determine the optimum polymer dose at the lab-scale, the jar-test mixing conditions must be matched to the full-scale mixing conditions. This, however, is quite a challenge since there is no good way of directly measuring the total mixing intensity that the sludge network is exposed to during full-scale mixing. An alternative is to use indirect methods, such as rheological characteristics of sludge, to match the jar-test mixing conditions to that of the full-scale mixer. Previous results indicated that the optimum polymer dose for this sludge was 5% and the optimum flocculant speed was 300 RPM (Figs. 2, 3 and 4). Fig. 8 shows the average of two rheograms obtained from a sludge sample conditioned at 5% polymer and 300 RPM mixing speed using the full-scale flocculant. Since the polymer dose and the rheograms of the conditioned sample were already known, what was unknown was the mixing intensity imparted by the full-scale flocculant. If a raw (unconditioned) sludge sample is conditioned at the same polymer dose (5%), and the mixing intensity is varied such that similar rheograms are obtained from the sample, it would be possible to determine the jar-tester mixing speed and time that would simulate the full-scale mixing. Fig. 8 shows that the rheological characteristics of a 500 mL sample mixed at 100 RPM for 30 s, 100 RPM for 60 s, and 200 RPM for 30 s. The rheological characteristics of the sample that was mixed at 200 rpm for 30 s were very similar to the rheological characteristics of the sample mixed in the full-scale flocculant. Both samples dewatered similarly as well (CST values were 6.6 and 6.9 s respectively). This simple test provides a valuable tool to the treatment plant operators to simulate their full-scale mixing with the jar test experiments, and to accurately predict the polymer dose that would generate the highest cake solids at the full-scale.

Use of rheological measurements for the optimization of dewatering operations provides additional insights into sludge properties, behavior and dewatering that cannot be obtained with the traditional capillary suction time (CST) and specific resistance to filtration (SRF) tests. CST and SRF parameters are not indicative of material properties of sludge and they only allow relative predictions (Dentel et al., 2005). Rheological parameters, on the other hand, are indicative of material properties and provide not only descriptive but also predictive tools (Dentel et al., 2005). Method 1 presented in this study provides several advantages. First, it is directly applied to the unconditioned sludge. Thus, it eliminates the need for the conditioning step as well as the effect of mixing on the polymer dose and dewaterability. Second, the method allows direct observation of the effect of polymer, and the flocculation and deflocculation phases. The method allows

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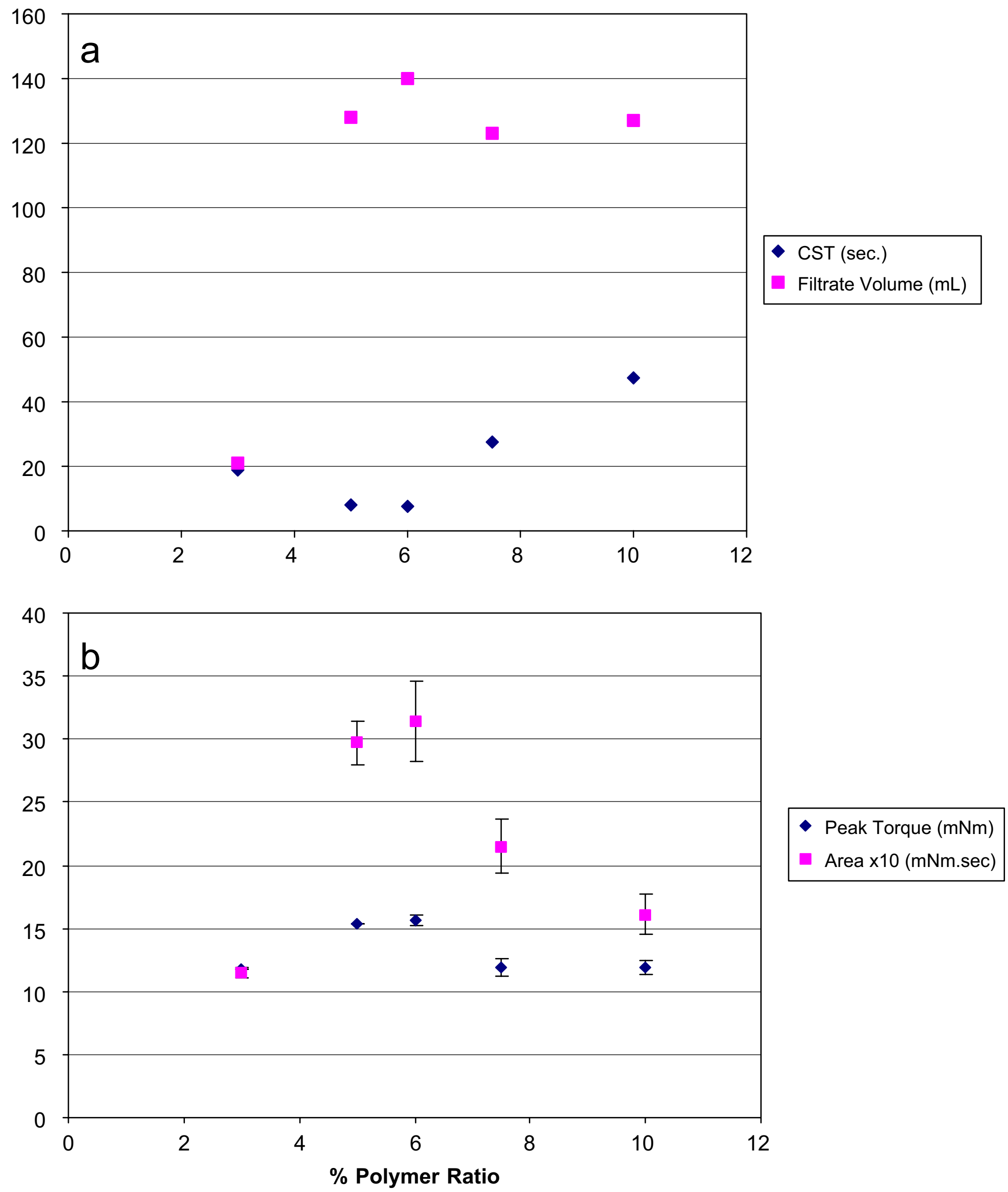

Fig. 6 – (a) Results from the CST and filtration tests indicate that the optimum polymer dose is at 6% (6 g/kg DS). (b) The height of the peaks and the area under the peaks are maximum at the optimum polymer dose.

Table 2 – CST, filtrate volume and cake solids data from samples conditioned with the Clarifloc C-9545 polymer using the full-scale flocculant

Polymer dose (%) and mixing speed(RPM)	CST (s)	Filtrate (mL)	% Cake solids
4.5, 350	6.65 ± 1.06	86 ± 4.24	18.05
5, 350	9.75 ± 0.07	120 ± 7.07	18.8
5, 400	36.75 ± 18.74	14.5 ± 2.12	18.7
5.5, 400	25.7 ± 18.38	83 ± 4.24	19.25
6, 400	9.25 ± 0.49	140 ± 8.49	18.52

testing of several different polymers and doses in a short period of time. As it is illustrated with Method 2, rheological measurements can also be used to optimize the mixing used during conditioning. In short, rheological methods provide several advantages over the CST and SRF tests, and have great potential for the optimization of dewatering processes at the treatment plants. Treatment plant operators can easily operate a simple version of torque rheometers, which are basically made of an impeller and a beaker.

Mixed primary and secondary sludge was used during this study. The results presented herein are very encouraging, and further testing is being conducted in our laboratories using

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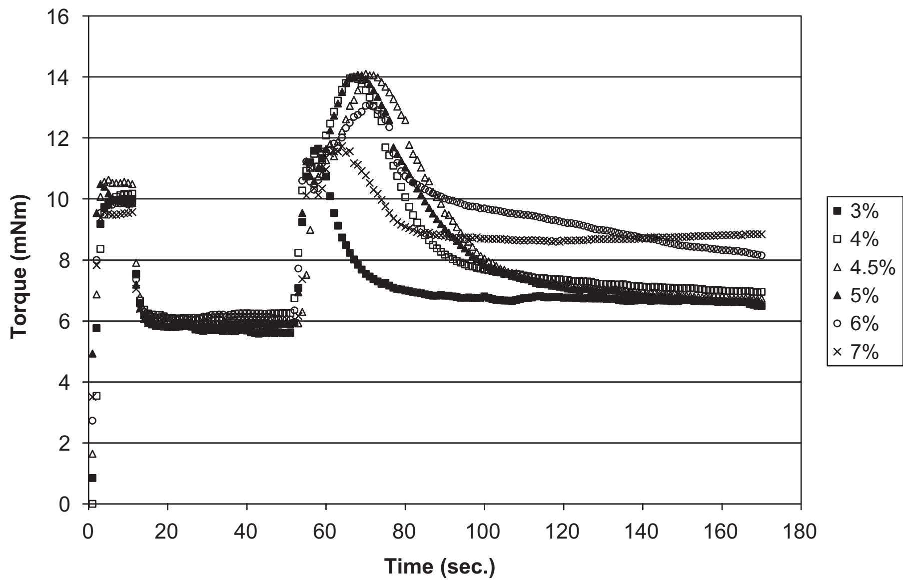

Fig. 7 – Torque–time rheograms obtained from sludge samples conditioned with the SE-914 polymer. The rheological measurements were conducted according to Method 1.

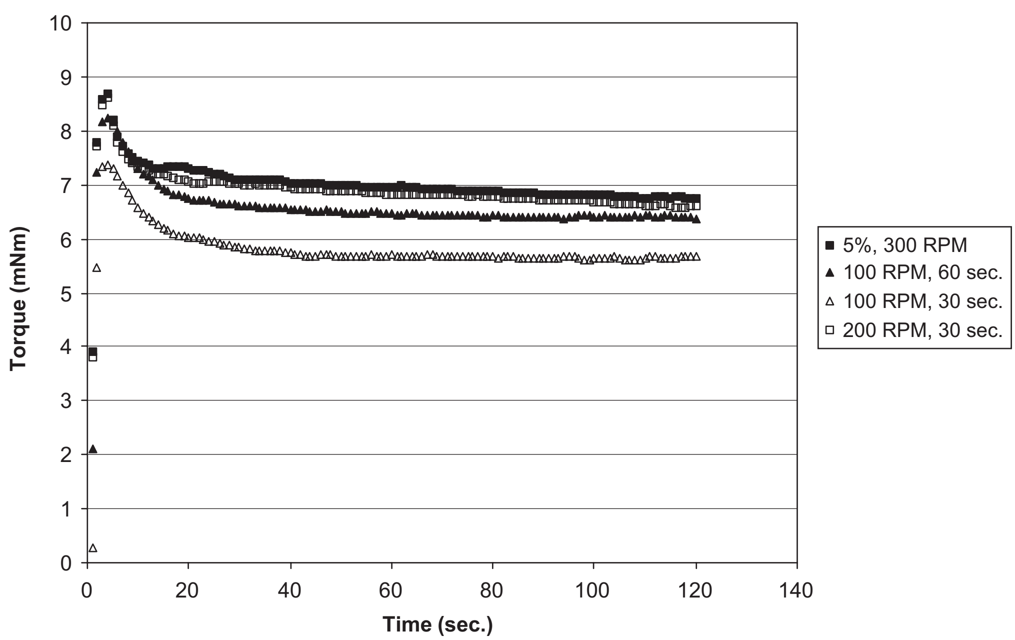

Fig. 8 – Rheograms obtained from samples conditioned using the full-scale flocculant and the jar tester according to Method 2. 200 RPM jar-tester speed and 30 s mixing time simulates the full-scale mixing, and produces sludge with similar rheological characteristics.

digested sludge and several different Mannich, emulsion, and dry polymers. Preliminary results from these tests indicate that multiple peaks might be observed after the injection of polymers, particularly in the overdose region. The chemical compatibility of the polymer and sludge appears to influence the shape, size, and formation of the peaks. Further testing is necessary to have a better understanding of the mechanisms involved behind the formation and destruction of the peaks (flocculation and deflocculation phases), and to determine whether the presented methods can be applied to other sludges as well.

4. Conclusions

1. This study presents two methods that are based on torque rheology and that can be used for the determination of the optimum polymer dose and mixing conditions as well as for

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the selection of the best performing polymers. The first method is used for unconditioned sludge, and utilizes the peaks observed in the torque readings after polymer injection. The second method is used for already conditioned sludge and utilizes the entire torque-time rheograms.
2. Torque rheology can be used to determine the shear intensity imparted to sludge during full-scale conditioning. This information is useful in identifying the jar-tester speed and mixing time that simulates the full-scale mixing.
3. The measurement of well-defined rheological properties provides a more reliable analysis compared to empirical tests used for characterizing wastewater sludges, and can be used as a control parameter for the optimization of conditioning and dewatering operations at wastewater treatment plants.

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