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# Network Strength of Waste Activated Sludge Using Rheological Tests

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## ABSTRACT

A rheogram of waste activated sludge is used to estimate the non-Newtonian behavior of original and flocculated flocs. The shearing energy, input by the rheometer, represents the plastic contribution of the floc network strength. This study estimated the binding strength of network flocs in waste activated sludge from rheological tests. Two sludge samples from a wastewater treatment plant were considered. The binding strength increased with polymer dose, indicating the structure's higher resistance to hydrodynamic shear. Although the $E_S$ value could not be used as a single index for comparing the ease of dewatering various batches of sludge, it can be used for online monitoring to flocculation status for sludge.

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*Key Words:* Rheology; Activated sludge; Flocculation; Network strength.

## INTRODUCTION

Wastewater sludges are non-Newtonian fluids.[1] A shear stress ($\sigma_s$) exerted on a sludge body is not proportional to the induced shear rate ($\dot{\gamma}$). The rheology of sludge is essential to its transportation. The rheology of flocculated dispersion depends on the microstructure of the aggregates in a suspension, its period of evolution, and the type and magnitude of the interparticle forces.[2] Typically, a rheogram of sludge generated by a rotating rheometer is different in the shear-rate increasing phase from that in the rate-decreasing phases. Abu-Orf and Dentel[3] reviewed pertinent literature in sludge rheology. Different flocculation processes produce significantly different rheological behavior of a suspension.[4]

Many studies have explored the correlation between sludge's rheological characteristics, like peak stress, yield stress, viscosity of the Bigham-plastic regime, and the area enclosed by the rheogram curve, and the sludge's physical properties, such as solid content, capillary suction time (CST), and the surface charges of the sludge particles.[5–9] Dentel[10] summarized the role of sludge's rheological characteristics in sludge management practice. Sludge rheology has recently developed the potential for use as an effective means of assessing and controlling chemical conditioners.[3,9,11] However, Yen et al.[12] established that the consistency of the commonly used rheological characteristics of sewage sludge samples was not supported by correlation with dewaterability. Dentel et al.[13] concluded similarly.

Various intended dewatering applications depend on specific floc characteristics.[14] For example, a "best" floc, most amenable to sedimentation, should be *large* and *compact*. However, flocs with the desired minimum filtration resistance should be highly porous, with a *strong* and *open* interior. A tough floc structure always benefits mechanical dewatering, since the cake does not easily collapse under pressure, permitting rapid dewatering. Accordingly, Yen et al.[12] claimed that, rather than the rheological indices proposed in the literature, the total network strength of the flocculated sludge correlated with the dewatering efficiency. A sludge more resistant to a shear force should be more readily dewatered under pressure.

Numerous attempts have been made to determine the network structure of flocculate colloid suspensions. Tadros et al. developed an approach to estimate the particle–particle bond strength of a flocculated suspension, using the yield stress in the Bingham plastic regime.[15,16] However, these approaches failed for strongly flocculated suspensions, such as activated sludges, which show an initial peak on the rheograms. Yen et al.[12] estimated the matrix strength of flocculated waste activated sludge, from the shear energy input by the rheometer. Their proposed method is adopted here and the binding strengths of the flocculated sludge matrix are discussed, considering floc–floc interactions.

## EXPERIMENTAL

### Samples

Waste activated sludge samples were taken from the Neili Bread wastewater treatment plant, President Enterprise Co., Taoyuan, Taiwan, which treats 250 $m^3$/day of wastewater from food processing by primary, secondary, and tertiary treatments. The conventional activated sludge process is used for secondary treatment. Two samples were collected from the recycling stream on different dates. The sediments formed by these two samples after 24 hours settling were the testing samples, referred to as sample #1 and sample #2. Sample #1 was collected on a sunny day and had a solid content of 0.37% (w/w), while sample #2 was collected after a long rainy season, and had a solid content of 0.60% (w/w).

Particle size distribution (PSD) of sludge flocs was determined using particle size analyzer (Coulter LS230). The mean particle sizes ($d_f$) of sludge samples #1 and #2 were 61 and 100 μm, respectively. Capillary suction apparatus, as described by Lee and Hsu,[17,18] was employed to estimate the filterability of the sludge. The inner cylinder radius was 0.535 cm, and the time required for the filtrate to move from 1.5 to 3.0 cm through the filter paper was defined as the capillary suction time (CST). Whatman No. 17 filter paper was used. The CSTs for the original samples, #1 and #2, were 38 and 101 s, respectively. Hence, a characteristic variation exists between these two samples. Sample #2 had a floc size approximately 64% greater than sample #1. The CST value of sample #2 was almost thrice that of sample #1.

Cationic polyelectrolyte, polymer T-3052, was obtained from Kai-Guan Inc., 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 into the mixing vessel. The polymer solution was then gradually poured into the mixing vessel with stirring at $G = 315\,s^{-1}$ for 5 min (rapid mix) followed by stirring at $G = 27.6\,s^{-1}$ for another 20 min (slow mix).

### Rheological Test

A programmable, rotational rheometer was used (Brookfield model DV-III +, USA), equipped with a spindle of diameter 25.2 mm (2*R*) and length 90.9 mm (*L*). The cell had an interior diameter of 27.6 mm ($2R_o$). The software Rheocalc 32 (Brookfield) recorded the rheogram and performed the subsequent data analyses. The following program was used for rheological measurement. (1) Increasing the rotational speed linearly from 0 to 101 rpm in 101 s; (2) decreasing the rotational speed linearly from 101 rpm back to 1 rpm in 50 s; (3) increasing the rotational speed linearly from 1 to 100 rpm in 20 s; (4) decreasing the rotational speed back to zero in 20 s. Simple laminar shear flow conditions were ensured in the testing cell. The maximum *G* value for rheological test is 122 $s^{-1}$. The rheogram produced by stages (1) and (2) forms a hysteresis loop, and is termed Loop I. Subsequent stages, (3) and (4), form Loop II.

### Light Scattering Test

Small-angle laser light scattering tests characterized the interior structure of the sludge flocs, using a Malvern Mastersizer 2000. The scattered light was collected at angles between 0.014° and 40.628° using a 44-element solid-state detector array. The Malvern Mastersizer 2000 was also used to measure the aggregate size between 0.02 and 2000 μm.



## RESULTS AND DISCUSSION

### Flocculated Sludge Characteristics

Figure 1 shows the CST values and the sludge floc diameter before and after flocculation. The range of doses for which the corresponding CST values are minimal, is labeled "optimum" in the figure. The optimum dose ranges from 30–40 ppm for sample #1, and from 40–60 ppm for sample #2. Doses exceeding the "optimum" are regarded as "overdosed"; while those that are less than the "optimum" are "underdosed."

These curves reveal that, although the samples were collected under different weather conditions, their corresponding characteristic changes when subjected polyelectrolyte flocculation, resemble each other, but have different magnitudes. The CST of sample #1 is reduced from 38 s to 22 s in the optimal dose, and then rebounds considerably in the overdosed regime. For sample #2,

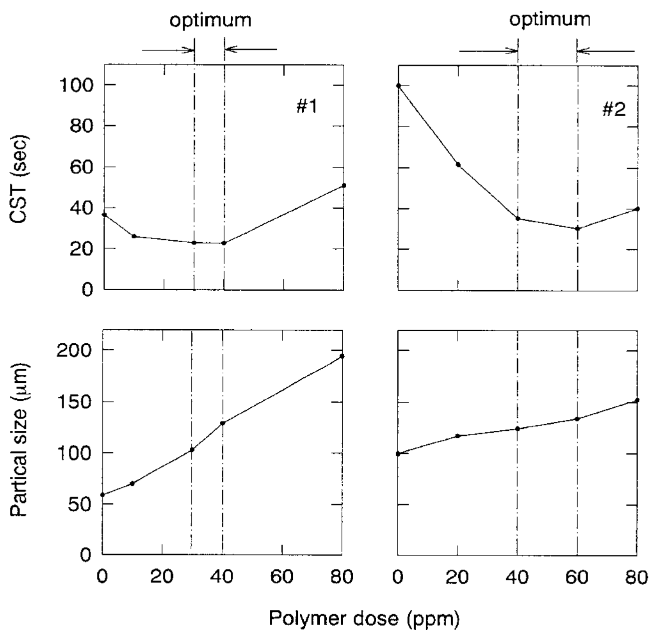
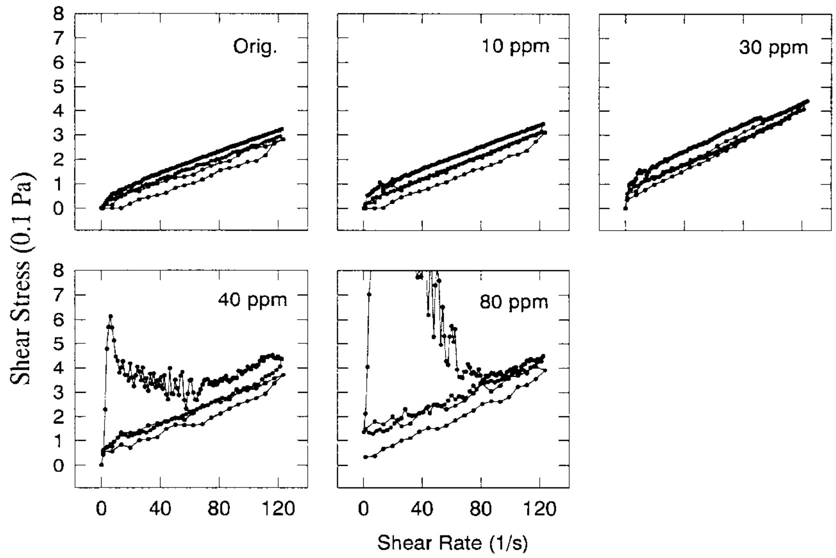



***Figure 1.*** Sludge characteristics of sludge before and after flocculation. The "optimum" regimes were determined at minimum CST.

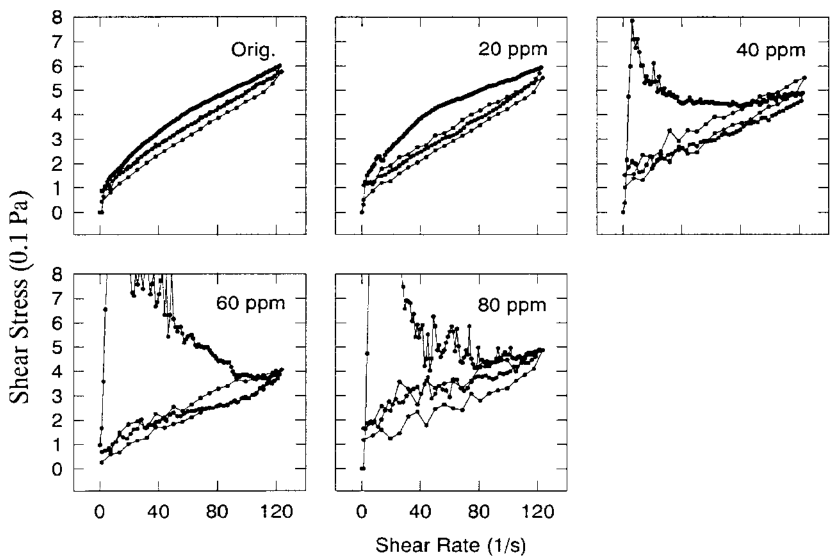
the CST declines markedly from 101 s to under 30 s at the optimal dose, but rebounds at a lower magnitude than that for sample #1. Moreover, the floc size of sample #1 increases from 60 to 190 μm, a three fold increase. However, the size for sample #2 changes only moderately with polyelectrolyte dose.

## Rheograms and Network Strength

Figure 2 displays rheograms of the original and the flocculated sludges for both Loop I and Loop II. Notably, although rheological characteristics were changed by flocculation, they did not correlate with observed sludge dewaterability. This observation agrees with the findings of Yen et al. The lack of correlation between the rheological indices discussed and the optimum dose is attributable to the fact that the rheogram of the sludge is sensitive to the floc characteristics under shear. When the sludge is subjected to polyelectrolyte flocculation, smaller particles are aggregated into larger flocs under the action




(a) Sample #1




(b) Sample #2

***Figure 2.*** The rheograms of the original and flocculated sludges. The two curves with denser points indicate the Loop I; while the looser, Loop II. (a) Sample #1; (b) sample #2.

of charge neutralization and/or bridging. Suspension mixing is commonly used to enhance sludge flocculation, and can lead to floc breakage if sufficient residual conditioner is left in the suspension, which situation typically applies in practice. Reflocculation then occurs and produces strong and tough flocs. This process is stochastic and the details cannot be exactly reproduced, such that the obtained rheograms are inconsistent. However, most rheological indices depend on numerical differentiation of the rheogram data, enlarging the error bars in tests.

Yen et al.[12] proposed that the power transmitted into the sludge body under shearing corresponds to the weakening of the sludge network. For completeness, Yen and colleagues derivation is briefly summarized as follows. The power to break down the sludge network is mainly input by tangential shearing. The power input, $P$ (W), to the suspension, by shear stress, can be estimated as follows.

$$P = \frac{GV}{R} = G\Omega \tag{1}$$

where $G$, $R$, $V$, and $\Omega$ 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), can be found by integrating with respect to time.

$$\begin{aligned} E &= \int_{t_1}^{t_2} P dt = \int_{t_1}^{t_2} G\Omega \mathrm{dt} = \int_{t_1}^{t_2} \tau_S 2\pi R^2 L \Omega(t) dt \\ &= 2\pi R^2 L \int_{t_1}^{t_2} \tau_S \Omega(t) dt \end{aligned} \tag{2}$$

Hence, the specific energy input to the suspension can be approximated as follows.

$$E_S = \frac{E}{2\pi RHL\rho W_t} = \frac{R}{H\rho W_t} \int_{t_1}^{t_2} \tau_S \Omega(t) dt \tag{3}$$

where $H$ (m) is the gap ($R_o - R$); $\rho$ (kg $-$ m$^{-3}$) is the water density, and $W_t$ is the weight percentage of the suspension (% w/w). $E_S$ represents the energy input over the time interval, ($t_1$, $t_2$) to overcome the internal friction and the breakdown of the flocculated matrix that contains 1 kg of solids. Assuming that the particle relaxation time in the suspension is much less than the characteristic time for increasing the rotational speed, a higher $E_S$ corresponds to a higher interaggregate strength in the flocculated matrix. In the following discussion, $E_S$ for Loop I is obtained at $t_1 = 0$ s and $t_2 = 151$ s, showing the difference between the energy input in the shear rate-increasing phase ($i = 1$) and that in the decreasing phase ($i = 2$). For Loop II, $t_1 = 151$ s and $t_1 = 191$ ($i = 3, 4$), whence the obtained $E_S$ value determines the difference between the energy input during the two phases in Loop II. The differentiation is clarified by denoting specific energy inputs at $i = 1$ to 4 as $E_1$ to $E_4$, respectively. Hence, $E_S$ for loop I equals $E_1 - E_2$ ($E_S = E_1 - E_2$), and that for Loop II equals $E_3 - E_4(E_S = E_3 - E_4)$.

Figure 3 plots curves of $E_i$ and $E_S$ vs. polymer dose. All the $E_i$ values decrease as $i$ increases ($E_1 > E_2 > E_3 > E_4$), indicating that the spin-on action in Loop I deteriorates most of the network structures of the sludge flocs, while further continuous shearing destroys the remaindering bonds. Physically, $E_S$ can be regarded as the plastic part of the strength of the flocculated network. Consider first Loop I. As Fig. 3 shows, $E_S$ for sludge #1 increases almost linearly with polymer dose, from approximately 58 kJ/kg for the original sludge to about 120 kJ/kg at a dose of 80 ppm. For sample #2, the $E_S$ value increases gradually with polymer dose, from 55 kJ/kg for the original sludge to around 73 J/kg at a dose of 60 ppm (optimal dose). This value falls to

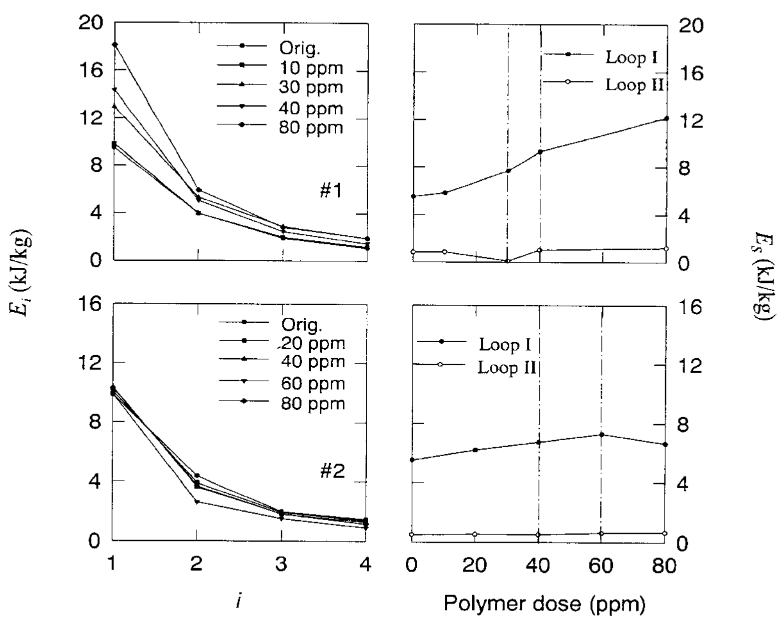



***Figure 3.*** The $E_i$ versus $i$ plot (left) and the $E_S$ versus polymer dose plot (right). (a) sample #1; (b) sample #2.

about 66 kJ/kg at a dose of 80 ppm. Restated, the cationic polyelectrolyte flocculation considerably affects the structure's strength in sample #1, but only slightly influences sludge #2.

For Loop II, however, most $E_S$ range 8 to 11 kJ/kg for sample #1 and that for sample #2 of 5–6 kJ/kg. Hence, the residual strength of sample #1 after shearing still exceeds that of sample #2. The next section focuses on the Loop I shearing during which most of the network structure has been broken down.

## Floc–Floc Contact Strength

The "floc–floc contact strength" ($E_C$) is defined by assuming that the breakage of inter-floc, rather than intra-floc, bonds has occurred and consumed most of the shearing energy in the rheometer. This strength is superficial and not present in the real binding between two flocs in contact. However, the effects of flocculation can be compared between the original and flocculated sludge flocs. This argument assumes an intact flocs structure after shearing. Figure 4 displays microphotographs of sample #2 before and after shearing. No significant structural changes are noted after shearing. Figure 5 is a log–log plot of scattered light intensity ($I$) vs. scattered angle function ($Q$) for sample #2. Table 1 specifies the fractal dimensions estimated from regressing the linear region in Fig. 5. A higher fractal dimension denotes a more compact floc structure. The fractal dimension of original sludge decreases as polymer is added to the optimal dose, and then slightly recovers with overdosing. The samples after Loops I and II shearing have a fractal dimension similar to those before shearing under underdosing or in the optimum regime. This observation, together with microscopic examination, reveals that the structure of well-flocculated flocs remains almost intact under shearing. However, shearing does impact the floc structure in the overdosed regime. The overdosed flocs are large and, thus, exhibit relatively weak intra-floc strength. They are considerably compacted by hydrodynamic shearing. The subsequent discussion is limited to flocs in the underdosed regime.

The original sludge sample #1 has a solid weight percentage of 0.37% and a mean floc size of 61 μm. The sediment of the sludge is the testing sample, in which all sludge flocs are in physical contact with each other in mechanical equilibrium. The flocs are randomly packed in the sludge sediment, and occupy a volume ratio of between 15 and 30% ($\phi_S$), if much water is included in the sludge flocs. Consequently, 1 liter of sediment includes $1.3–2.5 \times 10^9$ ($N$) flocs, if they are assumed to be spherical. The corresponding floc size and number of flocs for sludge #2

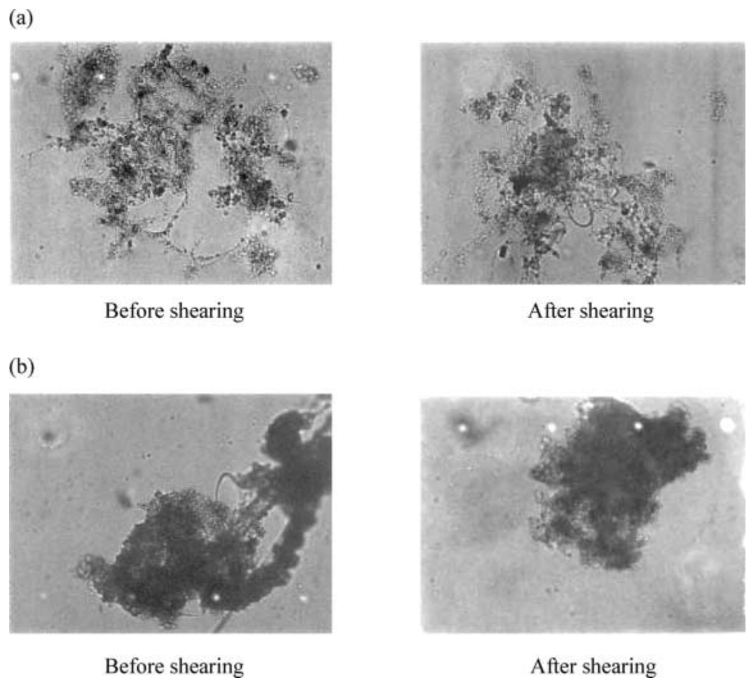



***Figure 4.*** Microphotographs for the sludge flocs before and after shearing. Sample #2. 400 × . (a) Original sludge. (b) Sludge conditioned with 40-ppm polymer.

are 100 μm and $2.9–5.8 \times 10^8$ per liter of sediment, respectively. Each floc in the sludge matrix is assumed to be in contact with $n$ neighboring flocs, where $n$ is the contact number. The sludge network thus effectively includes $nN/2$ contacts. The $E_S$ value for sample #1 is 5.8 kJ/kg (Loop I), yielding a contact strength for a specific floc with its neighbors ($nE_C/2$) of between 1.7 and $3.3 \times 10^{-8}$ J. The corresponding value for sample #2 is between 5.7 and $11.5 \times 10^{-8}$ J. Apparently, sample #2 has a much stronger floc–floc interaction than sample #1.

The presence of flocculating polymer considerably increases the floc–floc strength in sample #1. For example, $E_S$ for the 40-ppm sample is increased by 40 kJ/kg, as the floc diameter increases from 61 to 130 μm, equivalent to a contact strength between 6.8 and $13 \times 10^{-8}$ J, an increase of up to seven times. However, adding 40 ppm of polymer to sample #2 increased the $E_S$ value by only 20%. Considering the change in floc size (hence the floc number), the corresponding floc–floc strength becomes 15.4 to $31 \times 10^{-8}$ J for a 40-ppm

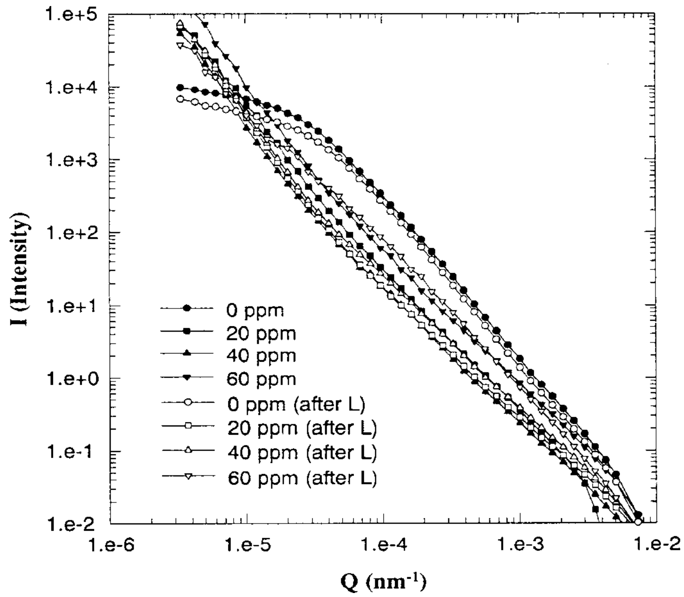



***Figure 5.*** The log($I$) versus log($Q$) plot for small-angle light scattering tests. Sample #2. After L: after shearing.

dose—a 170% increase. The flocculation efficiency of sample #1 is much higher than that of sample #2.

## Network Strength and Sludge Conditioning

The network strength, mentioned previously, represents the plastic part of the flocculated network strength. The $E_S$ value increases with polymer

***Table 1.*** Fractal dimensions of sludge flocs before and after shearing.

| Sample | Before shearing | After shearing |
|---|---|---|
| Original | 2.25 | 2.27 |
| 20 ppm | 1.95 | 1.84 |
| 40 ppm | 1.79 | 1.82 |
| 60 ppm | 1.84 | 2.24 |

dose near the optimal regime, as Yen et al. asserted. Although $E_S$ for the original sample, #1, is close to that for sample #2, the samples' CST values (or the modified CST, considering the solids contents) are very different. When polymer is present, $E_S$ of sample #1 increases much more quickly than that of sample #2. However, the corresponding CST value drops less for the former than for the latter. Consequently, $E_S$ cannot be used as a single index to compare the ease of dewatering of various batches of sludge. Other parameters, like the amount of fines or the change in supernatant viscosity, may be relevant. For samples collected within a finite period for a specific sludge, $E_S$ can be used for on-line monitoring of the flocculation efficiency of sludge, yielding information pertaining to conditioner access and control.



## CONCLUSION

This study estimated the binding strength of network flocs of waste-activated sludge, original and flocculated. The binding strength was derived from rheograms determined from rheological tests. Two sludge samples, #1 and #2, from a wastewater treatment plant were tested. The binding strength of sample #1 was between 1.7 and $3.3 \times 10^{-8}$ J, and that of sample #2 was between 5.7 and $11.5 \times 10^{-8}$ J. The binding strength increased with polymer dose, indicating the structure's increased resistance to hydrodynamic shear. For example, $E_S$ of a 40-ppm sample, #1, was increased by a factor of seven. However, adding 40 ppm of polymer to sample #2 increased $E_S$ by only 20%. Although $E_S$ cannot be used as a single index to compare the ease of dewatering of various batches of sludge, it provides on-line information on flocculation status of sludge, and thus can help to assess and control conditioner dose of samples collected from a given site within a finite period.

## ACKNOWLEDGMENT

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