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Water Research 36 (2002) 539–550

WATER RESEARCH

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Network strength and dewaterability of flocculated activated sludge

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Received 20 November 2000; received in revised form 12 April 2001; accepted 18 May 2001

Abstract

Works in literature proposed the use of the rheological properties of wastewater sludges as an index for conditioner assessment and control. We demonstrated in this work, on the contrary, that one could not justify the consistency of the commonly used rheological characteristics of the sewage sludge samples taken from the same site but at different dates. A physically relevant index was proposed instead for describing the total network strength, which was hypothesized to correlate the dewatering efficiency of flocculated sludge. Based on this index, the network of a sludge was demonstrated to be largely destroyed after shearing, while the relaxation in an unbound environment or mild pouring over action could partially reinstall the structure. Moreover, a uniform shear rate field could produce network of greater strength when compared with that conditioned in a stirred tank.

Keywords: Rheology; Activated sludge; Dewaterability; Flocculation; Network strength

1. Introduction

Wastewater sludges are non-Newtonian fluids [1]. The shear stress (τ_S) exerted on the sludge body would not be proportional to the induced shear rate (Ω). The rheology of sludge gives essential information to the pump design of sludge management processes. Various rheological models were proposed to interpret the observed sludge characteristics [16,17]. Furthermore, the rheology of sludge is thixotropic, that is, the internal structure of sludge collapses with time and shear rate. Normally, the rheogram of sludge constructed using a rotating rheometer would be different during the shear-rate increasing and the shear-rate decreasing phases, that is, the sludge is thixotropic. Abu-Orf and Dentel [2] reviewed the up to date pertinent literature for sludge rheology studies.

Rheological characteristics could be evaluated based on the rheograms experimentally obtained. Fig. 1 demonstrates a typical rheogram for a flocculated sludge with the existence of an initial peak. As the shear rate increases the shear stress accordingly increases. Prior to the initial peak (τ_{max}) the sludge is not truly flowable. Exceeding this threshold stress, or the yielding point, the sludge body begins to yield, leading to plastic deformation. The plastic deformation is irreversible. The stress hence decreases with increasing shear strain until it reaches τ_S in the rheogram. Afterward, the shear stress starts to increase linearly with increasing shear rate again, presenting a Newtonian-like fluid behavior. The average slope estimates the apparent viscosity (μ_n) for this Newtonian regime, while the intercept with the zero-shear rate axis yields the so-called yield stress (τ_0). The presence of the yield stress is most likely to correlate with the high volumetric concentration of the solid phase [16]. In the Newtonian regime, the apparent viscosity could be regarded as the resistance to shear with most networks in the sludge body having been destroyed. Besides the above-mentioned derived characteristics, Campbell and Crescuolo [3] proposed the index named "instantaneous viscosity" of the rheogram, which is the derivative of the shear stress versus shear

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0043-1354/02/$ - see front matter
PII: S0043-1354(01)00260-3

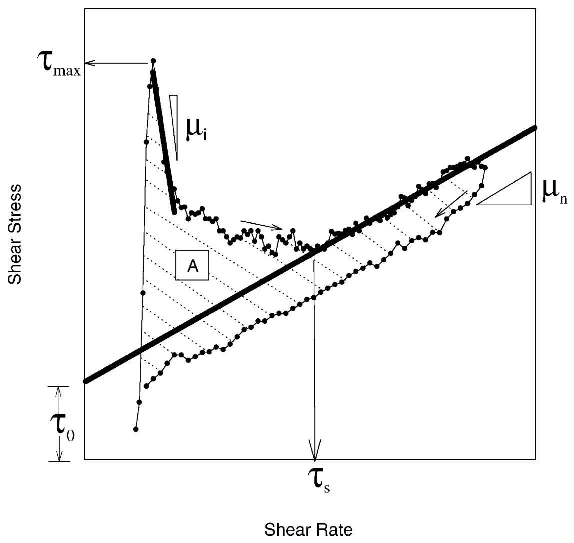


Fig. 1. Schematic of the rheogram of a flocculated sludge.

strain curves. Moreover, the area of the hysteresis loop could be taken as a measure of the degree of thixotropy exhibited by the sludge [3], which could be evaluated as follows:

$$A = \int_{t_1}^{t_2} \tau_S \, d\Omega(t). \quad (1)$$

Works in literature were devoted to explore the correlation between the sludge rheological characteristics, like τ_{max}, τ_0, μ_n, and A, and the other sludge properties, like solid content, capillary suction time (CST), and the surface features of the sludge particles [4–6,18–20]. Dental [7] summarized the role of sludge rheological characteristics in sludge management practice. The sludge rheology recently has found the potential to be used as a tool for chemical conditioner assessment and control. The basic assumptions include (1) some of the derived rheological characteristic changes that could correlate with the trends in sludge dewaterability after flocculation and (2) that the assessment of rheological test is simple and could be applied on-line. For instance, Campbell and Crescuolo [3] used the instantaneous viscosity, or the dose at which τ_{max} occurs, as the control index for conditioner dosing. Based on the knowledge that the residual conditioner should appear in a vast amount in the suspension only if the sludge is overdosed, Christensen et al. [6] and Abu-Orf and Dentel [8] proposed the use of the viscosity of the centrate to control polymer dose. Regardless of the index being employed, one of the prerequisites for using any rheological index for dose assessment and control is that it could consistently detect the occurrence of the optimum dose for a specific sludge regardless of possible quality change.

In this work, we demonstrated that the consistency of the above-mentioned rheological characteristics of the sewage sludge samples taken from the same site but at different dates is not justified. A physically relevant index was proposed based on the total shear energy input amount and was used to detect the occurrence of optimum conditioning condition. Effects of "sludge relaxation" and the uniformity of the shear rate field on the network strength of the flocculated sludge were demonstrated.

2. Experimental

2.1. The samples

Three sewage sludge samples were taken from the Min-Shen Sewage Treatment Plant, Taipei, which handles 15,500 m^3 of wastewater per day using primary, secondary, and tertiary treatments. The raw sewage is screened, degritted, and settled in the primary clarifiers. Then the treated sewage goes to the secondary treatment stage with conventional activated sludge process. Part of the waste activated sludge from the secondary clarifier is recycled back to the aerated tanks. Finally, the treated sludge goes through a tertiary treatment process, which comprises a filtration and a disinfection stage. Three activated sludge samples were taken from the recycled stream in the secondary treatment stage at different dates. The sediments of the sludges were the testing samples, referred to as samples #1–#3 in this work. Their solid weight percents were measured as 0.27%, 0.23%, and 0.64% w/w, respectively.

The zeta meter (Zeter-Meter System 3.0, Zeter-Meter Inc., USA) measured the zeta potentials of aggregates, which were −19, −13, and −18 mV for samples #1, #2, and #3, respectively. Particle size distribution (PSD) was determined via a particle size analyzer (Coulter LS230). The mean particle sizes of the sludge samples #1, #2, and #3 were 95, 73, and 120 μm, respectively. A capillary suction apparatus as described by Lee and Hsu [9,10], was employed to estimate the sludge filterability. The inner cylinder radius was 0.535 cm, while the time required for the filtrate to invade from 1.5 to 2.5 cm in the filter paper was defined as the capillary suction time (CST). Whatman No. 17 paper was the filter paper used. The CSTs for sludge samples #1, #2, and #3 were 30, 36, and 69 s, respectively. Characteristic variation exists among the three samples taken from the same sites but on different dates. Although the surface charges of the original samples resemble each other, sample #3 exhibits a floc size approximately 65% larger than sample #2. Meanwhile, the former presents a CST value almost two times that of the latter. Hence, particle size is not the most essential parameter that determines the dewaterability of the present sludge.

In brief, original samples #1 and #2 share the same zeta potentials, floc sizes, and CST readings. A somewhat greater deviation was noted for sample #3, although the field records revealed no marked changes in the loading or the weather conditions during the sampling period.

Cationic polyelectrolyte, indicated as polymer T-3052, was obtained from Kai-Guan, Taiwan. The polymer T-3052 is a polyacrylamide with an average molecular weight of 10^7, and a charge density of 20%. Sample sludge was first put in the mixing vessel. The polymer solution was then gradually poured into the mixing vessel with 200 rpm of stirring for 5 min (rapid mix) followed by 50 rpm for another 20 min (slow mix). After mixing and prior to settling, a small quantity of sludge-polymer aggregates in the vessel was transferred carefully into the fresh electrolyte at the same pH and electrolyte concentration as the original electrolyte for measuring the zeta potential.

2.2. Rheological test

The apparatus used was a programmable rotational rheometer (Brookfield model DV-III+, USA) equipped with a spindle of diameter 25.2 mm (R) and length 90.9 mm (L). The cell's inside diameter was 27.6 mm (R_0). The software Rheocalc 32 (Brookfield) recorded the rheogram and executed the subsequent data analyses. The following course of rheological measurement had been utilized: (1) increasing linearly the rotational speed from 0 to 100 rpm in 3.8 min; (2) decreasing linearly the rotational speed from 100 rpm down to 1 rpm in 1.9 min; (3) increasing linearly the rotational speed from 1 to 100 rpm in 0.8 min; and (4) decreasing linearly the rotational speed down to 0 rpm in 0.8 min. The simple laminar shear flow condition could be assured in the testing cell. The rheogram produced by stages (1) and (2) forms a hysteresis loop, and is named as Loop I. The subsequent stages (3) and (4) form Loop II.

Some sheared samples were removed from the cell and placed in a big glass beaker for a prescribed time to relax. The "relaxed" samples were then put back into the cell and were sheared according to the same course stated above.

In the previous mentioned tests, the conditioned sludge was flocculated prior to rheological tests in a jar tester. It is well known that the shear rate field in a stirred tank is highly heterogeneous [11]. The Couette laminar flow produced in the rotational rheometer could provide a constant shear rate over the entire cell gap, thus leading to a uniform environment for coagulation. For demonstrating the possible role of shear rate uniformity, independent tests were conducted using sludge #3 as the testing material. 16 mL of sludge was put into the cell with a rotational speed of 60 rpm. Then the flocculant solution was gradually injected into the suspension using a syringe to a prescribed dose within 5 min. Then the rotational speed of the cell decreased to zero in 20 s. This sludge is referred to as the "uniformly sheared sludge". Some uniformly sheared sludge remained in the cell for 5 min or for 1 h without replacement. The other uniformly sheared sludge was taken out from the cell and placed in a beaker for relaxation. Later the sludge was sheared according to the above mentioned course steps (1)–(4).

3. Results and discussion

3.1. Flocculated sludge characteristics

Fig. 2 depicts the sludge properties before and after flocculation. The range of dosage during which the corresponding CST values reach a minimum is labeled as "optimum" in the figure. The optimum dose ranges from 5 to 10 ppm for sample #1, and from 10 to 20 ppm for both the samples #2 and #3. The doses exceeding the optimum one would be regarded "overdosed", while those less than that, "underdosed".

As noted from these curves, although all the samples were taken from the same site and resembled each other in their surface charges and appearances, the corresponding characteristic changes subject to polyelectrolyte flocculation are markedly different. For example, the zeta potential for sample #1 could be neutralized at a dose that slightly exceeds the optimum one. However, the surface charges for particles in samples #2 and #3 could not be neutralized over the dosage range that was investigated. The CST of sample #1 could be reduced to a level of 25 s, at the optimum indicating satisfactory dewaterability, and exhibits a very large "rebound" in CST when overdosed, while those for samples #2 and #3 are not so obvious. Particle sizes for all samples increase steadily with the polyelectrolyte addition. The particles in sample #1 could reach a high level of 350 μm, which is much larger than those achieved for samples #2 and #3. Also, in sample #2 a peak for particle size is noticeable in the optimum dose range, which does not exist in the other two samples.

3.2. Rheograms and derived properties

Fig. 3a–c demonstrate the rheograms of the original and the flocculated sludges #1–#3 for both Loops I and II. The following observations correlate with the literature results: (a) Hysteresis is noticeable for Loop I, indicating that the present sludges are thixotropic in nature. (b) An initial peak is noticeable for all tests, especially for the sludge flocculated closer to and over

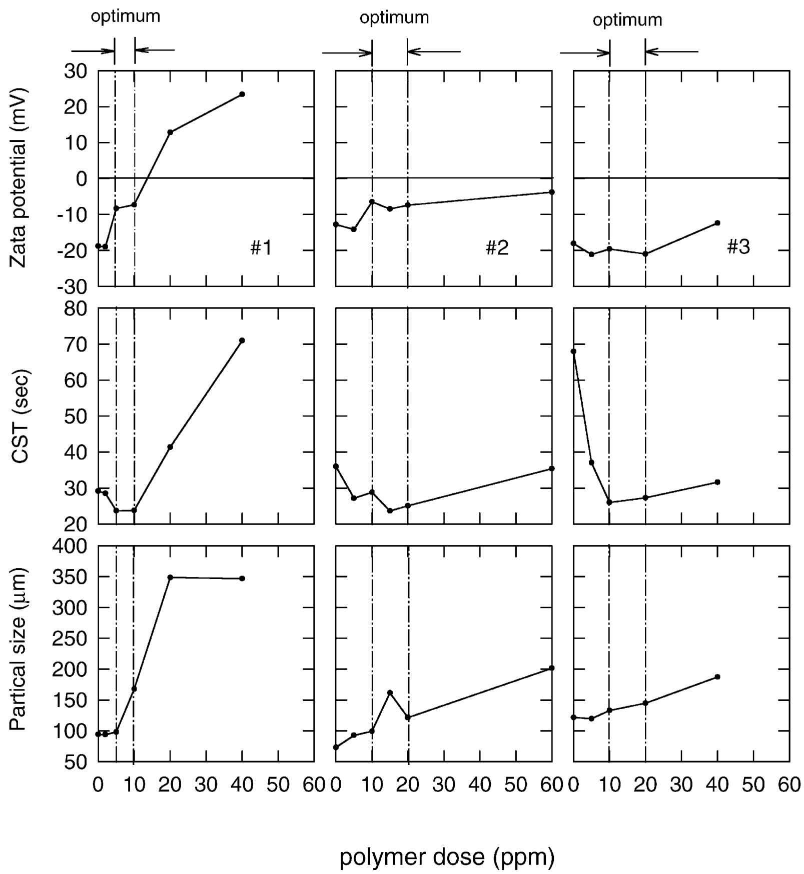


Fig. 2. Sludge characteristics before and after flocculation.

the optimum doses. (c) After the initial peak regime the sludge behaves as a Newtonian fluid, but with an apparent viscosity much greater than that for pure water (10^{-3} Pa s). Meanwhile, we also note that the initial peak vanishes for Loop II. Restated, regardless of the origin of the initial peak, the first spin-on has destroyed most of the network bindings over the entire sludge.

For demonstrating the rheological characteristic change after flocculation, the initial peak (τ_{max}), the yield stress (τ_0), and the apparent viscosity (μ_n), are derived from the rheograms using data smoothing and regressing. The integration area (A) could be estimated numerically. Fig. 4 demonstrates these results. Notably, the instantaneous viscosity proposed by Campbell and Crescuolo [3] could not be reliably derived since the rheogram obtained normally contains a degree of data-scattering, while the numerical differentiation enlarges the errors. Moreover, as Fig. 3 demonstrates, at optimum and overdosed regimes one may note more than one peak on the rheograms. The allocation of the so-called "initial peak" may not correspond to the highest stress achieved in the rheological test.

As Fig. 4 reveals, for sample #1, the yield stress, the initial peak, and the area (A) start to markedly increase at its optimum dose. On the other hand, the apparent viscosity reveals a little change when overdosed. Hence, using sample #1, one may conclude that all the indices except for apparent viscosity, especially the initial stress whose magnitude increases by over eight times when overdosed, could be regarded as a useful tool for dose control.

However, unlike those demonstrated for sample #1, the initial peak and yield stress for sample #2 exhibit a local maximum rather than a sudden increase at the optimum dose. To use the sudden increase in the initial peak as the dose control criterion may hence lead to an overdose. Meanwhile, its apparent viscosity reaches a local minimum in the optimum dose range, which starts to increase only in overdosed regime. The corresponding area A monotonically increases with the polymer dose. Therefore, none of the four above-mentioned rheological characteristics could be used as the indices for dose control.

For sample #3, the initial peak, yield stress, and integration area A monotonically increase with polymer dose covering underdosed to overdosed regimes, hence have no correlation with the optimum dose. Its apparent viscosity exhibits a minimum close to the optimum regime. Again, none of the four rheological characteristics correlate with the minimum of the CST—the optimum dose.

The derived rheological characteristics for Loop II are also demonstrated in Fig. 4 for comparison sake. As depicted in Fig. 3, the initial peak and the yield stress are noted close to zero for Loop II tests. Hence, the sheared sludge resembles a Newtonian-like fluid. Except for sample #3, the apparent viscosities for Loops I and II are close. These observations demonstrate that the breakdown of the networks for samples #1 and #2 is sufficient during Loop I, thereby making the sludge the Newtonian-like fluid in Loop II with a constant μ_n. For sample #3, nevertheless, the μ_n's for Loop II are greater than for Loop I, wherein certain network reconstruction must occur after Loop I shearing.

To summarize, although all the three samples are taken from the same site, however, their derived rheological characteristics change markedly. Also, there

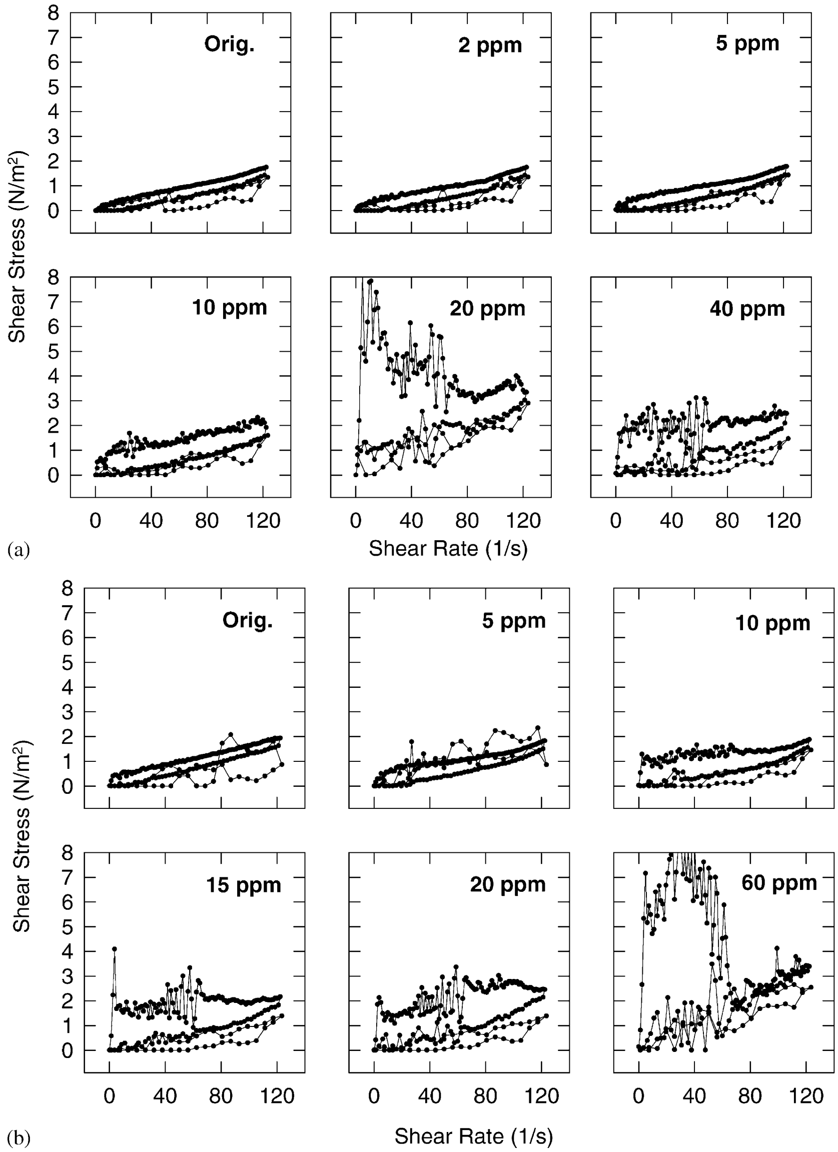
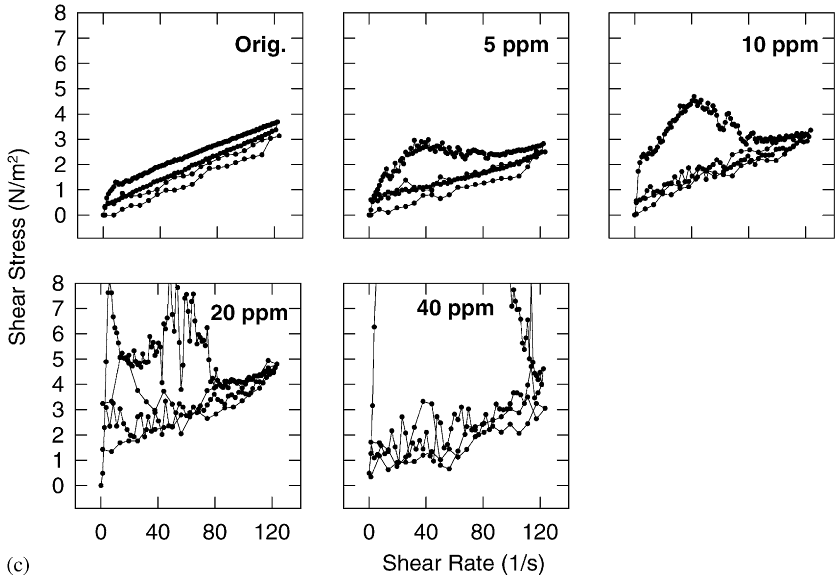


Fig. 3. The rheograms of the original and flocculated sludges. The two curves with denser points indicate Loop I, while the looser one, Loop II. The optimum regimes were determined using the CST tests. (a) Sample #1; (b) sample #2; and (c) sample #3.



(c)

Fig. 3. (*Continued*).

is no consistent correlation to exist between these rheological characteristics and the change in sludge properties as noted in Fig. 2. This finding suggests that the rheogram, and hence the derived rheological characteristics, like the peak value or the yield stress, could not be employed for conditioning control in the field for lack of data consistency. Such an inconsistency might arise from the fact that the sludge rheology is more sensitive to the particle shape/size/concentration and other process parameters than the changes in dewatering characteristics, while the proposed rheological characteristics could be regarded phenomenal in nature. A more fundamental index is required.

3.3. Rheograms for relaxed sludges

Fig. 5 demonstrates the rheograms of the relaxed samples, which had been sheared in Loop I and is relaxed in a beaker for 5 min. Apparently, the rheograms of the samples resemble those for the ones depicted in Fig. 3, although their initial peaks are of lesser height than the ones prior to relaxation. During relaxation, the network structure broken during Loop I was partially reinstalled. However, the reinstallation is not complete and the initial peak cannot be recovered to its original height (Fig. 3c). After the shearing by Loop I, the initial peak of the relaxed samples vanishes in Loop II. Restated, the network structure reinstalled during relaxation (5 min) is destroyed again in the subsequent Loop I shearing. Independent tests revealed that this relaxation could be accomplished in a rather short period of time.

Fig. 6 demonstrates the derived rheological characteristics for the relaxed samples, which resemble those depicted in Fig. 4. Despite the apparent viscosity, all the three characteristics are lesser for the former than the latter, reflecting the incomplete reinstallation of the network structure. The higher apparent viscosity for the relaxed samples might be attributed to the residual conditioners released from the sheared sample that have no chance to reflocculate the particles.

3.4. Rheograms for uniformly sheared sludge

Fig. 7 demonstrates the rheograms of the uniformly sheared samples, which are relaxed in the beaker. Its basic characteristics resemble those observed in Fig. 3c. The initial peak increases markedly in height at a dose of around 6 ppm, which is much less than that depicted, conducted in the jar tester (20 ppm in Fig. 3c). Restated, a uniformly sheared field could reduce the polyelectrolyte dosage required for sufficient conditioning. Such an observation might be attributed to the fact that the more uniform shear rate field in the cell gap could more evenly disperse the flocculants over the entire sludge body when compared with the heterogeneous flow field generated in the stirred tank. Abu-Orf and Dentel [2] also noted that the optimum dose changes with the applied mixing intensity. Furthermore, the initial peaks noted are even higher than those depicted in Fig. 3. The uniform shear rate field could hence produce more bonds in the suspension than those flocculated in the jar tester.

Fig. 8 demonstrates the rheograms of the uniformly sheared, and relaxed in the cell sludge samples.

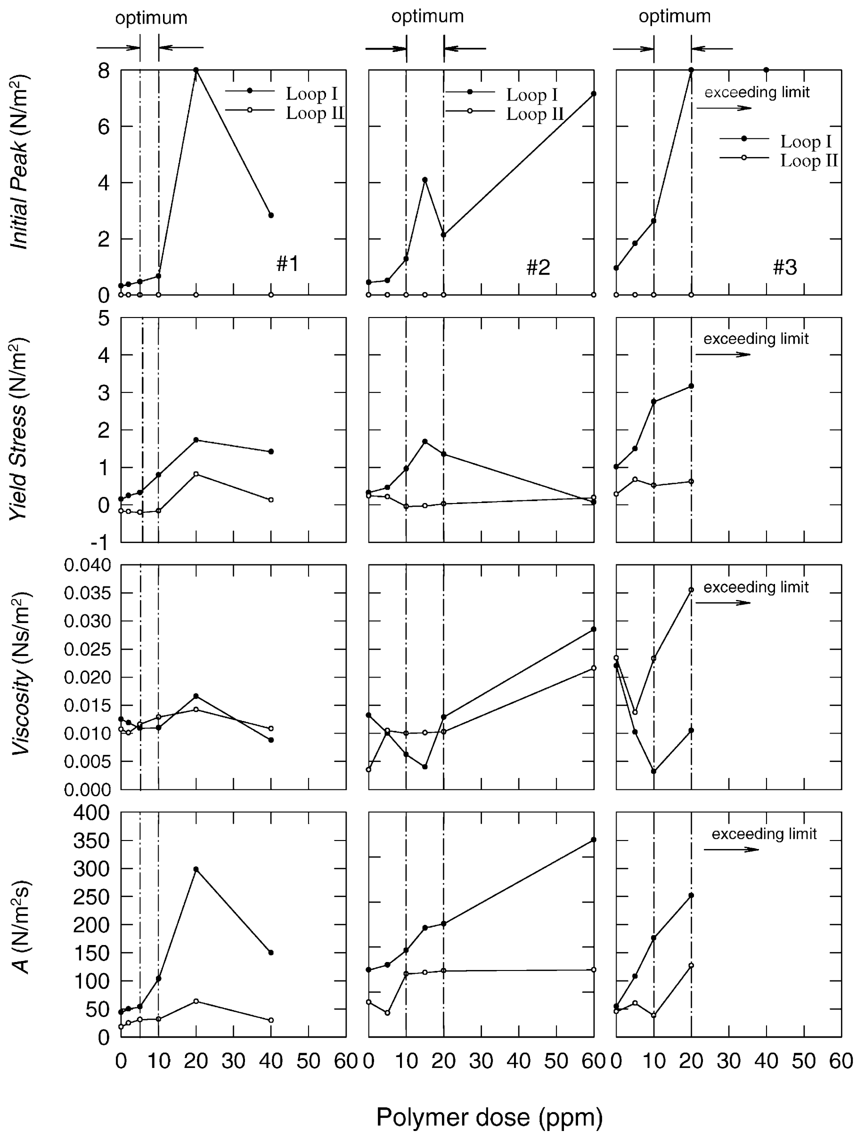


Fig. 4. The derived rheological characteristics of samples #1–#3. The optimum regimes were determined using the CST tests.

Surprisingly, no initial peak is detected for either the original or the flocculated sludge samples. This observation together with those depicted in Fig. 5 demonstrates that either a sufficiently large space is needed for the sludge to build the network bonds among particles during relaxation, or simply the mild pouring-over action among the cell and the beaker could induce satisfactory network reconstruction.

The data demonstrated in Figs. 5–8 reveals that the rheogram of sludge provided information regarding the "internal energy" of the formed network before and after flocculation, which will be discussed in the subsequent session.

3.5. Network strength and sludge dewaterability

Before one could utilize sludge rheological characteristics to assess or control the conditioner dosage one should first answer the following question: "Why the way the flocculated sludge flocs resists the shear correlates with the sludge dewaterability?" That is, certain physically relevant arguments had to be established between the proposed index and the conditioning mechanisms. For instance, based on the understanding a part of the flocculent should be left in the suspension in the overdosed regime. Dentel and Abu-Orf [12] utilize the viscosity of centrate in the control index, which

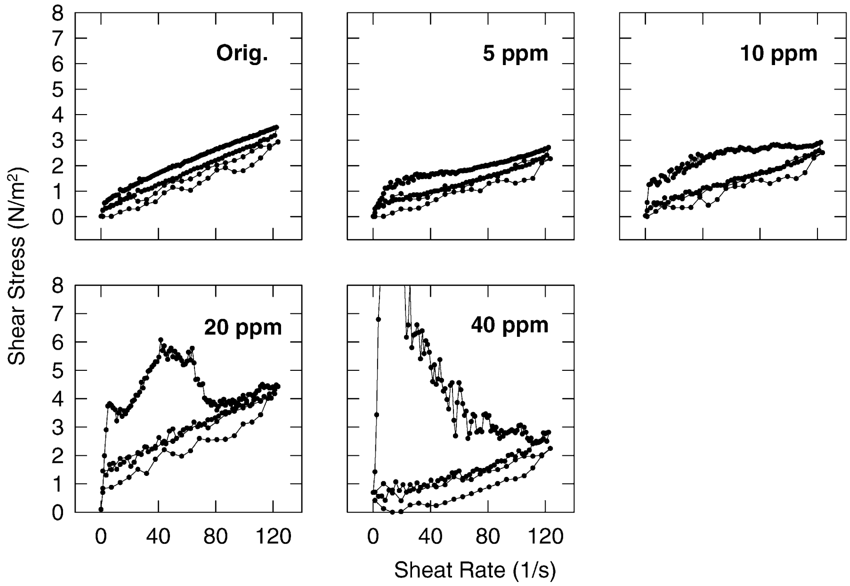


Fig. 5. The rheograms of the relaxed sample #3. The two curves with denser points indicate Loop I, while the looser one, Loop II.

should increase markedly overdosed. To believe that a strong network is beneficial to sludge dewatering, Campbell and Crescuolo [3] and Abu-Orf and Dentel [2] examined the correlation of initial peak and the optimum dose. However, as discussed in the preceding sections, all the previously proposed rheological characteristics lack consistency in describing the sludge conditioning processes.

When a sludge is subjected to polyelectrolyte flocculation, the particles of smaller size would be aggregated into larger flocs with the action of charge neutralization and bridging. Suspension mixing is commonly employed to enhance the sludge flocculation, which could also lead to floc breakage and, if the residual conditioner is left at a sufficient amount in the suspension, reflocculation could occur that produces strong and tough flocs. Then the conditioned sludge is sent to the dewatering device, like the sedimentation basin or the belt filter press. The optimum dose is the dosage that yields the best settleability and/or the least resistance to mechanical dewatering. However, different aggregate characteristics are required for various intended applications [21]. For instance, the "best" floc amenable to sedimentation should be of a large size and exhibit a *strong* and *compact* interior. On the other hand, the desired flocs that could yield the minimum filtration resistance should be of high porosity and exhibit a *strong* and *open* interior. The CST measurement characterizes the resistance to filtration, hence the optimum dose thus determined indicates the existence of a tough network structure comprising loose and strong flocs, which is achieved herein through polyelectrolyte flocculation. In fact, despite the reduction of residual moisture in the dewatered cake, a strong floc, where a tough network is established in the filter cake is beneficial to most dewatering practice. A rational way to detect the optimum dose should consider the strength of the total network of sludge after flocculation.

The physical meaning of the derived rheological characteristics of sludge could be realized as follows. The initial peak (τ_{max}) is proportional to an entanglement network strength occurring during the shear rate-increasing phase [13], while the yield stress is the minimum stress required to totally disintegrate the sludge flocs, which could be regarded as the binding strength between flocs [14]. Hence, these two indices provide an indirect measure to the total network strength. Difficulties arise in accurately allocating the τ_{max} values since multi-peaks are noticeable in the rheograms obtained. In the subsequent Newtonian regime, the suspension viscosity is affected by both the volume fraction of solids and the residual conditioner. Different floc size distributions could affect the value of μ_n [15]. However, there exists no direct correlation of the aggregates after the network disintegration (at $\tau > \tau_S$) with the total network strength prior to rheological tests. Finally, the area A bound by the shear rate-increasing and the shear rate-decreasing curves on the rheogram is demonstrated as follows:

$$A = \int_{t_1}^{t_2} \tau_S \, d\Omega(t) = \int_{t_1}^{t_2} \tau_S \frac{d\Omega(t)}{dt} dt. \quad (2)$$

Apparently, the area A could not represent the total network strength in the conditioned sludge.

The major power input to break down the sludge network is by tangential shearing. The power input, $P \times$

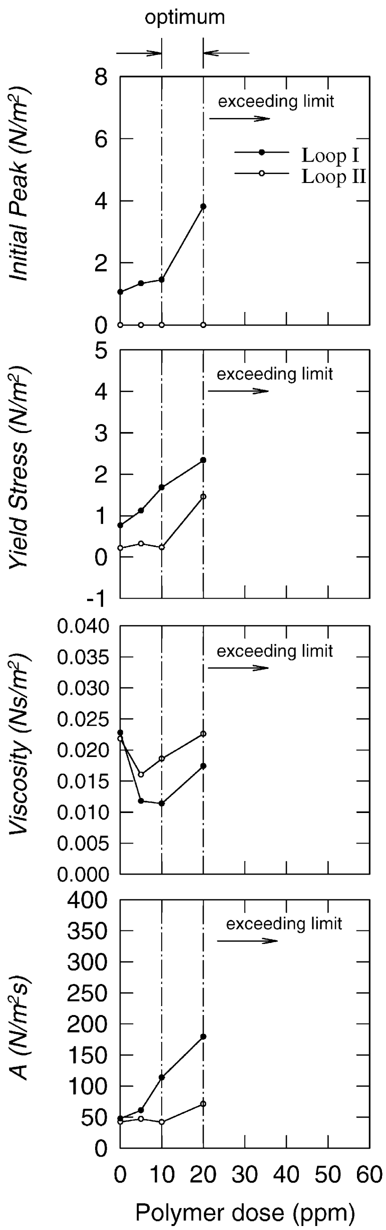


Fig. 6. The derived rheological characteristics of the relaxed sample #3. The optimum regimes were determined using the CST test.

(W), to the suspension by the action of shear stress could be estimated as follows:

$$P = \frac{GV}{R} = G\Omega, \tag{3}$$

where G, R, V, and Ω are the torque (N m), radius of the inner cylinder (m), tangential velocity (m s^{-1}), and angular velocity (s^{-1}), respectively. Hence, the total energy input, $E(J)$, could be found by integration with respect to time:

$$E = \int_{t_1}^{t_2} P\,dt = \int_{t_1}^{t_2} G\Omega\,dt = \int_{t_1}^{t_2} \tau_S 2\pi R^2 L\,\Omega(t)\,dt = 2\pi R^2 L \int_{t_1}^{t_2} \tau_S\,\Omega(t)\,dt \tag{4}$$

Notably, Eq. (4) is not identical to Eq. (2) while the former presents a relevant physical quantity to characterize the sludge network strength.

Hence, the specific energy input to the suspension could be approximated as follows:

$$E_S = \frac{E}{2\pi RHL\rho W_t} = \frac{R}{H\rho W_t}\int_{t_1}^{t_2} \tau_S\,\Omega(t)\,dt, \tag{5}$$

where H (m) is the gap ($R_0 - R$), ρ (kg m^{-3}) is the water density, and W_t is the weight percentage of the suspension (%). E_S (J kg^{-1}) denotes the energy input for breaking down the flocculated matrix containing 1 kg of solids. Assume that the particle relaxation time in the suspension is smaller than the characteristic time for rotational speed increment. Hence, the higher the E_S, the stronger the interaggregate strength existing in the flocculated matrix. In the following discussion, the E_S value for Loop I is obtained for $t_1 = 0$ s and $t_2 = 151$ s, indicating the difference of energy input to the shear rate-increasing phase ($i = 1$) and the decreasing phase ($i = 2$). For Loop II, $t_1 = 151$ s and $t_2 = 191$ s ($i = 3, 4$), whence the obtained E_S value denotes the difference of energy input for the two phases in Loop II.

Fig. 9a demonstrates the E_S versus polymer dose curves. Notably, the E_S in Loop I would be kept approximately constant in the underdosed regime, and then increased markedly during the optimum dose regime. The E_S data for Loop II are also demonstrated in Fig. 9a as the data connected by dashed curves. Since after Loop I, most network bonds have been broken down, Loop II yields a much lower E_S. However, there still exists a small initial peak corresponding to the optimum dose range, indicating that although the shear has broken down most bonds, the conditioning of sludge to the lowest CST value still retains most bonds between particles in a sludge.

As indicated above, high E_S corresponds to strong flocculated matrix. Overdosing commonly yields a greater E_S value when compared with the optimal one. However, the increase in residual polymer concentration in the suspension during overdosing could markedly increase the viscosity of filtrate as well, thereby deteriorating the dewaterability. Hence, the sudden rise of the E_S value indicates the significant enhancement of floc matrix strength, but has not had too much residual polymer in the suspension, whence corresponding to the occurrence of the optimal dose.

Fig. 9b depicts the E_S values for the relaxed samples. A mild increase in E_S is also noted for the reinstalled

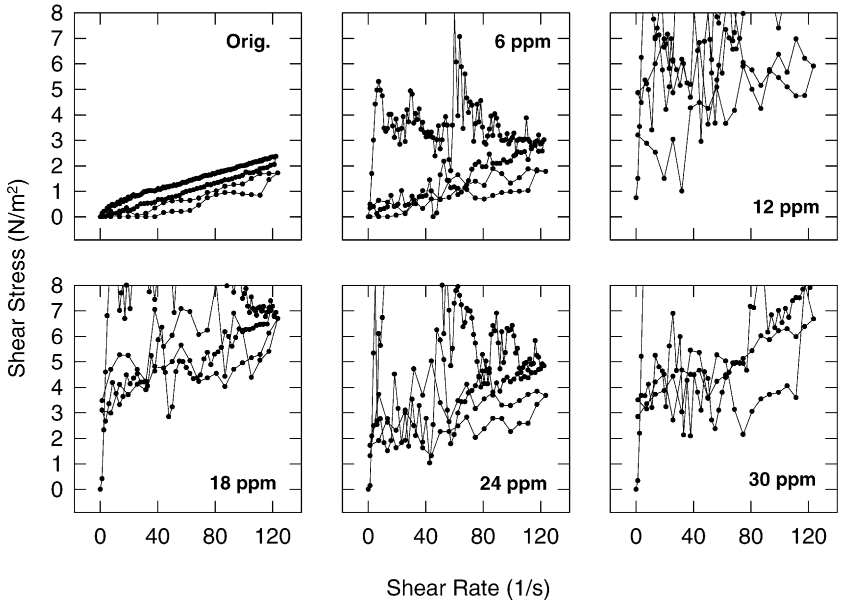


Fig. 7. The rheograms of the uniformly sheared sample #3 relaxed in a beaker for 5 min. The two curves with denser points indicate Loop I, while the looser one, Loop II.

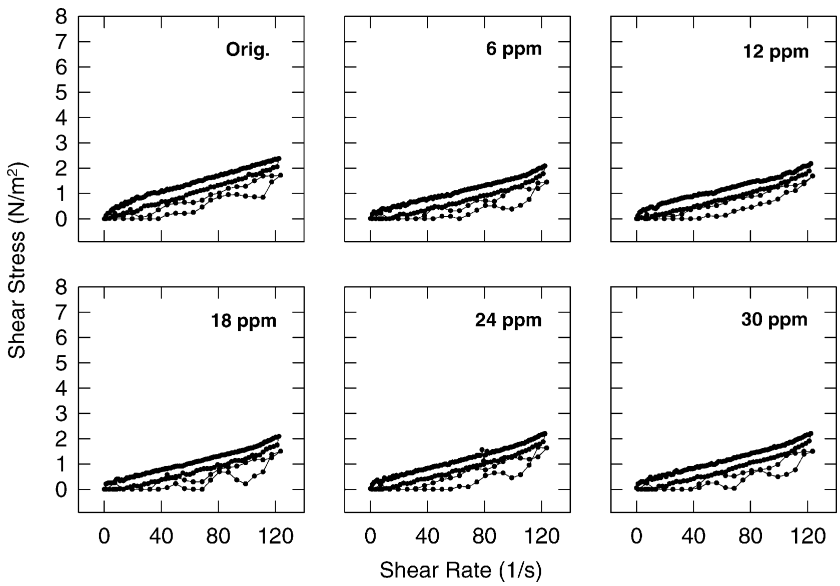


Fig. 8. The rheograms of the uniformly sheared sample #3 relaxed in the cell for 5 min. The two curves with denser points indicate the Loop I, while the looser one, Loop II.

network strength. Nevertheless, the reinstalled structure at 20 ppm dose exhibits a lower network strength of approximately 85% as that depicted in Fig. 9a.

Fig. 9c demonstrates the calculated E_S values for the uniformly sheared sludges. Notably, the network strength produced for the relaxed-in-beaker sample with a dose of 6 ppm could be 2 to 3 times higher than those flocculated in the jar tester at 20 ppm (Fig. 9a). The uniform shear rate field could produce a much stronger network of sludge with the less expense of chemical conditioners. However, the relaxed-in-cell samples exhibit a much lower E_S. Actually, all samples exhibit a strength of $7 \times 10^5\,\mathrm{J\,kg^{-1}\,ds^{-1}}$ regardless of the polymer dose. Although this strength is still comparable to the jar tester sludges, the role of polyelectrolyte has become insignificant. A sufficient space seems to be an essential factor for a comprehensive network to form after flocculation. Rheological tests with narrow-spaced channels thereby could yield erroneous judgement to dose control.

Therefore, unlike the four rheological characteristics depicted in Fig. 4, the proposed E_S values would represent the total hot work strength in a physically relevant way, and consistently correlate with the occurrence of optimum dose. Moreover, the changes in E_S values after treatment could provide more understanding to the network strength thus constructed or destroyed, which could be used for describing the performances of sludge processes where the strength of the total sludge plays an essential role.

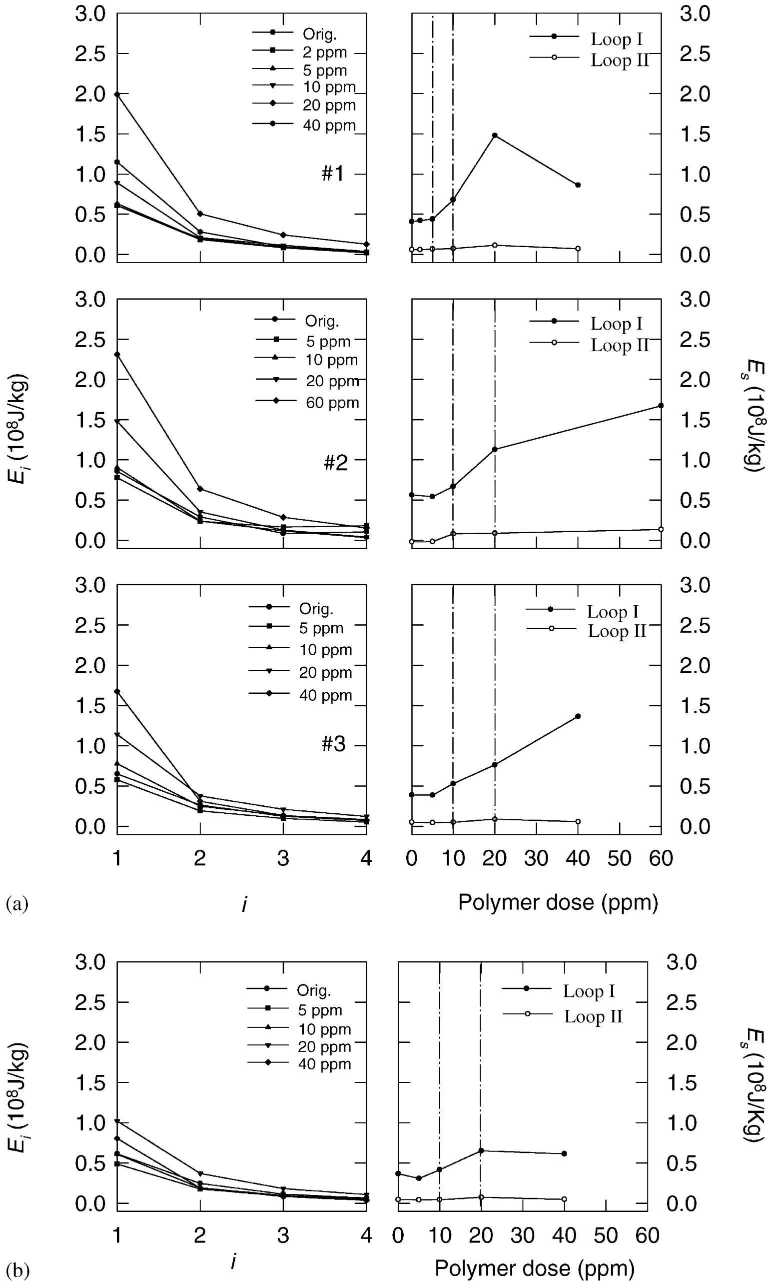


Fig. 9. The E_i versus i plot and the E_S versus polymer dose plots. (a) Samples #1–#3; (b) relaxed sample #3; and (c) uniformly sheared sample #3.

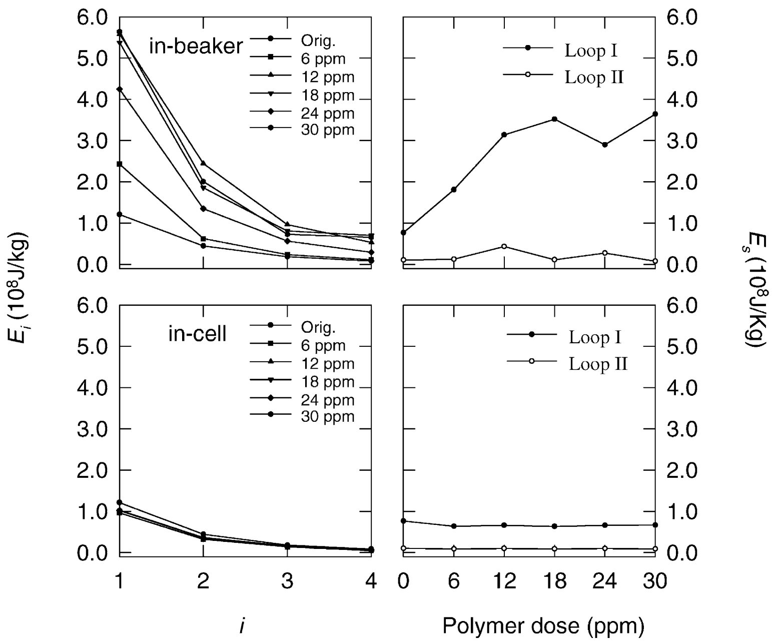


Fig. 9. (*Continued*).

Acknowledgements

National Science Council, ROC, financially supported this work.

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