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Optimization of slurry flocculation and dewatering based on electrokinetic and rheological phenomena

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Abstract

The use of chemical additives known as conditioners or flocculants is crucial in assuring the proper functioning of many solid-liquid separation processes, and dewatering in particular. The additive used is often a water soluble polymer with high molecular mass, strong adsorptive properties, and often a large amount of ionic charge. The type of polymer used, and its exact dose, may change with process or flow conditions, and these changes may lead to poor operation. However, advances in the understanding of conditioning and flocculation of slurries and sludges now make it possible to develop scientifically-based strategies for optimizing these processes. These advances have utilized new characterization methods that allow insight into fundamental aspects of the process. In several cases the analyses employed are also amenable to continuous reading, and therefore to automatic feedback control of the process. This paper describes these advances and suggests conditioning and flocculation control strategies that will allow optimization of subsequent dewatering processes. The research advances described are: (1) use of the streaming current detector for monitoring and controlling dewaterability; (2) evaluation of floc strength by streaming current and rheological and methods; (3) use of rheological characteristics of conditioned residuals for dose control; (4) application of liquid-stream viscosity for polymer dose monitoring and control; and (5) quantification and verification of mixing conditions in conditioning processes, and use for mixing similitude. These developments should aid in the proper initial selection of a conditioner product (flocculant) and its dose, and allow optimization based on continuous monitoring if the sludge conditions vary significantly over time.

Keywords: Flocculation; Dewatering; Conditioning; Centrifugation; Filtration

1. Background

Both the cost and difficulty of managing waste sludges are directly related to the amount of water remaining in these residuals after dewatering. Thus, producing a drier product should be an important objective in residuals management. Yet, achieving this goal is not an easy task. In a treatment facility with existing dewatering equipment, and with residuals flows and characteristics that could both vary over time, improved conditioner use and control may be the only ways to improve operation. Yet, while much research has focused on characterizing physical and chemical characteristics of residuals before and after dewatering, little information is available that can actually aid in optimizing the conditioner application prior dewatering.

For effective dewatering, the most appropriate chemical conditioner must be selected. In the applications considered here, the conditioner is most often a water-soluble, organic polyelectrolyte. The products available for this purpose vary in a number of properties such as physical form, active content, incorporated monomer types, average molecular mass and molecular mass distribution, electrical charge type and charge density, degree of cross linkage, and presence of other supplements or impurities. Typically, this additive is simply termed a polymer. However, it is clear that the selection of an effective product (in terms of both price and performance) can be a complex process. There is no workable algorithm to relate polymer properties to process optimality. Moreover, it is not unusual for conditioning to require a sequence of two or more chemical conditioners.

The degree and type of flocculation that occurs in the conditioning process is also strongly dependent on transport and turbulence. The mixing intensity and time allowed for mixing are inter-related with polymer characteristics, optimal dosage, and resultant floc properties. The polymer used may thus depend on flow properties in a given application and, additionally, on flow variability.

When the conditioning additive(s) are specified, the dosage parameters to assure optimal dewatering must not only be established but also be maintained. This task, however, is complicated by changes in treatment operations

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which affect the suspension properties on a daily, seasonal, and annual basis. This challenge is further complicated by changes in conditioner characteristics between batches and by changes in dewatering process operation.

In wastewater treatment, the variability of sludge properties has been reported frequently (e.g. [1,2]). Changes in the properties of water treatment residuals are only occasionally noted by researchers [3,4], but given the frequent changes often seen in coagulation conditions at such facilities, such variabilities should be expected. Dewatering in industrial applications varies according to the specific application, but vicissitudes in feed properties are not uncommon. In essence, there are many dewatering applications with a common tendency for the colloidal charge to vary significantly.

Commonly, the response to such variability is routine conditioner overdosing, since the deterioration in process efficiency is less than that observed with underdosing [5]. However, the economic (and environmental) impact of this practice may be more significant than often realized. This is because newer, more intensive dewatering processes, with significant increases in cake solids and capture efficiencies, require higher conditioner doses. Additions of 50 kg active polymer per metric ton dry solids are not unusual in many dewatering facilities. Furthermore, although the higher solids levels facilitate economic use of such processes as drying and composting, and help to control transportation and incineration costs, the economic sensitivity to dewatering results is heightened. Polymer dose control is becoming crucial to process cost control.

Over the past decade, new methods for optimizing biosolids conditioning and dewatering have been developed which have advanced our understanding of conditioning mechanisms, produced new parameters for optimizing conditioning, and enabled automatic control of dewatering output via control of conditioner dose. The developments have stemmed primarily from research on conditioning and dewatering of wastewater sludges (or biosolids). Most of the findings have proven to be transferable to water treatment residuals as well, and are likely to be usable for other process applications. This paper reports on these developments in a general context.

This work has utilized two types of mechanical dewatering in full-scale studies: solid bowl centrifuges and belt filter presses. The principles may be applicable to other dewatering processes which rely on floc properties. We have also found feasible applications where chemical conditioning precedes other solid-liquid separation processes such as clarification, thickening, and flotation.

2. Methods

Our research in dewatering process fundamentals has used three approaches: laboratory jar testing, full-scale dose-response testing, and use of feedback dose control systems on a continuous basis. In all cases, we characterize a very complex overall process with parameters measured before and after the conditioning/dewatering process. The measurements used should, ideally, be amenable to dependable full-scale use on a continuous basis, but also be based on fundamental properties of the sludge or slurry.

2.1. Laboratory jar testing

A 500-ml sludge sample is treated with different doses of a conditioner, usually the same product used in the full-scale process. Mixing conditions must simulate actual process conditions (if applicable) as closely as possible to assure comparable results. Tests are then conducted on conditioned residuals or supernatant to indicate the optimum conditioner dose. The streaming current (SC) is measured for both the conditioned residuals and the supernatant. Other indicators of optimum polymer dose are also employed, including capillary suction time (CST) and time to filter (TTF) test. The supernatant viscosity, turbidity, and total solids measurements are determined.

2.2. Dose-response testing

This uses a similar approach of controlled adjustment of the conditioner dose on a full-scale level. The dewatering device is allowed to initially stabilize at a relatively high conditioner dose. Different samples of conditioned residuals, the liquid stream (filtrate or centrate), and the cake are then collected at this dosage. The conditioner dose is then manually reduced in a stepwise manner. At each dose, after allowing the same time for the process to stabilize, the same samples are collected for further analysis. Dose reduction is halted once unacceptable performance is observed. Analyses include: solids measurements on cake and liquid stream; conditioned residuals analyses (CST, TTF, SC, rheology); and liquid stream analyses (SC, viscosity, turbidity, and polymer concentration).

2.3. Continuous use of feedback control

For selected measurement techniques, the instrument's output is used for control of the metering pump for feed of the flocculant polymer. Evaluation is undertaken only after troubleshooting and fine-tuning of controller parameters. Controlled, intentional variation of input parameters (such as sludge flow) is then used to cause controller responses, and the appropriateness of the response is determined by quantification of dewatering performance. Excursions in input parameters are also encountered in everyday plant operation and, while this can interfere with controlled studies, the performance of feedback control systems during extreme events provides useful information even when they are unexpected.

In the studies reported here, the measurements used for controller input were streaming current of the filtrate or centrate following dewatering, and rheometric properties of the conditioned slurry prior to dewatering.

3. Results

A variety of sludges, dewatering processes, polymers, and locations have been used in experiments to date. In the following five sections, the findings are grouped according to the key concept and application. Examples are presented from a variety of experimental contexts.

3.1. *Use of streaming current detector for monitoring and controlling dewaterability*

Extensive work has demonstrated the feasibility of on-line SCD use for continuous monitoring and control of polymer dose in biosolids conditioning [6–11]. This finding may seem contrary to earlier beliefs that sludge conditioning takes place entirely by bridging phenomena, such as posited by LaMer and Healy in 1963 [12]. For example, Fig. 1 shows typical results from jar test conditioning of anaerobically digested sludge with cationic polymer. The graph shows results of CST and SC for both conditioned biosolids and centrate at the same polymer doses. The figure clearly indicates that neutral SC values indicate optimum polymer dose as indicated by minimum CST values.

Fig. 2 shows results of Abu-Orf and Dental [2] in which manual, stepwise reductions in the sludge flow rate to a belt filter press led to appropriate controller responses in polymer feed rate. The controller used SCD measurements of colloidal charge in the filtrate. The polymer feed rate was reduced appropriately at each step change. In other experiments, at a different treatment plant, changes in polymer feed concentration due to faulty make up equipment were also handled well by the automatic dose controller also based on filtrate streaming current. This system also responded well when the type of sludge fed to the conditioning and dewatering processes was changed unexpectedly. This work is described more fully elsewhere [2]. The payback period for an SCD at the wastewater treatment plant was calculated to be 97 days.

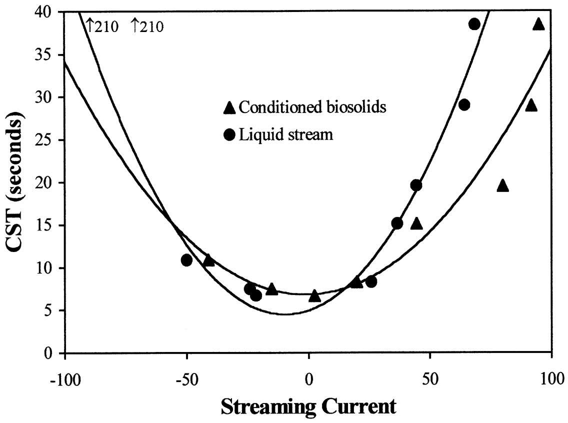

Fig. 1. Minimum CST values indicate near zero SC values in both conditioned biosolids and liquid stream at the same polymer dose. Jar test results using anaerobically digested sludge.

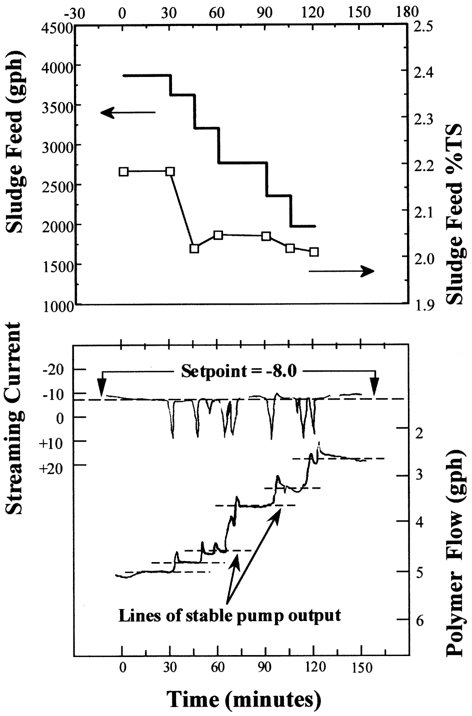

Fig. 2. Results of imposed step reductions in sludge feed rate during automatic polymer feed control with SCD. Conducted at Upper Morland, Pennsylvania (USA) wastewater treatment facility.

Several practical considerations were also noted in this study. Occasional clogging of the probe was corrected via the automatic and manual jet wash. Coating of the inside probe housing and piston was reported to shift the setpoint towards more negative values, resulting in polymer overdose. Thus, it is important that the inside surfaces of the probe be cleaned thoroughly on a weekly basis.

Ongoing research is testing the applicability of the SCD to water treatment residuals. Fig. 3 shows typical results

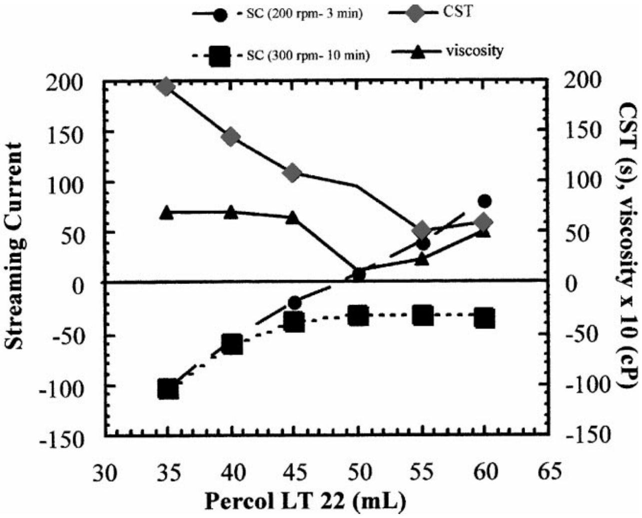

Fig. 3. Jar test results for conditioning of water treatment residuals (ferric chloride used as coagulant).

when using a cationic polymer for conditioning. A settled sludge following coagulation with ferric chloride and lime was obtained from the water treatment facility in Stanton, DE, USA and dosed with cationic polymer Percol LT22. The SCD measurements display a transition. With the less intensive mixing, the results pass though a point of zero charge, indicating flocculation due to charge neutralization may occur. This point of zero charge correlates with minimum CST values, which indicates that the SCD could also be used in water residuals for on-line monitoring and conditioner dose control if a cationic conditioner was used. All of the trends seen in Fig. 3 are quite similar to those previously reported for wastewater sludges. The liquid stream SC was also observed to follow the zeta potential measurements.

In the conditioning of water treatment residuals, anionic and nonionic flocculant polymers may be used successfully, in contrast to wastewater sludges which invariably employ cationic polymers. The distinction may be due to the amphoteric nature of colloidal surfaces following coagulation with aluminum or iron salts, providing negative, positive, or uncharged attachment sites. This implies a subtle role of charge–charge interactions. However, the SCD (and any other electrokinetic method) can only measure net electrical charge, and does not provide meaningful information when nonionic or anionic polymers are used with water treatment residuals that initially exhibit a net negative charge. In this case, flocculation by polymer bridging is established.

In fact, the apparent charge neutralization mechanism when using cationic polymers does not rule out an important role for bridging in these cases. This is demonstrated by the viscosimetry results, discussed later.

3.2. *Evaluation of floc strength by streaming current and rheological methods*

Fig. 3 also shows that increases in the mixing led to floc breakage and required the use of a greater polymer dosage. This phenomenon has been noted in previous studies for both wastewater sludges [13] and water treatment residuals [14]. However, the use of an SCD to determine charge properties of the conditioned sludge revealed an interesting phenomenon: an oppositely charged polymer can effect charge neutralization and reversal of the original particles in a suspension, but these trends are mitigated or even eliminated with continued mixing, finally reverting to the original (unconditioned) value. Evidently, floc breakage occurs across the particles themselves rather than by scission of the polyelectrolyte chains. This opens up new particle surface, with its original surface charge in need of neutralization. Thus, floc strength can be indirectly characterized with the SCD.

Floc strength can also be observed rheometrically [15]. Fig. 4 [16] shows typical rheogram curves for sludges with different polymer additions. The initial yield stress for the sludge increases as the polymer dosage increases, an initial peak becomes evident, and an optimum dose corresponds to a specific height for this peak. In the rheological literature, this peak designates the gel or entanglement network strength [17]. Increasing shear or duration of mixing disrupts the flocculated matrix, decreasing the apparent viscosity.

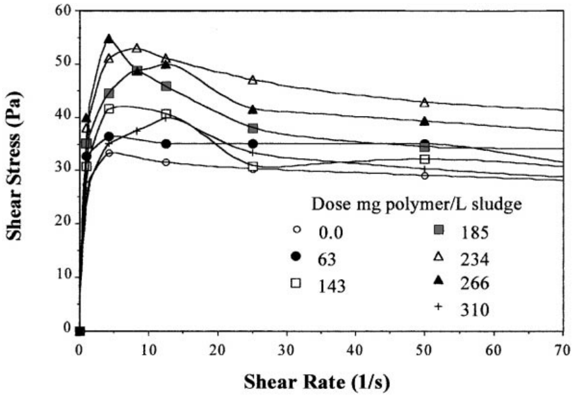

Fig. 4. The effect of polymer doses upon the rheogram of conditioned sludge.

3.3. *Use of rheological characteristics of conditioned residuals for dose control*

Noting the increase in yield strength up to the optimum polymer dose, Campbell and Crescuolo [18–21] used the shear stress versus shear rate curve of conditioned sludge for feedback control of chemical conditioning. Significantly, published work by Campbell and co-workers shows rheograms only up to the optimum dose, with no data offered in the overdosing region. However, using the derivative of the torque or shear stress versus shear rate curve (termed the instantaneous viscosity), successful dose control was reported following some modifications to the system's software and hardware. The principle was commercialized as the Zenofloc control system.

Dentel et al. [10] performed a later evaluation of this control system and found that the principle of control was valid, although quantification of the rheological response to polymer conditioning was difficult to apply in practice. Repeated rheometric characterizations under constant process conditions often produced inconsistent output. Furthermore, actual plant dose-response tests established no correlation between the conditioned residuals peak height value and optimum polymer dose as determined by TTF measurements and percent solids recovery (Fig. 5). Peak values continued to increase beyond the optimum dose and eventually decreased at even higher doses. Thus, there was no clear correlation of maximum height with optimum conditioner dose.

Fig. 6 is an example of the evaluation of this system in automatically controlling polymer dose [10] once properly tuned. The percent solids recovery was used as indicator of belt filter press performance. Although the system was able to reduce the polymer feed below the value set by the plant's operator (straight line at 42.5%), other factors should be

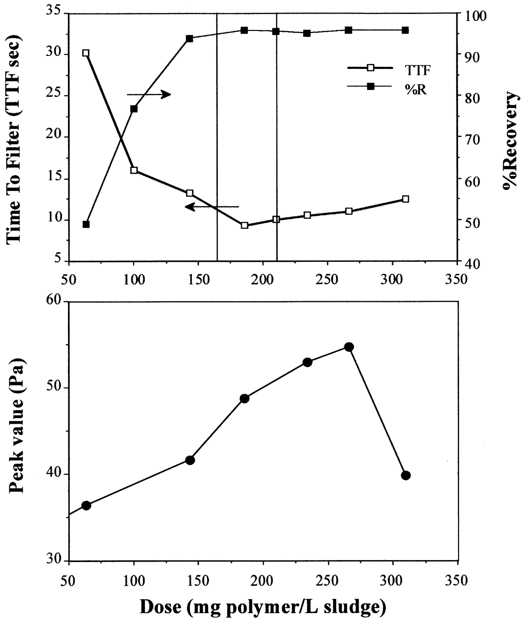

Fig. 5. Results from full-scale dose-response test on anaerobically digested sludge. Belt filter press performance indicated an optimum dose range of 170–210 mg polymer/l sludge. Peak values are from Fig. 4.

considered: system upsets (sludge overflow from the sides of the belt) and time devoted for monitoring the system (when the control system requests retuning). These factors are of equal concern to plant operators as is maintaining a high and consistent percent solids recovery. The high variation in the measured peak values at this specific site contributed extra difficulties to automatic control using this system.

Abu-Orf and Dentel [16,22] also showed that although the initial peak height indicated floc strength prior to breakup, the apparent viscosity indicated by the rheogram at high shear rates was a measure of floc strength after maximum shear. Since the resilience of floc under these conditions may be more relevant to downstream behavior in mechanical dewatering processes, this characterization technique may be usable for monitoring of conditioning processes.

3.4. *Use of liquid-stream viscosity for polymer dose monitoring and control*

Another manner in which rheological properties may be used for the improvement of slurry or sludge processing is through the monitoring of filtrate or centrate (liquid stream) viscosity following mechanical dewatering. Unlike either the incoming or flocculated suspension, the liquid stream is typically a low-turbidity liquid. The low concentration of suspended particles provides Newtonian behavior, and the viscosity can be measured directly by a sufficiently sensitive viscometer. The liquid stream is also more amenable to continuous sampling on a reliable basis, with less clogging than experienced with the sampling of incoming or flocculated flows.

Trends in liquid stream viscosity appear to be indicative of optimal flocculation when using polymers for conditioning. Christensen et al. [23] observed an increase in filtrate viscosity in the overdosing region, and attributed it to the polymer residual in this dose region. However, no effect was observed in the underdosing region due to the use of filtered samples for viscosity measurements. These results were confirmed by Dentel and Abu-Orf [5] in lab-scale centrifugation and full-scale dewatering by belt filter press, although viscosity was observed to increase on either side of the optimum polymer dose (Fig. 7) as indicated by the maximum solids recovery. Suspended solids analyses demonstrate that the increased viscosity at underdoses is due to increased sludge solids in the filtrate. Dissolved solids levels and residual polymer analyses (by ^{1}HNMR and other techniques [10]) show that viscosity increases in the overdose range are due to residual polymer. Thus an optimum polymer dosage can be determined as the dose at which the liquid stream viscosity begins to increase with increasing polymer addition. Results shown in Fig. 7 suggest a quite

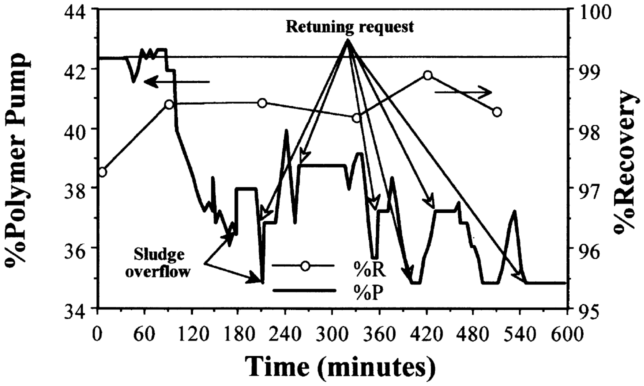

Fig. 6. Controlled polymer feed rate and % solids recovery with time. Results are for full-scale dewatering of anaerobically digested sludge by belt filter press. The polymer dose was automatically controlled by feedback from rheological measurements.

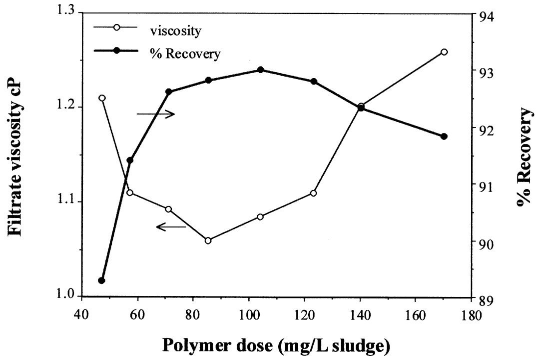

Fig. 7. Filtrate viscosity and percent solids recovery. Full-scale dose response experiment conducted on the dewatering of waste activated sludge by belt filter press.

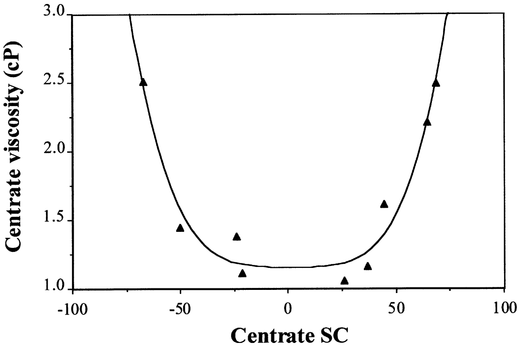

Fig. 8. Viscosity of centrates obtained by laboratory centrifugation following the same jar tests characterized in Fig. 1. The minimum corresponds with charge neutralization.

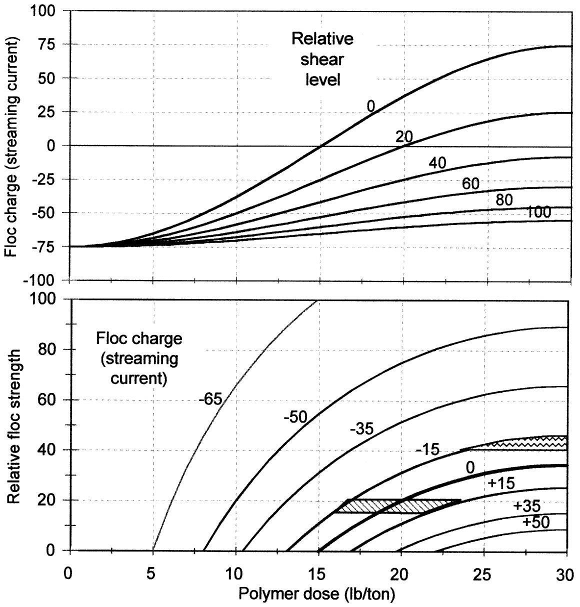

Fig. 9. Conceptual model of relationships between floc shear strength or resistance and electrical charge as functions of polymer dose. Shaded areas show desired conditions for shear resistance between 15 and 20, and between 40 and 45 relative shear strength units.

similar behavior occurs in the conditioning and dewatering of water treatment residuals. Minimum supernatant viscosity indicated good dewaterability as compared to CST and near zero SC.

Fig. 8 shows measurements of centrate viscosity and SC for the same doses as in Fig. 1. For these tests, the relationship between the rheological and electrokinetic characteristics is clear: minimum viscosity (minimum polymer residual) coincides with charge neutralization in determining the optimum polymer dosage.

Combined with results presented in the preceding sections, the overall mechanism of conditioning can be inferred. When using a cationic polymer for flocculation of an anionic suspension, the collection of finer suspended material into flocs is incomplete until a dose is provided that attains charge neutralization. Doses of polymer exceeding this level leave most of it in the solution phase, due to repulsion of the like-charged polymer-coated surfaces and the free polymer. Greater mixing times or intensities break the floc, exposing negative surfaces, and additional free polymer is consumed. SC measurements can show when the amount of mixing has been sufficient to consume all available polymer. Further mixing may break floc when no further polymer is available to repair it. Increased mixing will require greater polymer additions to reach the same final state of particle charge, but the increases will produce commensurate increases in floc strength. Inferentially, the floc strength desired to impart floc resilience for a specific mechanical dewatering process is attained at a unique combination of dosage and mixing. This notion is schematized in Fig. 9.

In applications such as the conditioning of water treatment residuals, the polymer charge may be anionic or essentially nonionic. Polymer attachment may then be by van der Waals or hydrophobic interactions. It should be noted that the hydrolyzing metal salts used in most water treatment plants form amphoteric species on colloidal surfaces, so locally attractive electrostatic forces may also provide for polymer attachment even when the overall measurement of colloidal charge suggests repulsion. Nonetheless, measured streaming current or electrophoretic mobility values cannot be used for monitoring or control of dose in such cases. It is observed, however, that regardless of the conditioning mechanism or the polymer type to by used for conditioning (cationic, anionic, or nonionic), polymer overdosing leads to increased viscosity.

This suggests the liquid stream viscosity to be a more consistent and useable parameter for assessing conditioning/dewaterability. However, practical aspects of this possibility remain to be explored. A viscometer for this application must reliably measure small variations in solution viscosity that slightly exceed the background viscosity of water. Problems with clogging and foam accumulation must also be addressed.

The NMR and viscosity results suggest that polymer attachment and bridging mechanisms are similar whether anionic, nonionic, or cationic polymers are used. Optimal bridging is apparent when the number of adsorption sites on colloidal surfaces approaches saturation, and excess dosed polymer remains in solution, increasing the viscosity. Since even the ostensibly nonionic polymers typically possess some anionicity, the attainment of surface saturation may occur over a narrow dose range due to increasing repulsion between attached and solution-phase polymers. This explains why optimal polymer coverage corresponds with the sharp transition in streaming current when using cationic polymers. In general, the fraction of maximum coverage that corresponds to optimal flocculation appears to be much higher than the 1/2 value posited by LaMer and Healy [12] and the 1/3 value suggested by Mabire et al. [24].

3.5. Effect of mixing on conditioning parameters, and use for mixing similitude

As indicated above, mixing time and intensity are very important factors for optimal conditioning and subsequent dewatering (e.g. [13]). Unfortunately, polymer-slurry mixing in most full-scale systems occurs in the fixed configuration of the piping system until entering the dewatering device. Mixing can only be controlled by relocation of the injection point or device, or by retrofitting of specific in-line devices. Inevitably, any change in flow rate alters both the time and intensity of mixing. Yet, as suggested above, this may affect the desired polymer dose.

Previous research with controlled mixing of polymer has thus been limited primarily to laboratory studies. Mixing has been quantified as the velocity gradient, or G, determined based on the operational relationship

$$G = \sqrt{\frac{P}{\mu V}}$$

where P is the applied power, μ is the suspension viscosity, and V the reactor volume. The power is determined based on classic impeller equations, calculated head loss, or applied mechanical power after heat losses. Recently, Christensen et al. [25] have demonstrated that mixing conditions ostensibly having identical G values, but attained using different impellers, give significantly different dewatering results. As with other laboratory studies, the work utilized the CST to quantify the effects of shear on dewaterability, even though this test has a limited relationship to floc strength.

In full-scale trials, Abu-Orf and Dentel [22] studied the effect of mixing intensity on a more extensive set of performance indicators such as electrokinetic and rheological characteristics. Mixing intensity was shown to have a substantial influence on the rheological and mechanical characteristics of the conditioned sludge. Higher optimum doses were required when mixing was increased, and the critical or yield stress (peak height) of conditioned sludge increased with decreased mixing at the same polymer dose, thus increasing the initial strength of flocs. The rheological findings, as stated previously, may not relate well to full-scale application, since the relatively weak flocs may break in the increased shear of the subsequent dewatering process.

Given the importance of mixing in determining the necessary polymer dose and the subsequent floc strength, laboratory tests of conditioning must be performed under similar mixing conditions to those at full-scale being simulated. One method is to calculate velocity gradients for both cases and rely on equal values giving equivalent flocculation and dewaterability. The findings cited above, however, cast some doubt on the validity of this approach.

However, the floc strength effects discussed above, and illustrated in Fig. 3, create an experimental means of establishing equivalent levels of mixing. Simply stated, a known, relatively high dose of polymer is applied at full scale. The streaming current value is read for the conditioned sample immediately prior to the dewatering device (this must be done by batch SC measurement, because flow-through sampling of this material may lead to clogging). A sludge jar test is then performed using the same initial slurry and polymer dose, and paddle stirring estimated to duplicate the full-scale conditions (for high mixing intensity, an impeller blade is required). The appropriate mixing time and intensity are found when this sample's SC equals that measured at full scale [26].

This approach to establishing mixing similitude circumvents the uncertainties of calculated G values cited above, by relying on experimental comparisons. Ironically, the method has also confirmed the mathematical approach to mixing similitude in at least one treatment facility for which the calculated G value based on pipe flow analysis agreed with the calculated jar test G [26]. Further comparisons appear necessary, but it is probable that the SCD method gives an indication of the maximum mixing intensity. If the spatial and temporal distributions of mixing are comparable, the calculated average G for two systems will agree with that based on the hydraulic calculations.

4. Conclusions

Much previous research on chemical conditioning and dewatering has been based on the correlation of an initial solids concentration, a set of polymer doses, a mean velocity gradient (G), and an average capillary suction time (CST). While these are useful parameters in some respects, they are of limited value in others. They do not provide mechanistic information, nor are they easily measured on a continuous basis.

This paper has summarized research developments using somewhat different measurement techniques. These data provide new insights into particle destabilization phenomena and also make it possible to develop scientifically-based strategies for optimizing these processes.

These recent results show an unexpected importance of charge neutralization in sludge conditioning when the flocculant polymer is opposite in charge to the original colloidal material. NMR and viscosity measurements demonstrate that the charge neutralization is indicative of a near-optimal extent of polymer attachment, such that the enhancement of particle–particle flocculation is due to bridging by the attached polymers and not solely due to absence of charge repulsion. This was demonstrated by the failure of SC measurements when anionic polymers successfully flocculate water treatment residuals, which possess amphoteric surface sites.

When cationic polymers are used, floc breakage can be inferred by alteration in charge, with a reversion toward the original, negative value observed with increased mixing time or intensity. This phenomenon allows mixing similitude to be experimentally, rather than theoretically, verified, and allows the increase of floc strength to be observed as it develops with increases in both conditioner dose and mixing intensity. Rheological measurements illustrate the same process.

Beyond the theoretical implications of these findings, the parameters measured in these studies are also amenable to continuous reading, and therefore, to automatic feedback control. Practical barriers must also be overcome in implementing these technologies, and they proved an insurmountable obstacle in the case of rheology-based dose control. However, improvements in sensor technologies have clearly enabled use of the SCD for conditioner dose control, and may eventually enable other measurements to be employed equally successfully.

Acknowledgements

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