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Polymer dose assessment using the streaming current detector

Mohammad M. Abu-Orf, Steven K. Dentel

ABSTRACT: The streaming current detector (SCD) is an electrokinetic analyzer for characterizing charge properties of particles in aqueous suspension. Its use in water treatment is well established. This research evaluated its use for automatic monitoring of polymer dosage in three wastewater treatment facilities using centrifuges or belt filter presses for dewatering. Continuous SCD readings from the liquid stream (centrate or filtrate) and other process responses were recorded while imposing stepwise changes in the polymer dose. The polymer caused a transition from negative to positive charge in both the conditioned solids and the liquid stream. 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 times. Thus, charge neutralization is a key mechanism in solids conditioning, and the SCD is suitable for monitoring of polymer dosage. For its use in automatic polymer dose control—evaluated in a subsequent phase of the study—modifications were required to provide more reliable continuous sampling. *Water Environ. Res.*, **69**, 1075 (1997).

KEYWORDS: biosolids, conditioning, dewatering, polyelectrolytes, streaming current.

Solids management is often a problematic aspect of wastewater treatment, with conditioning and dewatering being critical processes in terms of overall performance and cost. Conditioning most often involves use of a chemical additive (typically a cationic, high-molecular-weight organic polyelectrolyte, or polymer) that is added to the sludge to facilitate and enhance the dewatering process. Polymer cost alone represents a significant expense and may exceed 50% of the overall solids-handling costs (U.S. EPA, 1987, and Vesilind, 1979).

The cost of solids treatment typically constitutes a large portion of total treatment cost, with solids disposal costs increasing rapidly (Balmér, 1994, and Evans and Filman, 1988). In 1993, the production rate of municipal wastewater solids in the U.S. was estimated at 5.3 million dry metric tons, with continued increases anticipated (Smith *et al.*, 1993). At an assessed polymer price of $1.5 per kg (lb), U.S. wastewater plants spend approximately $130 million per year on polymers. Improper conditioning may lead to unnecessary costs for wastewater solids incineration, transportation, and landfill disposal. Thus, a clear understanding of conditioning mechanisms, optimization, and control is important for cost-effective wastewater treatment.

Because of the importance of polymer–particle collision and attachment, the dosage of polymer required for proper conditioning depends on both polymer and solids characteristics. Dose adjustment may be needed when changes occur in either case. Solids characteristics before conditioning are subject to seasonal, daily, or even hourly fluctuations, particularly if solids from different processes or other sources are mixed periodically before conditioning. Changes in the polymer demand may also be caused by variation in the conditioning products, the aging process, or differences between batches.

Polymer dosage is most often controlled manually based on either visual observation of the conditioned solids (in the case of belt filter presses) or by cake total solids measurements (for centrifuges). However, this paper will show that cake total solids may not provide an adequate indication of process performance if liquid stream characteristics are of concern; furthermore, an inadequate total solids level does not necessarily indicate whether the polymer feed rate should be increased or decreased.

Because of the factors listed above, overdosing is a common occurrence, which may lead to foaming problems, excessive liquid stream (filtrate/centrate) solids levels, environmental discharge of polymer, and substantial cost of unnecessary chemical consumption. Continuous optimization of polymer dosage is therefore important to make the most of solids recovery in dewatering and limit the effect of these polymers on the environment and the plant itself.

Deleterious effects within the plant can result from the recirculation of polymer to other treatment processes. Polymers attach tenaciously to solids unless the conditioner dose is excessive (Christensen *et al.*, 1993, and Dentel and Abu-Orf, 1993). Therefore, polymers may be associated with both wastewater solids and the recycle flows—centrate or filtrate—following conditioning. These recycle flows contribute polymers to other processes in the plant, such as secondary treatment.

Much is unknown concerning possible effects of polymer recirculation on treatment processes. However, excess polymers in liquid streams are commonly observed to cause foaming problems in these flows; thus, their recirculation during significant overdosing may contribute to foaming in other processes such as aeration basins and digesters.

Retained polymers with dewatered solids may affect downstream processing and disposal of biosolids, which might include composting, landfill disposal, and land application of biosolids. Polymer biodegradability in these processes appears to be limited (Raudenbush, 1994), and the polymer may also alter contaminant retention (DiVincenzo and Dentel, 1995).

Based on typical polymer use in the U.S., polymers make up approximately 0.5 to 1.0% of the solids mass in the final product (U.S. EPA, 1987). If not degraded, polymers must leave the treatment plant either with the cake or the treated effluent. The fate and environmental effect of these polymers have not been extensively studied, but the quantities disposed of indicate the need for more knowledge concerning their fate. In wastewater effluent, or if conditioned solids come in contact with natural waters, the toxicity of polymers to aquatic organisms may be a

concern. Evaluation of the aquatic and terrestrial toxicity of polyacrylamide polymers led Godwin–Saad *et al.* (1994) to conclude that free polymers in effluent are of sufficient toxicity that polymer overdosing should be evaluated and considered in toxicity reduction evaluation investigations. It should be noted, however, that polymer adsorption on solids may significantly decrease its bioavailability.

For these reasons, polymer overdosing should be avoided. This may not always be possible in practice because of changes in polymer demand experienced over time, the lack of knowledge regarding conditioning mechanisms, and the lack of reliable control by conventional polymer addition systems. An automatic chemical dosage control system, if operable, would allow timely response to changes in solids characteristics to avoid overdosing and achieve the benefits of polymer dose optimization. A control algorithm is also necessary to determine the appropriate dosage change according to varied conditions.

Technologies have been proposed, and in some cases commercialized, to allow continuous, automatic adjustment of polymer feed rate in response to changing conditions. These devices use feedback control based on characteristics of either the conditioned sludge (electrokinetic, rheological, or filtration properties) or the liquid stream (electrokinetic or rheological properties or concentration of solids). Feed-forward dose control may also be used, based on flow and solids concentration before conditioning (Dentel *et al.*, 1995).

In spite of the likely benefits of such systems, practical implementation has proven difficult in the challenging environment of full-scale dewatering processes. No polymer dose control system has achieved widespread use for conditioning, and at the time of this study, only two technologies were available for plant evaluation. One of these, the streaming current detector (SDC), is the subject of this paper; the second (Zenofloc system, based on rheological properties of conditioned solids) was found to be less successful, as described elsewhere (Dentel *et al.*, 1995). Other dose control systems may emerge in the future (Igarashi *et al.*, 1993, and Yasukawa and Shigemi, 1993), and the evaluation methodology described in this paper may be applicable in their assessment.

The SCD, which has also been termed a streaming current monitor or particle charge detector, is now widely used in coagulation control in many water treatment plants and appears to have the potential for polymer dose optimization and control in wastewater solids conditioning as well. Its operation is based on the electrokinetic characterization of colloidal surfaces in the liquid stream after dewatering. This relies on the assumption that partial or complete neutralization of negatively charged colloidal material in solids must occur for successful conditioning and dewatering. However, the validity of this assumed mechanism and the ability of the SCD to correctly characterize charge transitions with varying polymer dosages have not been previously demonstrated in long-term, full-scale dewatering applications.

Conditioning Mechanisms

Ideally, a charge-based control system requires that polymers operate by a straightforward mechanism of charge neutralization. In fact, most wastewater solids have a negative surface charge, and appropriate dosages of cationic polymers may neutralize this charge, thus limiting repulsive forces between these particles. This allows them to agglomerate, forming larger and

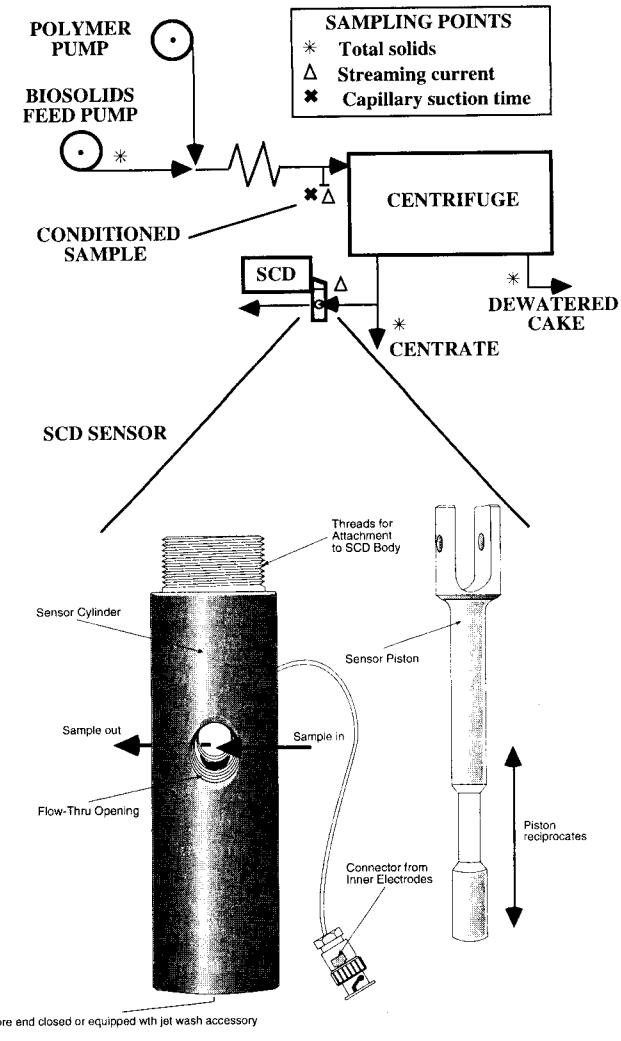

Figure 1—Flow diagram at Warminster site showing streaming current detector arrangement for continuous sampling and magnified view of the detector's sensor. The diagram also indicates sampling points for all analyses.

stronger flocs. However, other process characteristics (solids, polymer, and mixing properties) may alter the relationship between polymer dose and degree of charge neutralization. Evidently, solids flocculation is accompanied by floc breakage, requiring reattachment of solids by free polymer segments, forming denser and stronger flocs with increased mixing but also requiring greater polymer amounts (Bratby, 1980; Dentel and Abu–Orf, 1993; and Werle *et al.*, 1984). Nonetheless, charge neutralization is typically concomitant with optimal solids destabilization; thus, the SCD should be appropriate for monitoring this process.

Streaming Current Detector

The sensor, the main component of the SCD, consists of a reciprocating piston in a dead-end cylinder (Figure 1). Electrically charged colloids in a fluid sample momentarily attach to the piston and cylinder surfaces. The charged layer attached to the piston travels with the piston velocity while that attached

to the cylinder walls remains stationary. The fluid in the gap between the two moves at much greater velocity than that of the piston and it also transports the counter ions located beyond the shearing plane, thus providing a measurable current. This resulting streaming current (SC) is detected by electrodes at opposite ends of the flow path and sampled and amplified by the electronic components of the SCD to give a digital output. Because this SC is related to the electrical charge of the colloids, it may provide an indication of charge-related particle destabilization in a manner similar to zeta potential. Further details on SCD functioning are available elsewhere (Dentel and Kingery, 1988 and 1989; Dentel *et al.*, 1995; and Elicker *et al.*, 1992).

Most wastewater solids are negatively charged, thus have an initially negative SC value. This SC value is related to the zeta potential of the solids and the geometry of the SCD's probe and the motor speed as shown in Equation 1 (Elicker *et al.*, 1992).

$$SC = K_{amp} i = K_{amp} \left(\frac{8\pi f s \epsilon \zeta}{1 + \frac{1 + \lambda^2}{1 - \lambda^2} \ln \lambda} \right) \quad (1)$$

Where

SC = streaming current detector reading (relative units);
K_{amp} = streaming current amplification factor (A^{-1});
i = streaming current at electrodes (A);
f = frequency of piston motion (cycles/sec);
s = piston stroke (m);
ϵ = solution dielectric constant (SI convention);
ζ = zeta potential (V); and
λ = ratio of piston radius (λR) to housing inner radius (R).

This equation validates, in theory, the condition that the SCD must be characterizing colloidal electrokinetic properties because it correlates the measured current with the colloidal zeta potential. This correlation is important because zeta potential measurements have indicated charge neutralization to play an important rule in conditioning (Cole and Singer, 1986; Novak *et al.*, 1977; and Roberts and Olsson, 1975). Previous determinations of zeta potential used measurement of electrophoretic mobility, however, which was not readily converted to a continuous output for process control purposes. Use of a flow-through sensor allows the SCD to provide such a signal.

Use of the Streaming Current Detector in Dewatering Applications

Previous work typically indicated that when solids are conditioned properly with a cationic polyelectrolyte, the SC of the conditioned solids becomes less negative and eventually becomes positive. Dentel and Wehnes (1988) showed that when the SC of conditioned solids was near zero, this corresponded to good dewaterability as indicated by minimum CST. Ay *et al.* (1992) showed that the point of neutral charge in the filtrate, as indicated by SC, agreed with the minimum specific resistance to filtration in indicating optimum conditions. They also showed agreement between the point of neutral charge and percent solids recovery in laboratory experiments using kaolin suspensions. Richter *et al.* (1993) showed that if zero streaming potential of conditioned solids corresponds to good dewaterability, polymer consumption can be reduced by using higher charge polymers for the same solids. However, they failed to demonstrate any agreement between the charge characteristics of the filtrate and solids dewaterability parameters. Dentel and Abu-Orf (1993) showed that the SC could be measured using the centrate after dewatering and that this reading could also be used as a conditioning control parameter.

The studies described above considered the possibility of using streaming current for on-line automatic control of solids conditioning. Yet, only limited research has been conducted to test this applicability on a plant scale. Thus, the objective of this research was to test the utility of the SCD in monitoring performance of operational dewatering processes. In this context, it was important to identify any potential problems of the sampling and sensor systems of the SCD under everyday conditions at wastewater treatment facilities. It was also considered important to assess the correlation of SCD output to actual dewatering performance, rather than to surrogate laboratory measurement for these purposes. Investigations were conducted at three wastewater treatment facilities: the 0.36-m^3/s (8.2-mgd) Warminster Municipal Authority (WMA) wastewater treatment plant (Pennsylvania, U.S.); the 0.31-m^3/s (7-mgd) Upper-Morland Hatboro Joint Sewer Authority (UMHJSA) wastewater treatment plant (Pennsylvania, U.S.), and the 3.9-m^3/s (90-mgd) Wilmington Pollution Control Facility (WPCF) (Delaware, U.S.). Experiments and results are presented sequentially for work in each of these plants.

Tests at the Warminster Municipal Authority Facility

The Plant. The facility's anaerobically digested solids are dewatered using two parallel rotating bowl centrifuges. Cationic polymer (Pollu-Treat C426) was used for conditioning at a concentration of approximately 2.0 g/L as fed. The SCD was installed to characterize particle charge in the centrate (Figure 1) using a flow-through arrangement with a centrate sample flow rate of 3.8 L/min (1.0 gpm). Laboratory conditioning of solids samples previously showed that, when the SC of the conditioned solids was near zero, this indicated good dewaterability (Dentel and Abu-Orf, 1993).

A Milton Roy Gen. III (SC 4200) SCD model was used for the evaluation at WMA. Modifications to this SCD model allowed its general use in wastewater applications and included improved probe geometry, material, and sample collection systems; increased piston speed in the annulus to increase sensitivity; a new electronics design to eliminate interfering noise in the presence of high solids concentrations and to eliminate interfering phase-shift phenomena; and the addition of an automatic jet wash for probe cleaning with tap water to prevent any clogging problems.

Procedures. Previous experience showed that, when installing a new SCD unit or probe, up to 1 week may be required for signal stabilization, and this time was provided before the experiments. The test procedure entailed consecutive changes in polymer dose while maintaining a constant solids flow rate, monitoring the SCD response, and, after process stabilization, using total solids measurements of both the cake and the centrate to characterize centrifuge performance. We termed this procedure a dose-response test. It began with the highest polymer flow rate to be used followed by stepwise decreases because

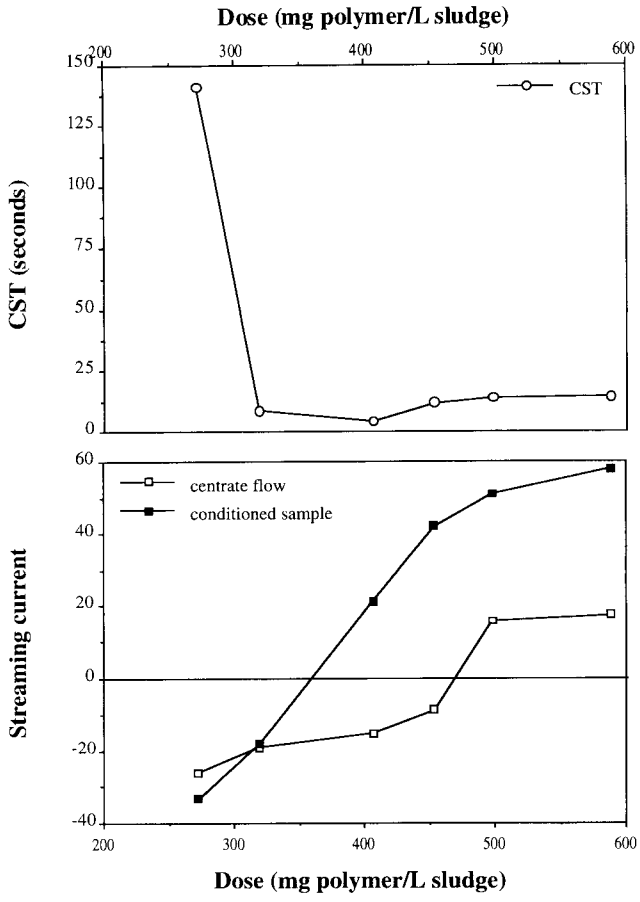

Figure 2—Results of polymer dose-response test conducted at Warminster Municipal Authority treatment facility, August 21, 1991, with total solids = 2.04%. All results here, and in subsequent figures, represent means of triplicate analyses.

this sequence appeared to give the most rapid transitions in centrifuge performance.

Before conducting each test, the SCD's probe was dismantled and cleaned thoroughly with a plastic brush and tap water. The instrument was then zeroed if necessary. The SCD reading was standardized to a value of −70 SC units with reference to a polyvinyl sulfate solution with known charge characteristics (Elicker *et al.*, 1992). The centrate SC required approximately 2 minutes to restabilize following each change in polymer dose. Conditioned solids samples were taken immediately before the centrifuge entrance for laboratory CST measurements. In a preliminary dose response test, the SC of the centrate, rather than the conditioned solids, was also measured at each dose after removing the SCD's flow-through housing to allow batch sampling with a 1-L sample size.

A second dose-response experiment was conducted with samples of centrate, cake, and conditioned solids also transported to the laboratory for solids measurements, performed the day of the field experiments. The SC of the centrate, rather than the conditioned solids, was measured in this experiment.

All CST and solids, determinations conducted for this research were performed in triplicate, with the mean value reported. Spearman's rank correlation tests were used for statistical analysis of all results. This procedure was selected because it indicates a correlation for any monotonic relationship between two parameters, as appropriate for process control relationships. Streaming current correlations with performance parameters were based on SC deviations from an indicated setpoint.

Results. Figure 2 shows the CST and the SC results for different polymer doses. When the polymer dose was decreased to 270 mg/L, the centrate became dark and no further decrease in dosage was feasible. The lowest CST value was measured at a 407-mg/L polymer dose. The SC for conditioned solids was +15 at this dose. The SCD indicated that solids maintained a negative electrical charge at low doses but that higher polymer doses imparted a positive charge. Highly charged solids of either sign resulted in greater CST values. Thus, polymer dose adjustment should be feasible, based on maintaining solids SC at a moderately positive value. Using the SC value of +15 as a setpoint, proximity of measured SC to this value was well correlated with lower CSTs ($P < 0.01$).

The conditioned solids SC also strongly correlated with centrate SC ($P < 0.01$). The same SC transition was observed with

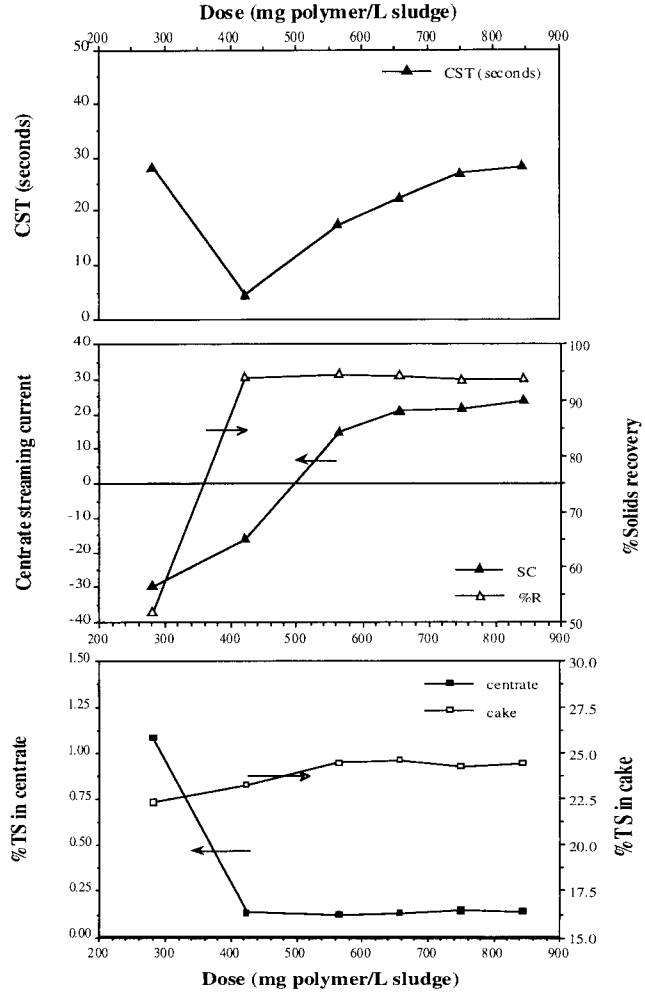

Figure 3—Results of polymer dose-response test conducted at Warminster Municipal Authority treatment facility, October 8, 1991, with total solids = 2.12%.

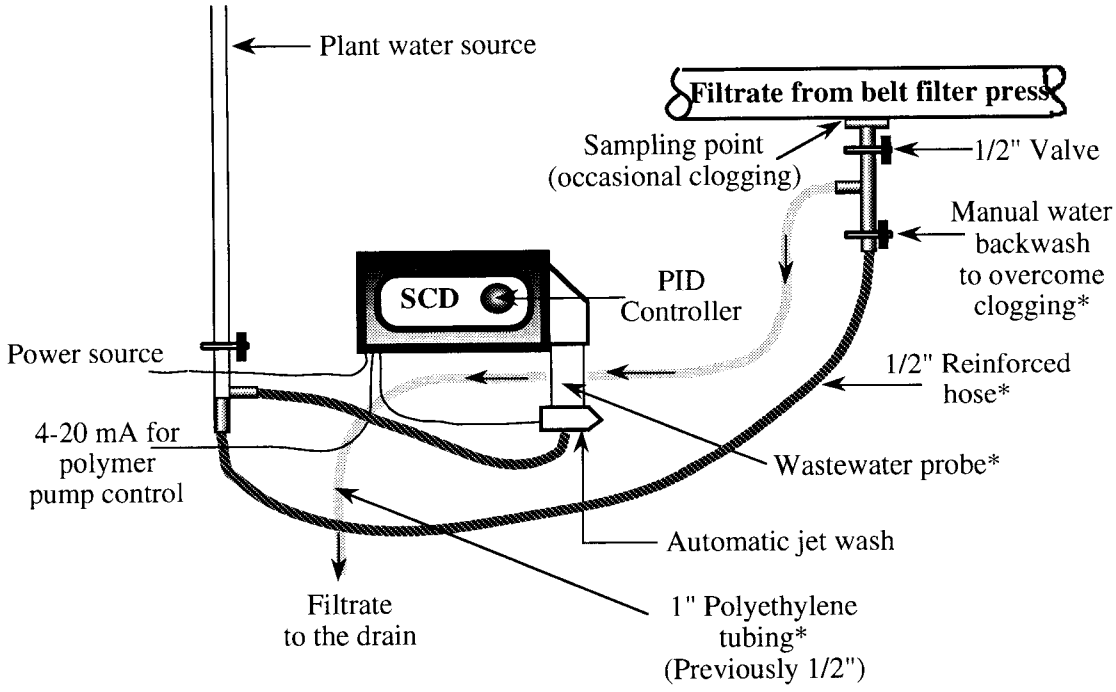

Figure 4—Streaming current detector arrangement for continuous sampling at the Upper-Morland Hatboro Joint Sewer Authority. Filtrate sample flow rate was approximately 2 L/min. Asterisks indicate modifications required for reliable sampling.

centrate measurements, but with these samples an SC of zero occurred at a higher polymer dose. At the 407-mg/L dose, the centrate SC was −15. If the centrate SC were used for dose adjustment, a setpoint of −15 would provide a good correlation with lower CST values ($P < 0.05$). Solids analyses were not performed in this experiment, so it is not known whether the setpoint based on CST would be appropriate in terms of machine performance.

The results of the second experiment are shown in Figure 3. The minimum in CST indicated an optimum polymer dose of 420 mg/L, which corresponded to a solids recovery of approximately 95%. This dose may be considered an operational optimum because slight improvements in performance could be obtained by substantial additional polymer use. The CST increased significantly at these higher doses, suggesting that a minimum in CST may indicate optimum conditions in a practical sense but is not strictly correlated with maximum dewaterability, which occurs at a higher polymer dose.

The centrate SC again exhibited the trend from negative to positive with increasing dose. Again, the centrate SC was −15 at the dose where the CST was at a minimum. This value could be used as a setpoint, although a value of +5 provides stronger correlations with actual dewatering results for both recovery ($P < 0.05$) and cake solids ($P < 0.01$). The CST data correlated with recovery ($P < 0.05$) but not with cake solids.

Results of both experiments at this plant indicated that the SCD was capable of monitoring the centrate SC under continuous flow conditions. Although the centrate's SC differed from that measured in the conditioned solids, the same trends were observed, and a setpoint based on centrate SC could be used to maintain optimum conditioning and dewatering.

Thus, the SCD appeared to be successful in indicating the optimum polymer dose. Further experiments had been planned at this facility to evaluate use of the SCD for automatic control of the polymer feed. However, the polymer pumps at WMA were not equipped with a 4- to 20-mA input, preventing implementation of automatic dose control. In addition, the plant suffers from struvite formation in solids piping, and struvite was also observed to accumulate on the SCD's cylinder and plunger surfaces. In the absence of proper manual or automatic cleaning, this would have impaired long-term use of the SCD at this facility. Manual cleaning successfully removed the deposits; automatic cleaning was not evaluated at the site.

Tests at the Upper-Morland Hatboro Joint Sewer Authority Facility

The Plant. At this plant, thickened waste activated sludge is pumped from holding tanks to either of the plant's belt filter presses for dewatering. The plant also receives industrial wastewater solids from outside plants on a periodic basis, and these may be thickened as necessary before their addition to the holding tanks. The plant's primary clarification residuals may also be combined or dewatered separately. During the test period, a Mannich polymer (Calgon WT-2530) was used in conditioning.

Procedures. A Milton Roy Gen. III (SC 5200) SCD model was installed in the belt press to sample a continuous 2-L/min filtrate flow from the initial drainage area as shown in Figure 4. Use of a liquid sample from the drainage area, rather than a true filtrate from the sump, appeared to provide greater sensitivity to process changes. This may have been because of ruptured flocs and belt wash water in the actual filtrate. Response time was also reduced by use of the gravity drainage sample. Tap water was used for probe cleaning using the automatic jet wash available with this SCD model. A typical cleaning frequency

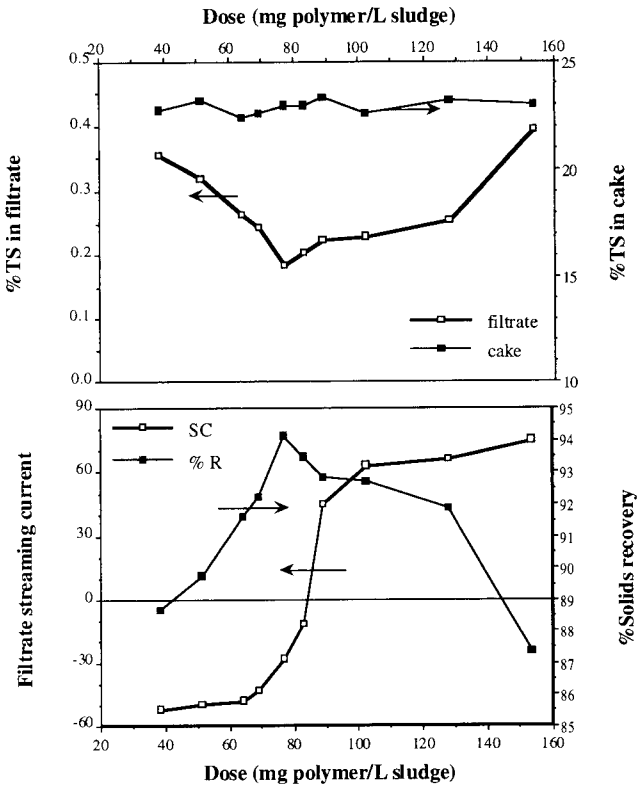

Figure 5—Results of polymer dose-response test conducted at the Upper-Morland Hatboro Joint Sewer Authority facility, March 17, 1992, with raw sludge total solids = 2.79% and a polymer concentration of 90.5 g/L.

was once per hour for a duration of 30 seconds. The SCD was calibrated similarly to the unit used at the Warminster plant.

After the appropriate stabilization period, the SCD was monitored for a day to examine its response to changes in polymer dose and to determine the time required for a stable SC reading, which would be important for later implementation of automatic control. The response time ranged from 15 to 90 seconds, and the time to attain a stable SC reading was between 10 and 15 minutes for each polymer dose change.

Dose-response tests were performed in a similar manner to those at Warminster. The solids flow rate was approximately 3 L/s (47 gpm) during these tests. The polymer pump output was raised to 60% of its capacity, and the system was allowed to stabilize for 15 minutes after each change in polymer dose. The SC of the filtrate at this dose was recorded and samples of the filtrate and cake were collected for total solids (TS) measurements. Samples of conditioned solids were also collected for CST measurements. Capillary suction time measurements were conducted at the plant, but TS measurements were conducted at the University of Delaware laboratory the day of the field experiment. Results for two dose-response tests, conducted 2 weeks apart, are shown in Figures 5, 6, and 7.

During the testing period it was also necessary to address clogging problems at the filtrate sampling point and at the SCD's housing connection (Figure 4). The clogging was thought to be a result of large conditioned flocs unable to pass through the 12.7-mm (0.5-in.) diameter sampling point. Running the SCD with no filtrate sample caused inaccurate SC inputs and, if occurring for long periods, resulted in damage to the probe and the motor. This led to use of a specially designed probe for wastewater operations, provided by Milton Roy. A new housing made of Teflon™ was used; although it had the same inside annulus as the previous probe, it enabled use of 25.4-mm (1-in.) diameter hose and connections. These new changes reduced the clogging problem significantly; a tap water hose (Figure 4) was also connected to the sampling point through a new valve, which enabled manual flushing of both the sampling point and the probe itself, if necessary. The new SCD, which also included a stainless steel frame to prevent observed severe corrosion, was installed and allowed to stabilize before conducting experiments.

Results. Filtrate and cake TS results for the various polymer doses used in the first experiment are shown in Figure 5. Percent total solids in the cake was almost constant at approximately 23%; thus, it was not a good criterion for polymer dose optimization in this particular case. However, high filtrate TS occurred at both lower and higher polymer doses, with the optimum dose indicated by the minimum filtrate TS obtained at approximately 78 mg polymer/L sludge. The maximum percent solids recovery was approximately 94%. As shown in the same figure, this dose resulted in a filtrate SC of approximately −28. Statistical evaluation using the entire dose range indicates best control at a setpoint of +10 for both filtrate quality and recovery ($P < 0.01$), with cake solids giving no correlation.

The CST data are shown in Figure 6. The CST decreases with increasing polymer dose and becomes almost constant at the higher doses. The rapid times shown in the upper dose range were near the practical minimum for the procedure, but at least three replicates were performed with each of the solids to provide a more precise mean value. Additional CST tests performed on samples returned to the laboratory confirmed the indicated trends. Because the minimum CST supposedly indicates the optimum dose, the CST is evidently a poor indication of the optimal dosage in this case. At the 5% probability level, the

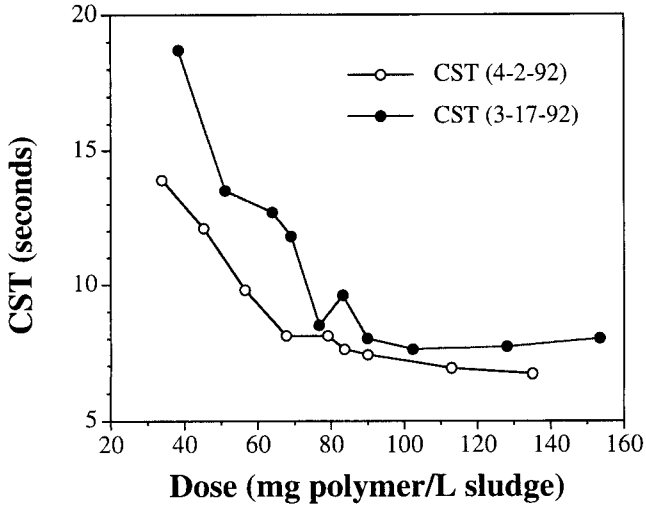

Figure 6—CST results at Upper-Morland Hatboro Joint Sewer Authority facility corresponding to test results in Figures 5 and 7.

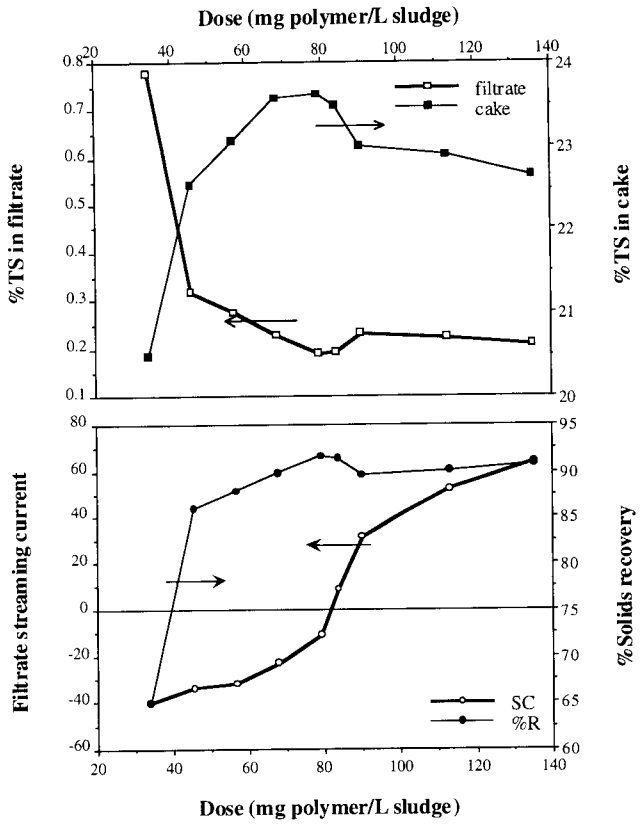

Figure 7—Results of polymer dose-response test conducted at the Upper-Morland Hatboro Joint Sewer Authority facility, April 2, 1992, with raw sludge total solids = 2.08% and a polymer concentration of 78.5 g/L.

CST showed no correlation with cake solids, filtrate solids, or percent recovery.

Figure 7 shows the results for the second dose-response test at UMHJSA. Unlike the previous results, cake TS increased with increasing polymer dose, reaching a maximum value of 23.5% and then decreasing with the further polymer dose increases. The behavior of the filtrate TS was similar at low doses to its behavior in the previous experiment, but in this case, filtrate solids did not increase again at higher doses as in the previous test. The optimum dose was approximately 80 mg polymer/L sludge, also shown by the maximum in percent recovery. This optimum dose was at a slightly negative filtrate SC of −12 units. If assumed as a setpoint, proximity of measured SC data to this value would correlate with cake total solids ($P < 0.05$) but not with solids recovery. As with the previous experiment, use of a higher setpoint improves the overall statistical correlation between control and performance data; a +15 setpoint provides SC correlation to both cake solids and solids capture at the 5% level.

The CST results for this experiment were shown in Figure 6. Again, no useful information is available from the CST data, which decreased with increasing polymer dose and provided no minimum value even though an optimum polymer dose occurred. The CST results do not correlate with either cake solids or solids capture data ($P > 0.05$).

Both tests showed the transition from negative SC to positive with increasing polymer dose. Although the filtrate SC values under optimal conditions differed somewhat, it appears that near-optimal conditioning doses could be provided on both days with a setpoint in the neutral range. (The precise setpoint used could be anywhere in the −15 to +15 range, depending on the defined "optimum.") Thus, use of the SCD in dose control was indicated as feasible at this facility.

Tests at the Wilmington Pollution Control Facility

The Plant. Percol 757, a cationic copolymer, was used to condition the WPCF solids during these tests. Aged polymer solution (~0.5%) is injected to the sludge feed line before dewatering with static mixing provided by a series of pipe elbows. Additional slow mixing is accomplished in a 1.5-m^3 (400-gal) flocculation tank.

Fourteen Carter belt filter presses are available for dewatering in this facility. In contrast to most typical belt filter presses, two rotating drums with fine-mesh cylindrical screens provide initial solids drainage. The drained filtrate at approximately 0.05% solids is collected separately in one of two sumps beneath the unit and recycled to secondary treatment or used as wash water. Conditioned solids are then dewatered by the belt filter press, and the actual filtrate is collected in the second sump. This second filtrate is completely recycled to the flocculation tank and never leaves the dewatering process unless recycling is shut off. In this work, filtrate drainage from the rotating drum is described as "drum filtrate" to distinguish it from the typical filtrate obtained directly from the belt filtration stage of the process. Dewatered solids, typically at 18 to 22%, are transported to a nearby landfill.

The SCD was evaluated at WPCF in June 1993. Filtrate sampling for the SCD used drum filtrate, equivalent to collection of the gravity drainage sample in a conventional belt filter press, as used during UMHJSA evaluations. A sump pump was required for drum filtrate pumping from the sump through the SCD probe because no other sampling point was available. The pump was placed in a plastic container to provide an adequate depth of drum filtrate and ensure actual and instantaneous drum filtrate sampling from the sump. Figure 8 represents the SCD arrangement at WPCF. A modified SCD probe and 25.4-mm (1-in.) sampling lines were used as at the UMHJSA facility.

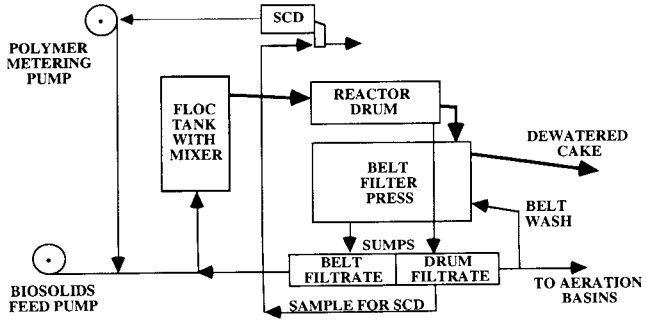

Figure 8—Streaming current detector arrangement for continuous sampling at Wilmington Pollution Control Facility, with sampling points shown by asterisks. Sample flow rate to streaming current detector was approximately 2 L/min. The system for timed backwash of sample line and detector are not shown.

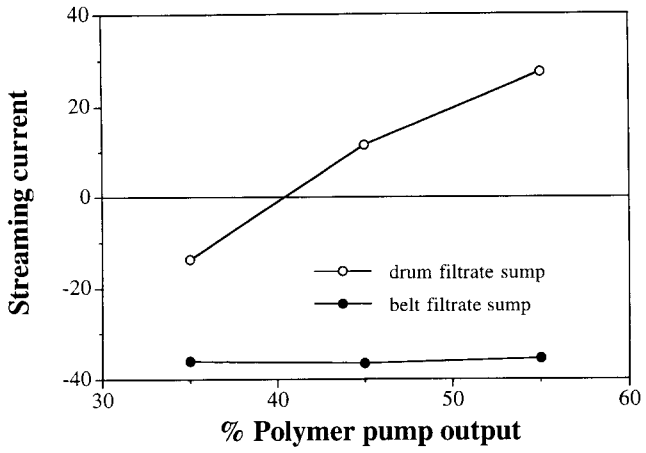

Figure 9—Effect of polymer dose on streaming current of the filtrate from both the drum sump and the belt filtrate sump. Full-scale, dose-response test was conducted at Wilmington Pollution Control Facility.

Initial observations suggested that occasional sump pump blockage was caused by large flocs falling from the sides of the filter press's belt into the container. To overcome this problem on a temporary basis, tap water was flushed into the connection lines and the pump when necessary using the tee connection between the tap water hose and the filtrate hose (not shown in Figure 8). An improved collection system would be necessary to avoid entry of this flow on a permanent basis. Tap water was also used to prime the sump pump when starting the SCD operations if necessary. Subsequent observations showed that the SCD response time for polymer changes varied between 2 and 2.5 minutes, while the complete signal stabilization time ranged from 10 to 15 minutes after any polymer dose change.

Procedures. Although satisfactory SCD response to changes in process inputs was observed using the drum filtrate flow, use of actual belt filtrate flow for SC measurements was also evaluated. The conventional dose-response procedure was used for measurement of drum filtrate SC at three polymer doses, but filtrate samples from the middle of the belt filtrate sump were also used for the SC measurements by batchwise measurement using the same SCD.

The results of this experiment are shown in Figure 9. While the drum filtrate SC changed from −13.6 at a polymer pump setting of 35% to +27.5 at a 55% setting, the belt filtrate changed only from −39 to −38 for the same polymer dose range. The more negative SC observed with the belt filtrate might have been caused floc breakage from pressure and shear during filtration, exposing unconditioned particle surfaces, or by interferences from the wash water used in this loop. Results indicated that the drum filtrate SC provided a better indication of changes in the conditioning process; therefore, this flow was used for the SCD sampling.

Further dose-response tests were then conducted as described earlier. The turbidity and the viscosity of the drum filtrate were also measured because these were considered as possible control parameters in addition to SC (Dentel and Abu-Orf, 1995). These tests were also used to evaluate the general system's performance and its sensitivity, response time, and stabilization time.

After each dose, measurements of CST, time to filter (TTF), drum filtrate turbidity, drum filtrate viscosity, drum filtrate TS, and cake TS were conducted at the plant's laboratory according to accepted procedures (APHA *et al.*, 1992) on the day of the field experiment. Viscosity measurements used a Brookfield LVT viscometer with Ultra-Low (UL) Adapter (Brookfield Engineering Laboratory, Inc.). The geometry of the UL-Adapter allows accurate viscosity measurements in the range of 0 to 15 cP using a 60-rev/min rotational speed. Measurements used a 16-mL centrate sample maintained at constant temperature of 25°C using a water bath as recommended by the manufacturer. Turbidity measurements were performed using a calibrated DRT-100B Turbidimeter (HF Instruments).

The percent solids recovery as a result of dewatering was calculated as described by Vesilind (1979). The drum filtrate solids content was used in this determination because the second filtrate was completely recycled to the flocculation tank retained in the dewatering process. The drum filtrate solids content was also more appropriate because the SC, viscosity, and turbidity measurements used the drum filtrate only.

Many dose-response experiments were conducted at this site, although the results of only one experiment are presented here. Additional findings are reported elsewhere (Dentel *et al.*, 1995).

Results. Figure 10 shows the TTF, CST, drum filtrate SC, and percent solids recovery results as a function of the used polymer dose. Below the 150-mg/L dose, solids recovery decreased sharply and was unacceptable. Above 210 mg/L, the recovery remained constant and unaffected by the polymer increase. Slight increases in cake solids were obtained as the polymer dose was increased from 100 to 266 mg/L (not shown). Based on TTF and CST results, the optimum dose range would be between 160 and 210 mg/L, which corresponds to a maximum solids recovery of approximately 95%. The optimum dose range, shown in Figure 10, corresponds to a drum filtrate SC range of −20 to +25. Thus, the drum filtrate SC is a good indicator of dewatering performance with a setpoint for optimum dose control within the above range; a −10 SC value (Figure 10) represents the lowest dose (175 mg/L) that provides maximum solids recovery. Only an SC setpoint in the positive range (approximately +25) provided statistical correlation (cake solids only, $P < 0.05$).

In this dose-response test, the CST results appeared to agree with the solids recovery data in the lower dose range. However, because of minor changes in recovery and cake solids at higher doses, no statistical correlation was found between CST and these parameters. This was also the case in comparing TTF data to dewatering performance.

Figure 11 shows drum filtrate turbidity and viscosity. The turbidity for the two lowest polymer doses exceeded 1 000 NTU (the upper limit for the used turbidimeter) and was not determined. Both minimum turbidity and viscosity fell in the previously stated optimum dose range with a significant increase in the turbidity and slight increase in the viscosity in the overdosing region. Polymer doses lower than 150 were not acceptable because of the sharp increase in the drum filtrate turbidity. These results indicated that both turbidity and the viscosity may be feasible control parameters but with possible control difficulties (particularly for drum filtrate viscosity) in the overdosing region because of decreased parameter sensitivity to dose change. Lack of statistical correlation of these data with dewatering results largely stemmed from these effects at higher

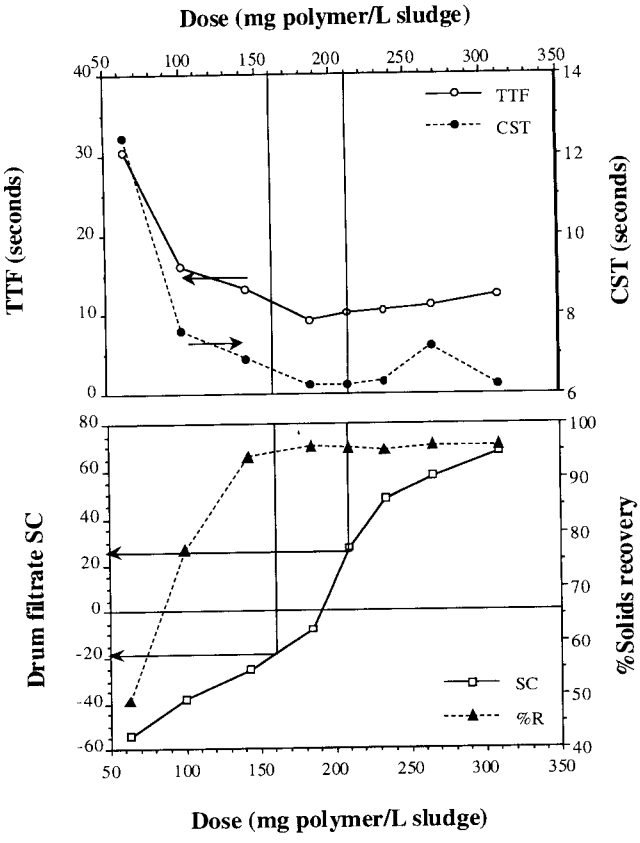

Figure 10—Conditioned sludge CST, time to filter, drum filtrate streaming current, and percent solids recovery versus polymer dose. Full-scale, dose-response test was conducted at Wilmington Pollution Control Facility, August 20, 1993.

doses. The use of liquid stream turbidity and viscosity in polymer dose optimization is considered elsewhere in more detail (Dentel and Abu–Orf, 1995).

Discussion

Use of Dose–Response Tests. The plant results shown in this paper illustrate the importance of maintaining a proper polymer dose. A slight underdose can cause a significant deterioration in dewatering efficiency, whereas a large overdose can bring little improvement in performance while increasing chemical costs substantially. Between these two extremes lies an optimum dose. Ideally, this dose should be determined quantitatively by considering such factors as dewatering effects on solids transportation costs and subsequent processing economics, as well as the incremental treatment cost of recirculated streams at various solids concentrations. In practice, most treatment facilities will use qualitative assessment of dewatering results, as we have in interpreting the preceding data. It should also be recognized that, to ensure reasonably constant treatment conditions, the time and number of doses used in full-scale tests must be limited. Inevitably, the determination of dose optima involves some uncertainty because of subsequent interpolation from available dose levels.

Although identification of an exact dosage optimum may be difficult, such "dose-response" tests enable an optimum dosage range to be determined. Although treatment facilities seldom perform tests of this type, the results should be of value for this purpose.

Such tests conducted under different operating conditions will also indicate the variability of dose optima that may be encountered. With significant variability, the potential value of polymer dose control increases.

This variability was illustrated by conditions at the UMHJSA site on the 2 days of dose-response tests. Between the two dates, the sludge TS decreased by 25% and the polymer solution TS decreased by 13%. Even though the same optimum polymer dose (as mg/L) was obtained in both experiments at UMHJSA (80 mg/L), underlying fluctuations demonstrate that significant variations in polymer flow rate can be anticipated in maintaining an optimal dosage.

Evaluation of Streaming Current Detector Results. Conditioning and dewatering processes at the three facilities included in this study provided a range of conditions: both digested and undigested solids, both Mannich and copolymer types of flocculants, and two types of belt filter presses as well as centrifugal dewatering. Nonetheless, a consistent trend emerged, with transitions in particle charge and SC readings invariably related to full-scale dewatering performance. Results at all three treatment facilities indicated that a liquid stream SC in the neutral range occurred at the optimum polymer dose. This suggests that charge neutralization plays an important role in conditioning, with complete neutralization occurring previous to dewatering and the liquid stream SC measurement. This is supported by the results in Figure 2: between the 319 and 407 mg/L doses, charge neutralization occurred in the conditioned sludge and optimum dewatering was obtained. In this dose range, however, the centrate SC was negative.

When the charge-neutralized (or reversed) flocs are subjected to dewatering, the SC evidently reverts to a more negative value. This phenomenon may be caused by shear effects as previously hypothesized (Dentel and Abu–Orf, 1993, and Dentel and Wehnes, 1989). Plausibly, floc shear exposes more negatively charged particle surfaces, resulting in a negative measured SC when there is no remaining polymer in solution to neutralize

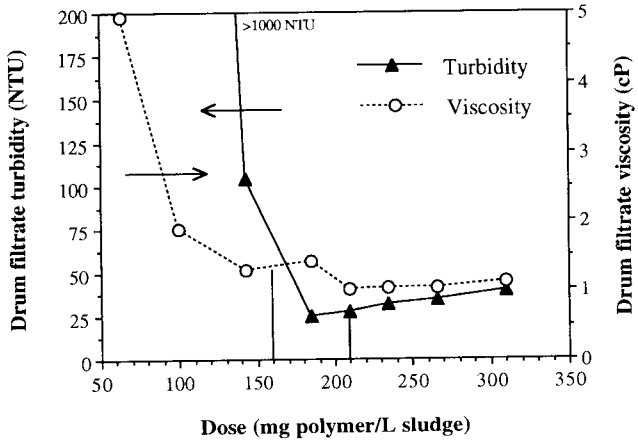

Figure 11—Drum filtrate viscosity and turbidity versus polymer dose. Full-scale, dose-response test was conducted at Wilmington Pollution Control Facility, August 20, 1993.

this charge. In the overdosing range, however, excess polymer in solution neutralizes the negative charge on the liquid stream particles, reflocculating the suspension. Thus, the liquid stream's SC transition from negative to positive occurs at a slightly higher polymer dose than does the SC of the conditioned solids, and the optimum dose indicated by the liquid stream SC will not be in the positive range.

Figure 9 suggests that with sufficient shear, the SC transition virtually disappears. A sampling point after the most intensive stages of belt filtration led to an SC value that was undistinguishable from readings in the underdosing range and would not be usable for control. Thus, the liquid stream sample should be taken before the most intensive stages of any dewatering process. As long as the mixing intensity remains consistent upstream of such a sampling point, the SC required for optimum conditioning and dewatering should not vary significantly.

The correlation between SC and percent solids recovery data in solids argues for charge-based destabilization: an SC value near zero or slightly negative SC values give the optimum percent solids recovery value. This suggests that, although physical bridging is frequently invoked as a conditioning mechanism, particle charge also plays an important role. However, it is also clear from these results that charge reversal does not seriously impair effective conditioning.

This phase of our study indicated that the SCD output provides a good indication of dewaterability. Unlike other possible control parameters examined in this study, the SCD response to dose changes was most sensitive around the optimum dose, rather than at higher and lower doses. Furthermore, the actual SC value at any time, rather than its change in value with dose change, can be used for dose adjustment. This simplifies use of the instrument either by operators or by an automatic dose control system.

Because the SCD appeared successful in continuous monitoring of conditioning, the devise was considered to be potentially applicable in immediate feedback control of polymer dose.

Evaluation of CST Results. The CST procedure is widely used as a laboratory-scale indicator of dewaterability. Results shown here suggest that this practice is qualitatively valid and particularly appropriate at polymer doses up to and including the practical optimum. At higher doses, changes in CST and dewatering performance are of lesser magnitude but, nonetheless, may lack agreement in their trends. Previous work has shown that increases in CST values in the overdosing range are attributable to polymer effects on solution viscosity (Christensen *et al.*, 1993, and Dentel and Abu-Orf, 1995), although high doses of polymer may enhance floc resiliency as an additional mechanism in mechanical dewatering processes. It should be noted that intense mixing has been recommended before CST analyses to simulate shear effects in the full-scale dewatering process (COST, 1995); because our samples were taken before the dewatering process, with no additional mixing provided, such shear effects may account for observed discrepancies. In this case, the additional step of intense mixing would be an essential component of dewaterability assessment by the CST procedure.

Conclusions

Streaming current detector readings show that conditioning polymers cause a transition from negative to positive charge in both conditioned solids and the liquid stream. Near-neutral 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) the capillary suction times. The agreement between SC results and other conditioning and dewatering parameters indicates the role of charge neutralization as a significant mechanism for conditioning with organic polyelectrolytes.

The SCD is suitable for monitoring of polymer dosage. This was shown at three facilities providing a range of conditioning and dewatering processes: both digested and undigested solids; both Mannich and copolymer types of flocculants; and two types of belt filter presses as well as centrifugal dewatering.

Measurements of cake TS alone may not provide a sufficient indicator of belt filter press performance if filtrate quality is important because this property may vary independently of cake solids. The CST test results were not strongly correlated with full-scale dewaterability. Qualitatively, CST results provided an appropriate indication of dewaterability up to a practical optimum dose, but higher doses led to less satisfactory agreement.

Liquid stream flows (centrate or filtrate) can be used for SCD readings because particle charge transitions resulting from conditioning are still evident. Because shear effects may attenuate this transition, the liquid stream sample should be taken before the most intensive stages of dewatering. In belt filter presses, the gravity drainage zone provided a satisfactory sampling source. Clogging of the sampling lines or sensor should be limited if the SCD is to be successfully used for monitoring or control. This requires proper sampling point location, generous dimensions for sampling lines, and the capability for manual or timed backwash of sampling lines and the SCD probe.

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