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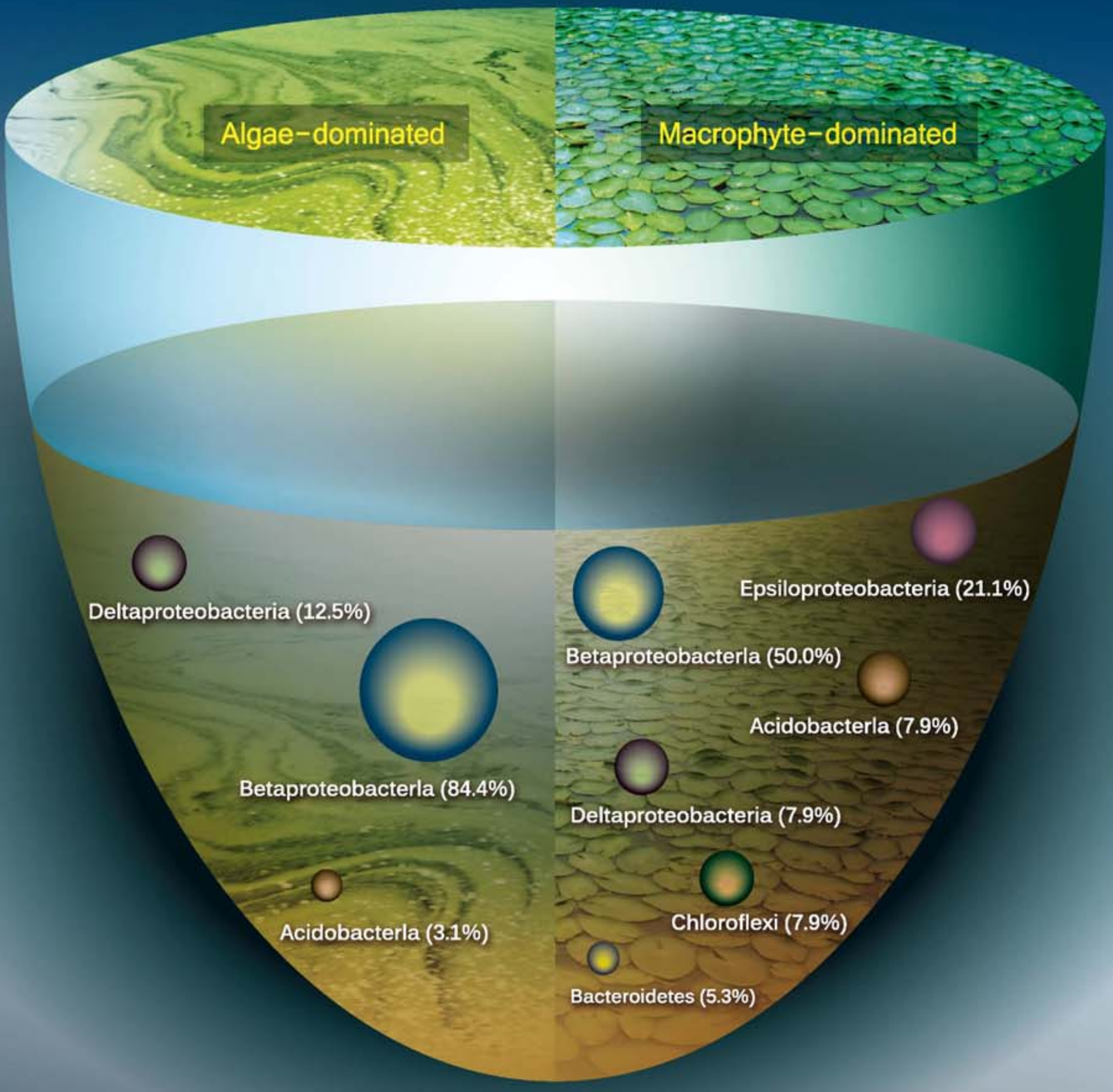

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Differences in rheological and fractal properties of conditioned and raw sewage sludge

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Abstract

Rheological tests for raw and conditioned activated sludge (AS) or anaerobic digested sludge (ADS) show that power-law relationships can be used to describe the evolution of several rheological parameters, i.e., limiting viscosity (η_∞), yield stress (τ_y), cohesion energy of the sludge network (E_c), and storage modulus (G'), with total suspended solid (TSS) content in raw and conditioned sludge. A gel-like structure that behaves similar to weak-link flocs/aggregates was observed in AS and ADS. As derived from the double-logarithmic plots of G'-TSS content, the mass fractal dimensions of the raw and conditioned AS or ADS flocs/aggregates were 2.70 and 2.53 or 2.85 and 2.79, respectively. The rheological tests also indicate that both polymer conditioning and increased TSS content led to improved elastic behavior, cohesion energy, and yield stress of the sludge network, as well as expanded the corresponding linear viscoelastic range. The porosity of AS or ADS flocs/aggregates will be improved by polymer conditioning.

Key words: sewage sludge conditioning; rheology; power law; fractal; total suspended solid

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Introduction

The activated sludge (AS) process is an important biological treatment process in most wastewater treatment plants (WWTPs). A conventional AS WWTP produces excess biological sludge, which is an unstable solid suspension given its high organic solid content. Obtaining a product that is easier to handle and dispose of necessitates the stabilization of excess biological sludge by anaerobic digestion, thereby converting it into anaerobic digested sludge (ADS).

Many studies used rheological methods (Chen et al., 2005; Dentel et al., 2005) and indicated that AS and ADS suspensions are well-known non-Newtonian fluids with a gel-like structure (Poxon, 1996; Mezger, 2002; Ayol et al., 2005; Dursun, 2007). Understanding the rheological properties of sewage sludge is important for its management, possibly yielding design parameters that may be used in transporting, storing, landfilling, and spreading operations, as well as control parameters that may be applied in many treatments such as stabilization and dewatering (Chen et al., 2005; Dentel et al., 2005).

Rheology describes the flow and deformation of materials under stress. Corresponding rheological measurements can reveal complementary information about the internal structure of a suspension. In general, flow measurements are taken to determine the viscous and viscoplastic properties of sludge, as well as corresponding rheological parameters such as limiting viscosity (η_∞), yield stress (τ_y), cohesion energy of ADS networks (E_c), shear modulus (G), and critical strain (γ_c). An exponential or power law has been observed in the evolution of these parameters with solid concentrations in sludge (Seyssiecq et al., 2003; Tixier et al., 2003; Khongnakorn et al., 2010). As an alternative, dynamic measurements enable access to the viscoplastic and viscoelastic components of sludge (Seyssiecq et al., 2003; Dentel et al., 2005; Mori et al., 2006; Dursun, 2007); such measurements can also help derive parameters such as τ_y, E_c, and γ_c for the linear viscoelastic range and storage modulus (G'). However, only a few studies have discussed the effect of solid concentrations in sludge on the aforementioned dynamic rheological parameters (Mori et al., 2006).

Numerous studies on the treatment and disposal of biosolids have confirmed that polymer conditioning can change the microstructure, incorporated water content, and other operational properties of sludge aggregates (Langer et al., 1994; Dentel et al., 2005; Ayol et al., 2005; Dursun, 2007). When AS (excess biological sludge) is stabilized

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and converted into ADS, unstable heterotrophic bacteria are reduced by biological assimilation, which leads to low levels of organics and incorporated water contained in ADS, and the rheological and dewatering properties of the sludge are modified (Monteiro, 1997). Furthermore, these two types of sludge present discrepancies in terms of conditioning with polymers as well.

Many flocs/aggregates relevant to engineering, such as those formed during wastewater treatment (Li and Ganczarczyk,1990; Chu and Lee, 2004), have generally been characterized as highly porous fractal-like forms of many primary particles. When a raw sludge is conditioned with a polymer, the aggregates packed by the aforementioned flocs also present a fractal structure (Wang and Dentel, 2010). According to Zhong et al. (2004), the fractal dimension is a quantitative parameter that indicates the compactness of the flocs/aggregates comprising the gel-like matrix. Recent studies have indicated that colloidal and polymer gels are characterized by viscoelastic behavior and aggregation formation. The empirical power-law dependence of the storage modulus on the (solid) volume fraction of primary particles was established, and a subsequent gel mass fractal dimension was calculated from a log-log plot (Shih et al., 1990; Vreeker et al., 1992; Larson, 1999; Zhong et al., 2004; Tang et al., 2008). Although raw and conditioned AS or ADS are recognized as a collection of closely packed fractal flocs or aggregates throughout the gel matrix, no study has examined that the fractal scaling behaviors of the storage modulus at the limit of linearity with respect to the solids contents. Thus, determining whether or not a fractal relationship exists in raw or conditioned AS and ADS matrices is of considerable interest.

This study aims to explore the differences in the rheological and fractal properties of raw or conditioned AS and ADS suspensions. Rheological tests for the raw and conditioned AS/ADS with different total suspended solid (TSS) contents under controlled shear rate and dynamic modes were conducted to determine the corresponding parameters. The inherent link between specific rheological parameters and corresponding gel mass fractal dimensions was analyzed on the basis of the power-law dependence of the solid content. The obtained results will provide further information on the AS/ADS microstructure and polymer conditioning mechanism, as well as on practical dewatering applications.

1 Materials and methods

1.1 Raw sewage sludge

The raw AS and ADS were collected from a WWTP in Beijing, China. The WWTP handles 6.0×10^5 m^3 of wastewater per day using an anaerobic-anoxic-oxic process. AS-1 and AS-2 were collected from the recycled sludge stream at two different times, while ADS was obtained from the anaerobic digestion unit. The samples were immediately transferred to our laboratory at Beijing Forestry University and stored at 4°C. Prior to the experiments, the sludge samples were warmed to 25°C. All measurements were performed within 5 days from the date of sampling. The TSS in the sludge sample was determined from the weight loss of the filtered sludge samples that were dried at 105°C over 24 hr (APHA, 1995). To estimate sludge filterability, a Triton 304B instrument was used for capillary suction time measurements. The characteristics of the AS/ADS samples are shown in **Table 1**.

Table 1 Characterization of sewage sludge samples

Sewage sludge sample	TSS (g/L)	Incorporated water ratio	pH	Capillary suction time (sec)
AS-1	7.19 ± 0.094	99.28% ± 0.0084%	7.16	49.77 ± 1.21
AS-2	7.39 ± 0.036	99.27% ± 0.0067%	7.12	34.57 ± 1.04
ADS	28.84 ± 1.32	97.08% ± 0.0039%	7.10	580.30 ± 13.50

TSS: total suspended solid.

1.2 Sewage sludge conditioning

Cationic organic polymer, a polyacrylamide known as CZ8698, was used as a conditioner. The conditioning procedure and device are the same as that described by Dong et al. (2011). On the basis of capillary suction time evolution with CZ8698 dose, the optimum dosages for AS-1, AS-2, and ADS conditioning with polymer CZ8698 were determined. The optimum CZ8698 dosages were observed at 1.39, 1.35, and 17.33 kg/ton dry sludge, with corresponding capillary suction time values of 11.10 ± 0.35, 10.57 ± 0.35, and 9.90 ± 0.63 sec, respectively. All the rheological tests were repeated for the raw and conditioned sewage sludge at optimum polymer dosages.

1.3 Rheological measurements

Rheological testing was performed using a Physica MCR 300 rheometer (Anton Paar, Austria) with the temperature maintained at 25°C by a Peltier control. A PP 50 plate and plate sensor with a 49.94 mm diameter and 2.0 mm gap was used. Two rheological test modes were employed to determine the parameters that represent the viscoplastic and viscoelastic properties of the raw and conditioned AS/ADS at the optimum polymer dosage.

For the first rheological testing mode (controlled shear rate), a continuous shear rate (γ_{dot}) ramp was applied from 0.1 to 1000 sec^{-1} in a logarithmic manner. A constant γ_{dot} of 1000 sec^{-1} was then held for 30 sec. Subsequently, the γ_{dot} was decreased in a logarithmic manner from 1000 sec^{-1} back to 0.1 sec^{-1}. The rheograms of the shear stress (τ)–γ_{dot} for the raw sewage sludge samples were recorded and analyzed. The constant value of apparent viscosity (a quotient of τ and γ_{dot}) at infinite γ_{dot} can be determined using the rheograms and be considered as the limiting viscosity η_∞ (Midoux, 1988; Steffe, 1996; Tixier et al., 2003; Mu and Yu, 2006; Mori et al., 2006; Pevere et al., 2006; Khongnakorn et al., 2010). η_∞ represents the sludge matrix viscosity that corresponds to the maximum dispersion of flocs under the influence of γ_{dot} (Tixier et al., 2003); it is correlated with the optimal opening and orientation of sludge in the flow direction (Yen et al., 2002).

The second rheological test mode is commonly called the strain amplitude sweep test (Wang et al., 2011). This test was conducted to determine the linear viscoelastic range. The flow curves of the moduli (storage modulus G', loss modulus G'', and complex modulus G^*) as a function of the strain on the logarithmic coordinates show that the rheological properties (including the above-mentioned moduli) were independent of strain up to a critical strain level γ_c. Beyond γ_c, G^* or G' declined with the loss of structural integrity of the material (Larson, 1999; Dentel et al., 2005). Nonlinear behavior was observed in the material, and the transition can be used to determine γ_c. This determination is primarily based on the data collected before yield stress τ_y is reached, in contrast to the procedure done in a traditional steady shear test. The dynamic mechanical test is advantageous because it is simpler, model-independent, and leaves the sample more intact (Larson, 1999; Mezger, 2000; Dentel et al., 2005). Given the values of τ_y and γ_c determined from the aforementioned strain amplitude sweep test, the corresponding value of E_c is equal to half the product of τ_y and γ_c (Mori et al., 2006; Khongnakorn et al., 2010).

Each experiment was performed in triplicate to ensure the consistency of results.

1.4 Scaling theory and determination of fractal dimensions in rheological mode

Hiemenz and Rajagopalan (1997) and Sanin (2002) showed that the contribution to non-Newtonian behavior should originate from the colloidal properties of solids more than from the molecular properties of a suspension. According to the model of Shih et al. (1990), a colloidal gel comprises closely packed fractal flocs/aggregates. The relationship between the rheological properties of colloid gels and particle concentration (Φ) can be described by Eqs. (1) to (4).

In the strong-link regime:

$$K \propto \Phi^{(3+x)/(3-D_f)} \tag{1}$$

$$\gamma_c \propto \Phi^{-(1+x)/(3-D_f)} \tag{2}$$

In the weak-link regime:

$$K \propto \Phi^{(d-2)/(3-D_f)} \tag{3}$$

$$\gamma_c \propto \Phi^{1/(3-D_f)} \tag{4}$$

where, K is the elastic constant of G' (Shih et al., 1990; Zhong et al., 2004), d is the Euclidean dimension, D_f denotes the gel mass fractal dimension of flocs/aggregates, and x represents the backbone fractal dimension of flocs/aggregates, which varies from 1.0 to 1.3 as Φ decreases (Shih et al., 1990; Vreeker et al., 1992). The D_f values of the AS/ADS flocs/aggregates were calculated by regression analysis of the logarithm of K or γ_c versus the logarithm of the TSS content of AS/ADS.

G' is the deformation energy stored in the sample during the shear process. It represents the elastic behavior of the sample. The value of G' can be calculated according to Eq. (5):

$$G' = G^* \times \cos\delta \tag{5}$$

where, G^* is defined as τ divided by shear strain (γ). The complex modulus can be divided into two components: G' and G''. δ originates from loss factor (or damping factor) tan δ, which is the quotient of G'' and G'. In addition, η_∞ has also been regarded as K by Mu and Yu (2006) for granular sludge in upflow anaerobic sludge blanket reactor and Dong et al. (2011) for water treatment residuals.

The D_f of AS/ADS can be calculated in accordance with the fractal scaling relationship between the parameters (η_∞, G' and γ_c) and Φ. In addition, both TSS and solid volume contents can be used in scaling equations.

2 Results and discussion

2.1 Differences in the rheological properties of raw and conditioned AS/ADS

2.1.1 Controlled shear rate testing of raw and conditioned AS/ADS

Figure 1 presents the typical rheograms of the raw and conditioned AS-1 and ADS at specific TSS contents. The rheograms of the raw and conditioned AS-1 or ADS at other TSS contents exhibited similar shapes. As illustrated in **Fig. 1c**, the τ values increased with increasing γ_{dot}, and vice versa. For the conditioned ADS (**Fig. 1d**), τ sharply decreased when γ_{dot} was increased to approximately 500 sec^{-1}. After this, a gradual increasing trend was observed during subsequent increases in γ_{dot}. Even though differences occurred, the shear stress values were higher on the ascending path than on the descending path in these rheograms, demonstrating that the raw and conditioned AS-1 or ADS have distinct thixotropic (shear thinning) properties (Larson, 1999; Mezger, 2000; Seyssiecq et al., 2003).

The thixotropic properties of the raw and conditioned AS-1, as well as raw ADS, were also demonstrated by the

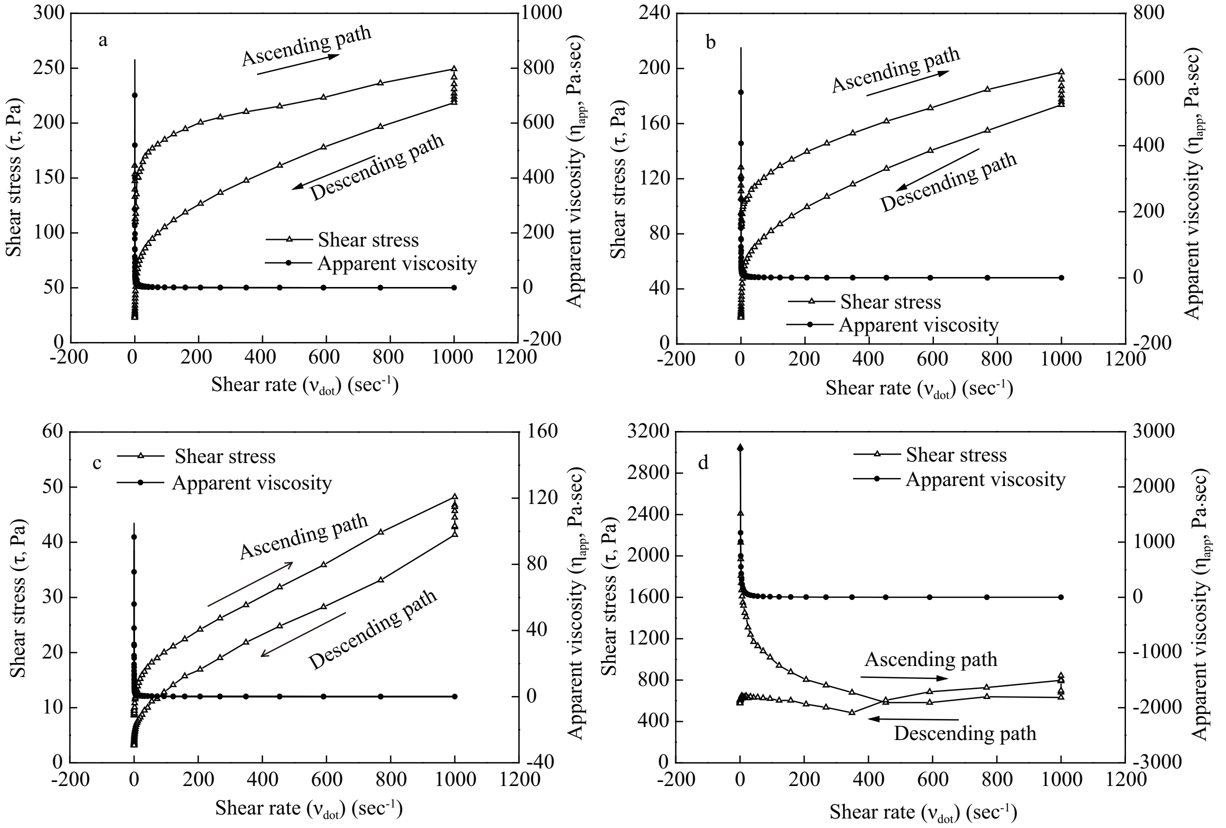

Fig. 1 Typical flow curves at 298 K. (a) raw AS, total suspended solid (TSS) = 57.52 g/L; (b) conditioned AS, TSS = 59.92 g/L; (c) raw ADS, TSS = 57.69 g/L; (d) conditioned ADS, TSS = 57.69 g/L.

evolution of their own apparent viscosities η_{app} with shear rate. η_{app} sharply decreased when shear rate increased from 0.1 to 55.3 sec^{-1}, and slowly decreased to a constant value at higher shear rates. The η_{app} evolution in **Fig. 1a–c** shows that the limiting viscosity (η_∞) values of these types of sludge were derived by extrapolation at a very high shear rate using a rheological model of Sisko (Mori et al., 2006), which includes the parameter η_∞ (Mori et al., 2006). The data matrix for η_∞ calculations was the array of shear stress-shear rate greater than 300 sec^{-1}.

For the conditioned ADS (**Fig. 1d**), the rapid decrease in η_{app} was observed when γ_{dot} was increased to 72 sec^{-1}. A constant η_{app} value did not occur even at a γ_{dot} value approaching 1000 sec^{-1}.

Figure 2 shows the changes in the η_∞ values of the raw and conditioned AS-1 and ADS with varying TSS contents. Prior to the controlled shear rate test, the sludge samples were condensed by centrifugation and their TSS contents were adjusted as 23 to 65 g/L for AS-1, and 37 to 87 g/L for ADS with their own sludge suspension supernatants. As shown in **Fig. 2**, η_∞ increased with rising TSS content in the raw and conditioned AS-1 and raw ADS. In addition, an empirical exponential-law relationship was observed between these two parameters via the regression of these plots. The values of the coefficients of determination (R^2) of the regression equations were greater than 0.98, suggesting that the regression equations adequately describe the abovementioned relationship. In

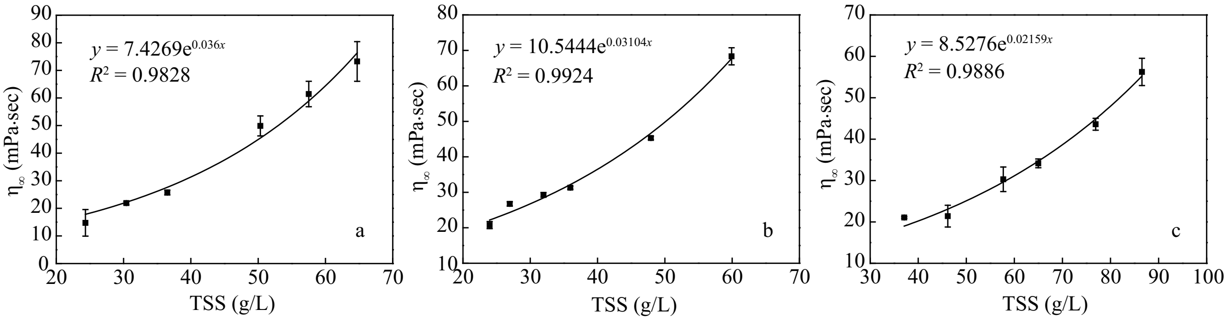

Fig. 2 Limiting viscosities of raw AS-1 (a), conditioned AS-1 (b) and raw ADS (c) as a function of TSS.

other studies, exponential-law relationships were observed in activated sludge with low TSS contents (Tixier et al., 2003) and granular sludge in upflow anaerobic sludge blanket reactor (Mu and Yu, 2006). In general, a regression law represents the manner by which particle-particle interactions influence sludge rheology (Forster, 2002). This phenomenon implies that CZ8698 conditioning changes the effect of particle-particle interactions on the rheology of ADS.

Compared with the η_∞ values of AS-1 at the same TSS content (**Fig. 2**), the values of the conditioned sludge were greater than those of the raw sludge. This finding implies that the conditioned AS-1 requires a considerably higher τ to force optimal opening and orientation in the flow direction because conditioning can strengthen the resistance of sewage sludge to τ. In addition, the η_∞ values of the raw AS-1 were higher than those of the raw ADS.

According to Section 1.3, AS-1 or ADS can change into a continuous fluid with assimilated Newtonian behavior (Yen et al., 2002; Khongnakorn et al., 2010) when a specific high γ_{dot} is employed for η_∞ determination. In the Newtonian region of these sludge types, η_∞ can be regarded as the resistance to shear when most networks in the sludge body are destroyed, the TSS content has an important effect on the η_∞ values, whereas the corresponding interactions between the flocs/aggregates do not (Yen et al., 2002; Khongnakorn et al., 2010). On the basis of the aforementioned situations, it can be inferred that η_∞ reflects the history of the elastic property of sludge. The difference in η_∞ values between the raw and conditioned AS-1 or ADS can be ascribed to their individual behaviors, and the conditioning effect of the CZ8698 polymer can lead to a stronger historical elasticity.

2.1.2 Dynamic oscillatory testing for raw and conditioned AS/ADS

In dynamic oscillatory testing, small strain amplitude sinusoidal variations are advantageous in distinguishing linear from differential effects in a manner that is readily separable (Dentel et al., 2005). For the raw and conditioned AS-2, the TSS content variations for strain amplitude sweep testing were 22.17 to 66.53 g/L and 24.63 to 61.58 g/L, respectively. For the raw and conditioned ADS, the TSS content variations were 33.85 to 84.62 g/L and 37.46 to 84.29 g/L, respectively.

The results of the strain amplitude sweep testing for the raw and conditioned AS-2 or ADS show that storage modulus G' was considerably higher than loss modulus G'' when strain amplitude increased from 0.01% to 10% at a constant frequency f of 1 Hz. In general, these two parameters characterized the elastic and viscous properties, respectively. Therefore, both the raw and conditioned AS or ADS showed much stronger elastic than viscous behaviors, although this difference gradually decreased when the strain amplitude increased beyond the critical value.

In the moduli versus amplitude flow curves, an almost strain-independent G' value was observed with a constant plateau of up to a critical strain value (γ_c) (Wang et al., 2011). This G'-strain curve interval can be taken as the linear viscoelastic range. The corresponding τ_y and E_c were then determined according to the previously described methods in Section 1.3. **Figure 3** illustrates the changes in G', τ_y, E_c, and γ_c with increasing TSS content for the raw and conditioned AS-2 and ADS.

In both AS-2 samples (**Fig. 3a** and **b**), G', τ_y, and E_c showed a general and gradual increase with rising TSS content. Higher and rapidly increasing regions for these parameters were observed at TSS concentrations higher than 50 g/L. Generally, γ_c also increased with rising TSS content. A fluctuation region of γ_c was found within a TSS content of 29.57 to 44.35 g/L.

For the raw ADS (**Fig. 3c**), τ_y and G' showed slightly rapid increasing with increasing TSS contents from 45.13 to 84.62 g/L, but slightly decreasing as the TSS content rose from 33.85 to 45.13 g/L. E_c presented a general and gradual increase with rising TSS content. The γ_c values fluctuated as the TSS content increased within the test range. **Figure 3d** indicates that G', τ_y, E_c and γ_c generally increased as the TSS content rose to 74.92 g/L, and then decreased at a higher TSS content of 84.29 g/L.

As indicated by Khongnakorn et al. (2010), increased TSS content favors interaction among biosolids. This phenomenon can generate a more rigid structure of the sludge network and enhance sludge cohesion. For the raw AS-2 or ADS, therefore, both the elasticity and cohesion of the sludge network rose with the increasing of TSS content in the aforementioned ranges. The τ_y and γ_c of the samples also increased in most of the cases. These results show that for both sewage sludge samples, a higher τ is generally necessary to break the network with higher TSS contents.

Compared with the raw AS-2 or ADS, the conditioned AS-2 or ADS was characterized by higher values of the four rheological parameters (G', τ_y, E_c and γ_c) at most of the TSS contents. These results indicate that polymer conditioning improves the elastic behavior, cohesion energy, and yield stress of the AS or ADS network. The corresponding linear viscoelastic range also expanded at a higher critical strain.

In addition, the four rheological parameters of the raw AS-2 at the tested TSS contents were much higher than those of the raw ADS. At most of the tested TSS contents, the G', τ_y and E_c of the conditioned ADS showed higher values than did those of the conditioned AS-2. This result can be attributed to the differences in the sludge components and the properties of the suspended flocs in the sludge matrix. In comparison with raw AS, the raw ADS flocs/aggregates presented lower level of organics, lower incorporated water content, greater size, more compact structure and higher zeta potentials (Li et al., 2012). Furthermore, the optimum polymer dosage had an important effect on the differences of above rheological

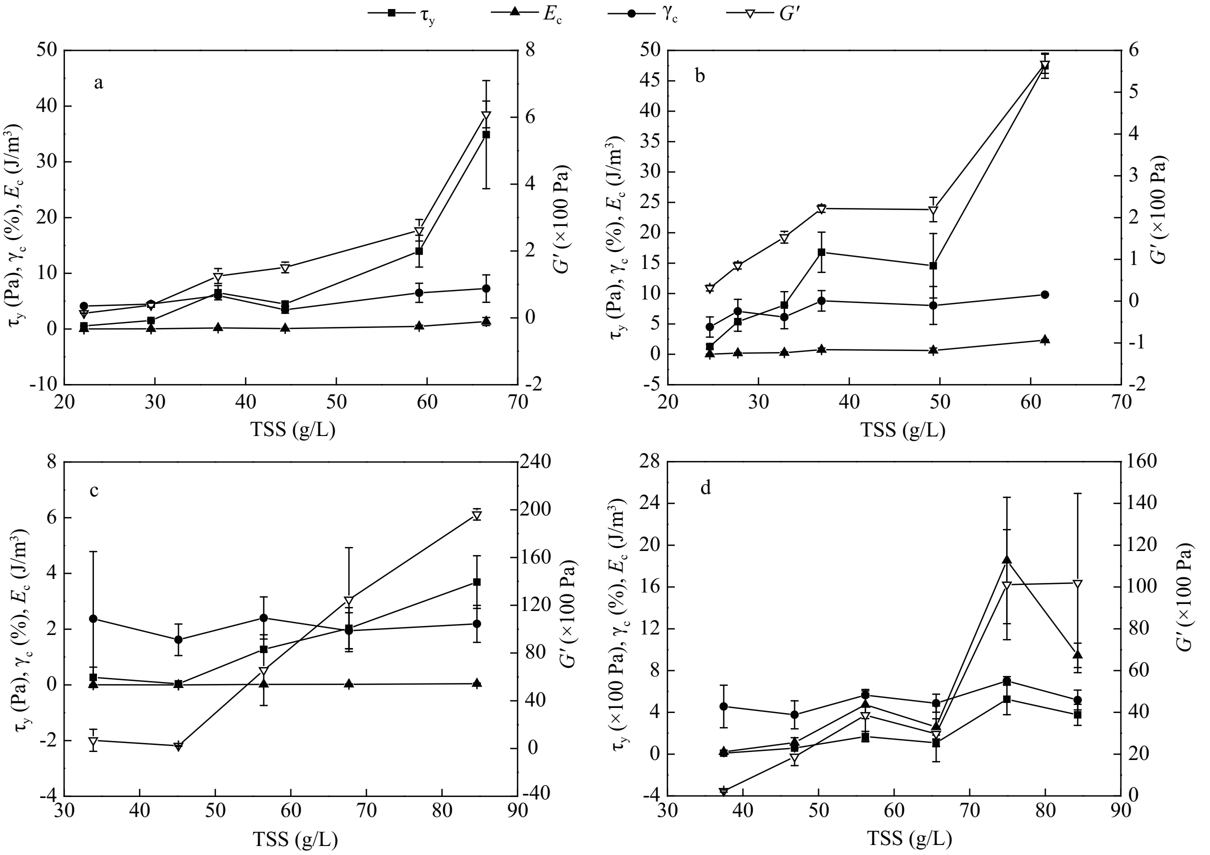

Fig. 3 G', τ_y, E_c, and γ_c of raw AS-2 (a), conditioned AS-2 (b), raw ADS (c), and conditioned ADS (d) as a function of TSS in the strain amplitude sweep testing mode.

parameters between the conditioned AS and ADS as well.

2.2 Fractal characterization of raw and conditioned AS/ADS

2.2.1 Power-law relationship between rheological parameters and TSS content

Power-law equations were used to describe the relationship between the rheological parameters and TSS content through regression of the data matrix in **Figs. 2** and **3**. **Tables 2** and **3** present the regression results. As indicated in **Table 2**, good linear relationships between $\log\eta_\infty$ and log(TSS) were observed in the raw and conditioned AS-1 samples with R^2 values higher than 0.95. In **Table 3**, G' and γ_c, τ_y and E_c also correlated well with TSS content in a power-law manner for both the raw and conditioned AS-2. τ_y and E_c were also directly proportional to each other (Roche et al., 1996; Mori et al., 2006).

Table 2 Power-law regression equations for AS-1/ADS samples as determined by the CRS tests ($P < 0.01$)

Sewage sludge sample	Regression equations (η_∞)	R^2
Raw AS-1	$\log\eta_\infty = 1.6076\log(\text{TSS}) - 1.0634$	0.9699
Conditioned AS-1	$\log\eta_\infty = 1.1024\log(\text{TSS}) - 0.1945$	0.9517
Raw ADS	$\log\eta_\infty = 0.9875\log(\text{TSS}) - 0.2278$	0.9823

Table 2 shows that for the raw ADS, the η_∞ values depended on the TSS content through a power-law relationship, with R^2 values of 0.9823. **Table 3** indicates that a good power-law dependence of G' on TSS content was observed in raw and conditioned ADS samples, as evidenced by the regression coefficients higher than 0.90. The relationship between τ_y or E_c and the TSS content of the conditioned ADS can be described by power-law equations with regression coefficients higher than 0.70. τ_y and E_c were directly proportional to each other (Roche et al., 1996; Mori et al., 2006). However, a poor power-law relationship was observed between the other dynamic rheological parameters and TSS content.

2.2.2 Determination of the mass fractal dimensions of raw and conditioned AS/ADS

Table 4 provides the D_f values of the raw and conditioned AS, raw ADS, calculated from the evolution of the aforementioned rheological parameters with TSS content. The D_f values of the raw AS-1 were 0.33 ($x = 1.3$) and 2.38, as calculated using Eqs. (1) and (3), respectively. The structure of the raw AS-1 is dominated by a weak-link region, and the strength of the links between the flocs of raw AS biosolids were weaker than those within the flocs (Shih, 1990). This result is supported by the very low D_f value (< 2.0), calculated using Eq. (1); this value

Table 3 Power-law regression equations for AS-2/ADS samples as determined by the strain amplitude sweep test ($R^2 > 0.70$, $P < 0.05$)

Sewage sludge sample	G'		τ_y		E_c		γ_c	
	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
Raw AS-2	$\log G' = 3.3870\log(\mathrm{TSS}) - 3.3709$	0.9942	$\log\tau_y = 3.2916\log(\mathrm{TSS}) - 4.6821$	0.9734	$\log E_c = 3.9119\log(\mathrm{TSS}) - 7.2097$	0.9404	$\log\gamma_c = 0.5656\log(\mathrm{TSS}) - 0.1479$	0.7635
Conditioned AS-2	$\log G' = 2.1385\log(\mathrm{TSS}) - 1.0640$	0.9245	$\log\tau_y = 3.0480\log(\mathrm{TSS}) - 3.7746$	0.9322	$\log E_c = 3.4669\log(\mathrm{TSS}) - 5.8355$	0.9203	$\log\gamma_c = 0.5204\log(\mathrm{TSS}) + 0.06053$	0.8040
Raw ADS	$\log G' = 6.7011\log(\mathrm{TSS}) - 10.6218$	0.9621	$\log\tau_y = 6.0418\log(\mathrm{TSS}) - 10.5913$	0.5656	$\log E_c = 5.6781\log(\mathrm{TSS}) - 12.0325$	0.5783	$\log\gamma_c = 0.2328\log(\mathrm{TSS}) - 0.1050$	0.1614
Conditioned ADS	$\log G' = 4.8339\log(\mathrm{TSS}) - 5.0556$	0.9015	$\log\tau_y = 3.9390\log(\mathrm{TSS}) - 4.8431$	0.8762	$\log E_c = 3.5209\log(\mathrm{TSS}) - 5.7553$	0.7367	$\log\gamma_c = 0.5786\log(\mathrm{TSS}) - 0.2624$	0.5528

Table 4 Mass fractal dimensions of raw and conditioned AS/ADS as determined by rheological tests

Sewage sludge sample	D_f ($\log\eta_\infty$-log(TSS))		D_f ($\log G'$-log(TSS))		D_f ($\log\gamma_c$–log(TSS))	
	Weak-link	Strong-link at $x = 1.3$	Weak-link	Strong-link at $x = 1.3$	Weak-link	Strong-link at $x = 1.3$
Raw AS	2.38	0.33	2.70	1.73	1.23	–
Conditioned AS	2.09	–0.90	2.53	0.99	–1.08	–
Raw ADS	1.99	–	2.85	2.34	–	–
Conditioned ADS	–	–	2.79	2.11	–	–

–: no calculated values.

was unfavorable to the three-dimensional structure of the flocs. For the conditioned AS-1, the D_f values were –0.90 ($x = 1.3$) and 2.09, as calculated using Eqs. (1) and (3), respectively. These findings imply that the conditioned AS-1 also behaves similar to a weak-link aggregate (Shih, 1990).

For the raw and conditioned AS-2, the positive slope of the straight line of the $\log\gamma_c$–log(TSS) relationship indicates that the raw and conditioned AS-2 behave similar to weak-link flocs/aggregates. According to Eq. (3), the D_f values of the raw and conditioned AS-2 derived from $\log G'$–log(TSS) relationships were 2.70 and 2.53, respectively. Even though Eq. (1) can also be used for D_f calculation, the corresponding D_f values were less than 2.0. This result also confirms that the raw and conditioned AS-2 present weak-link behaviors.

The D_f value of the conditioned AS aggregates was lower than that of the raw AS flocs, possibly indicating that the former has a less compact and less dense structure than does the latter. As previously described, the flocs of the raw AS were formed via the adhesion-bridging effect of EPS on inorganic and organic matter, as well as microorganisms in the sludge, by contrast, new flocculated aggregates were produced via the adhesion-bridging effect of both polymer and EPS when the raw AS was conditioned with polymer CZ8698. In the model of Shih et al. (1990), the mass fractal dimension was used to describe the structural heterogeneity of the flocs/aggregates. Therefore, the lower D_f of the conditioned AS aggregates (compared with that of the raw AS flocs) may indicate that polymer conditioning improves the porosity of conditioned AS aggregates, which favors the filterability and dewaterability of conditioned AS (Chu et al., 2004).

Table 4 shows that the D_f value of the raw ADS was negative when calculated using Eq. (1) or 1.99 when calculated with Eq. (3). The structure of the raw ADS is dominated by a weak-link region. The D_f value of the raw ADS was slightly less than 2.0, implying that the raw ADS under infinite γ_{dot} shows a nearly planar structure.

According to the data matrix obtained from dynamic rheological testing, the D_f values calculated using Eqs. (1) and (3) for the raw ADS were 2.34 ($x = 1.3$) and 2.85, respectively, while those for the conditioned ADS were 2.11 ($x = 1.3$) and 2.79, respectively. Although D_f values based on the $\log\gamma_c$–log(TSS) regression results were not calculated using Eqs. (2) or (4), the positive slopes of the straight lines of the $\log\gamma_c$–log(TSS) relationship indicate that the raw and conditioned ADS behave similar to weak-link flocs/aggregates. In addition, the D_f value of the conditioned ADS was slightly lower than that of the raw ADS. These results demonstrate that polymer conditioning leads to a slight increase of the porosity in the flocs/aggregates of conditioned ADS.

Although power-law relationships were observed between τ_y or E_c and TSS content, the relationships between the corresponding slopes of the regression equations and D_f have not yet to be determined. According to the model of Shih et al. (1990), the scaling parameters used in Eq. (1) or (3) are macroscopic elastic constants of the systems. Both τ_y and E_c should also be divided into two parts that can represent the elastic and viscous properties of a suspension system, respectively, and then the corresponding elastic part can derive the macroscopic elastic constants for D_f calculation. According to Eq. (5), if the rheological parameters of δ and G' are introduced into the expressions of τ_y and E_c, the D_f value can also be calculated by a converted form of Eqs. (1) and (3).

2.2.3 Different values from mass fractal dimension calculations

Some previously reported mass fractal dimensions for raw AS of different origins are 2.3–2.5 (Li and Ganczarczyk, 1990), 2.34 ± 0.04 (Motta et al., 2001), 1.96–2.44 (Jin et al., 2004), and 2.18 ± 0.02 (Chu et al., 2004). In the present study, the D_f of raw AS-1 was within the range of the above-mentioned results, whereas that for raw AS-2 went beyond the range. Compared with raw AS-2 or ADS, the conditioned AS-2 or ADS had a decreased D_f value. This result agrees with the observation of Chu et al. (2004), the D_f value decreased from 2.18 ± 0.02 to 1.94 ± 0.05 when AS was conditioned with a cationic polymer, and a large networked floc structure containing long rugged tubes was produced. **Table 1** indicates that the AS collected at two different time presented differences in properties, which may cause the differences in D_f values between AS-1 and AS-2.

3 Conclusions

Both the raw and conditioned AS/ADS at the optimum polymer dose showed shear-thinning behaviors. Power-law relationships were observed between η_∞, γ_c or G' and the TSS content. The mass fractal dimensions indicate that both raw and conditioned AS/ADS behave similar to weak-link flocs/aggregates. The strain amplitude sweep test results show that the linear viscoelastic range and gel-like structure were observed in the raw and conditioned AS or ADS; polymer conditioning and increased TSS contents generally strengthened the elastic behavior, cohesion, and τ_y of the AS or ADS network. The linear viscoelastic range increased with rising TSS content.

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