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CONTENTS

Aquatic environment

Atmospheric environment

Terrestrial environment

Environmental biology

Environmental health and toxicology

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Effect of solid contents on the controlled shear stress rheological properties of different types of sludge

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Abstract

Controlled shear stress (CSS) test was used to study the effect of solid contents on the corresponding rheological parameters for sludge. Three types of sludge with or without conditioning, including activated sludge (AS), anaerobic digested sludge (ADS), and water treatment residuals (WTRs), were collected for the CSS test. Results showed that the yield stress and the cohesion energy of the sludge networks were improved with increased total suspending solid (TSS) contents in most cases. For the conditioned AS/ADS and the raw WTRs, exponential law was observed in the relationships between cohesion energy of material networks or yield stress and the TSS contents, whereas for the conditioned WTRs, only exponential law dependence was found between the parameters of shear modulus or critical strain and the TSS contents.

Key words: controlled shear stress test; exponential law; rheology; sludge; solid contents

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Introduction

Activated sludge (AS), anaerobic digested sludge (ADS) in wastewater treatment plants (WWTPs), and water treatment residuals (WTRs) in water treatment plants (WTP) are well-known solid wastes. Chemical conditioning is commonly employed to change the microstructure, the incorporated water content, and other operational properties of sludge aggregates (Langer et al., 1994; Dentel, 1997; Abu-Orf and Dentel, 1999; Dentel et al., 2005; Ayol, 2005; Dursun, 2007), which favors dewatering and other management processes for these solid wastes. In a rheological manner, all the aforementioned types of sludge before or after conditioning are obviously non-Newtonian fluids with gel-like network structures (Poxon, 1996; Sanin and Vesilind, 1996; Keiding and Nielsen, 1997; Higgins and Novak, 1997a, 1997b; Poxon and Darby, 1997; Dentel, 1997, 2001; Legrand et al., 1998; Abu-Orf and Dentel, 1999; Keiding et al., 2001; Mezger, 2002; Ayol, 2005; Dursun, 2007), and many studies have indicated that these properties have an important effect on the treatment, disposal, and management of sludge, such as stabilization, dewatering, transporting, storing, landfilling, and spreading operations (Lotito et al., 1997; Dentel et al., 2005; Chen et al., 2005). Therefore, rheological testing can be an important method to identify these properties and to provide complementary information on the internal structure of sludge suspensions.

In general, rheology describes the flow and the deformation of materials under stress. Flow measurement with controlled shear stress (CSS) mode is conducted to obtain the viscous and viscoplastic properties of the sludge, as well as the corresponding rheological parameters of yield stress (τ_y), cohesion energy of material networks (E_c), shear modulus (G), and critical strain (γ_c). Determination of τ_y can be derived from test results based on specific empirical models. Moreover, an exponential or power law has been observed in the evolution of these parameters with solid concentrations of sludge (Monteiro, 1997; Slatter, 1997; Battistoni, 1997; Forster, 2002; Seyssiecq et al., 2003; Tixier et al., 2003; Mori et al., 2006; Mu and Yu, 2006; Pevere et al., 2006; Khongnakorn et al., 2010; Dong et al., 2011).

Both AS and ADS originate from different stages in WWTP processes, while WTRs are produced in WTP processes. These three types of sludge naturally contain different levels of inorganics, organics, bacteria, and other components, and they present discrepancies in terms of conditioning with polymers, rheology, and dewaterability. However, detailed information on these contents and properties is limited.

Consequently, this study aimed to explore the changes in rheological parameters derived from the CSS testing with the total suspending solid (TSS) contents of AS, ADS, and WTRs suspensions before or after conditioning. Comparison among the values of the rheological parameters for different types of sludge with and without conditioning was

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also conducted. The results provide further information on the microstructure and the conditioning mechanism of the sludge samples, as well as their practical application in dewatering.

1 Materials and methods

1.1 Raw sludge

Raw AS and ADS used 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 (A^2O) process. AS was collected from the recycled sludge stream, and ADS was taken from the anaerobic digested unit. The raw WTRs were collected upstream of the conditioning and dewatering processes in a water plant of the Beijing Waterworks Group Ltd., China. Thereafter, the samples were immediately transferred to the laboratory at the Beijing Forestry University and stored at 4°C. The sludge samples were warmed to 25°C prior to the experiments. All measurements were performed within 5 to 7 days from the date of sampling. The TSS of 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). A Triton 304B instrument was used for capillary suction time (CST) measurements to estimate sludge filterability. The corresponding characteristics of the sludge samples are presented in Table 1.

1.2 Sludge conditioning

Cationic organic polymer, a polyacrylamide (PAM) known as CZ8698, was used as conditioner (Dong et al., 2011). The conditioning procedure and the device were the same as those described by Dong et al. (2011). The optimum dosages for AS, ADS, and WTR conditioning with polymer CZ8698 were determined based on CST evolution with CZ8698 doses. The optimum polymer CZ8698 dosages were 1.35, 17.33, and 18.75 kg/ton dry sludge, and the corresponding CST values were 10.57 ± 0.35, 9.90 ± 0.63, and 13.10 ± 0.63 sec, respectively. All rheological tests were repeated for the raw and the conditioned sludge at optimum polymer CZ8698 dosages.

1.3 Rheological measurements

Rheological testing was performed with the use of 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. A CSS rheological test mode was employed to determine the corresponding parameters that represent the viscoplastic properties of the raw and the conditioned sludge at optimum polymer dosage.

Table 1 Characterization of the sludge samples

Sample	TSS (g/L)	MLVSS/MLSS	pH	CST (sec)
AS	7.39 ± 0.036	67%	7.12	34.57 ± 1.04
ADS	28.84 ± 1.32	60%	7.10	580.30 ± 13.50
WTRs	15.97 ± 0.093	21%	7.64	131.68 ± 2.50

AS: activated sludge; ADS: anaerobic digested sludge; WTRs: water treatment residuals; TSS: total suspending solid; MLVSS: mixed liquor volatile suspended solid; MLSS: mixed liquor suspended solid; CST: capillary suction time.

CSS test mode is a type of transient rheological test. In this test, the shear stress was increased from 0.1 to 33 mN·m in a linear ramp manner to determine strain (deformation) response as a function of the imposed values. The critical points of the shear stress and the strain can then be determined from the strain-shear stress curve according to tangent crossover method as described in the literature (Steffe, 1996; Mezger, 2002; Dentel et al., 2005; Dursun, 2007). These points were considered in terms of yield stress τ_y and the corresponding critical shear strain γ_c. Meanwhile, shear modulus G can be determined as the inverse of the slope of the first linear part of the curve (Khongnakorn et al., 2010). According to Khongnakorn et al. (2010), both τ_y and γ_c limit the linear elastic domain, and G represents the rigidity of the sludge network. In addition, the energy of cohesion of the network sludge E_c is equal to half the product of τ_y and γ_c.

2 Results and discussion

2.1 CSS rheological testing of the raw and the conditioned sludge

Raw and conditioned AS were used for the transient CSS test. Figure 1a, b presents the CSS flow curves of both AS samples. For the raw AS, the applied TSS content interval was 22.18 to 66.53 g/L. The CSS flow curves of the raw AS with TSS contents lower than 51.74 g/L, the shear strain increased rapidly with the increase in the first several imposed shear stresses. The critical point for the τ_y determination was not observed according to the tangent crossover method (Steffe, 1996; Mezger, 2002; Dentel et al., 2005; Dursun, 2007). Meanwhile, the CSS flow curves of the raw AS with TSS contents from 51.74 to 66.53 g/L generally presented three linear sections, and the critical point for the τ_y determination between the first two linear sections was easily observed. For the conditioned AS at the optimum polymer dosage, Fig. 1b indicates that τ_y values could be determined from the double logarithmic stress-shear strain curves at TSS contents except for 24.63 g/L. Other rheological parameters (γ_c, G and E_c) were also determined from the corresponding CSS test results.

For the raw ADS (Fig. 2c), the shear strain increased rapidly with the increase in the first several imposed τ values, and no critical points for τ_y and γ_c determination were observed. The values of the corresponding rheological parameters of G and E_c were not found as well. Conditioned ADS yielded results which differed significantly from those of the raw ADS (Fig. 1d). At all tested TSS contents in the conditioned ADS system, the corresponding CSS flow curves exhibited critical points for τ_y and γ_c determination. The corresponding τ_y, γ_c, G, and E_c values could be determined at each TSS content within the range of 37.46 to 84.29 g/L.

The CSS test was also conducted for the raw and the conditioned WTRs. The corresponding flow curves of the

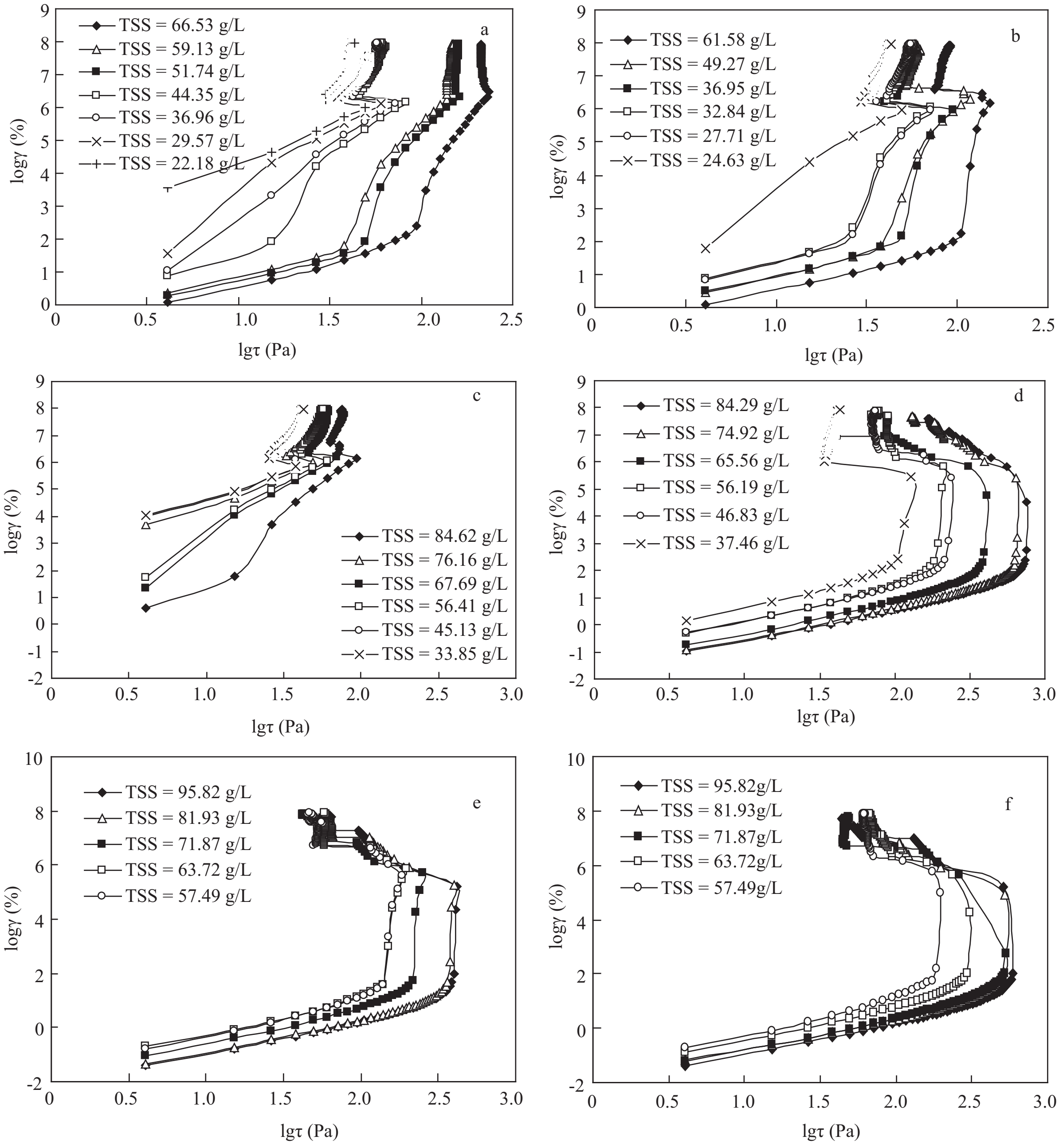

Fig. 1 Typical CSS flow curves of the raw and the conditioned sludge. (a) raw AS; (b) conditioned AS; (c) raw ADS; (d) conditioned ADS; (e) raw WTR; (f) conditioned WTR.

CSS test at different TSS contents (57.49 to 95.82 g/L) are presented in Fig. 1e and f. As shown in these flow curves, the critical points for τ_y and γ_c determination can be easily observed. The rheological parameters, such as τ_y, γ_c, G, and E_c, were then determined at each TSS content.

2.2 Effect of solid contents on the rheological parameters in the CSS test mode

Figure 2a shows the variations in the four aforementioned rheological parameters (τ_y, γ_c, G, E_c) with the TSS contents in the conditioned AS. In Fig. 2a, both τ_y and E_c of the conditioned AS increased as the TSS contents increased. G and γ_c had a general opposite trend.

As previously explained, for τ_y, G, and E_c, the rigidity of the network sludge and the energy required to overcome the cohesion of the sludge network can be indicated as G and E_c, respectively. Both the sludge network structure and the interactions among biosolids were almost disrupted under the effect of critical shear stress τ_y. Hence, the changes in these parameters (Fig. 2a) implied that the energy of cohesion of the conditioned AS network increased with the increase in the TSS contents. This result was accompanied by a similar trend for yield stress. Meanwhile, the rigidity of the network sludge did not always increase, which was not in accordance with the results obtained by Khongnakorn et al. (2010). In addition, for the raw AS, the CSS test results as well as the corresponding τ_y, γ_c, G, and E_c values at only three TSS contents did not provide distinct information on the network structure and interactions of the raw AS with biosolids.

Khongnakorn et al. (2010) indicated that G and E_c exponentially increased with the increase in the TSS contents

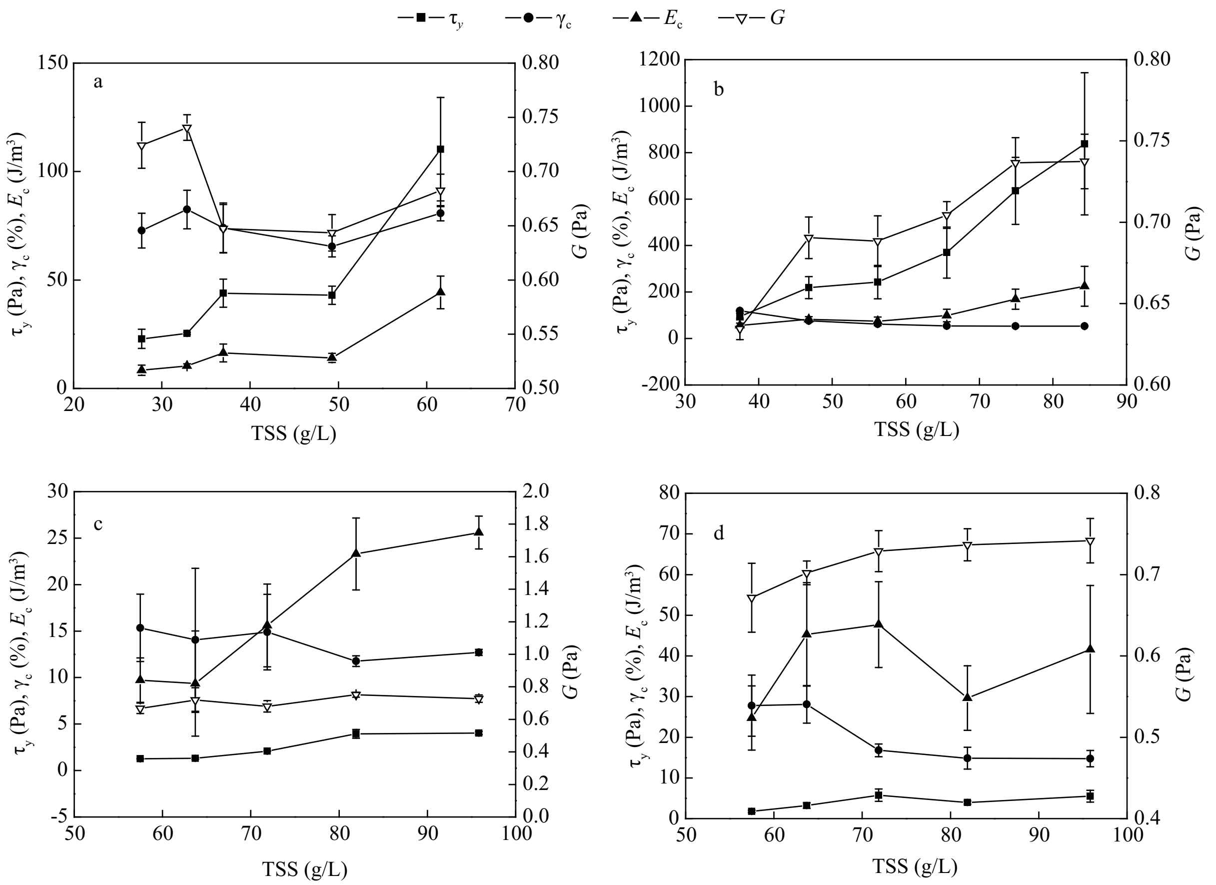

Fig. 2 Rheological parameters τ_y, γ_c, G, and E_c of the conditioned AS (a), conditioned ADS (b), and raw (c) and conditioned WTRs (d) as a function of TSS in the CSS test mode.

of the sludge in a submerged membrane bioreactor. In this study, for raw AS, no regression equation was determined, while for the conditioned AS, the exponential law was observed in the relationships between E_c or τ_y and the TSS contents. The corresponding regression equations are as following:

$$\tau_y = 5.2240e^{0.04888\text{TSS}} \quad R^2 = 0.9207 \tag{1}$$

$$E_c = 1.5909e^{0.0532\text{TSS}} \quad R^2 = 0.8900 \tag{2}$$

$$G = 0.7614e^{-0.00246\text{TSS}} \quad R^2 = 0.2646 \tag{3}$$

$$\gamma_c = 74.4371e^{0.00022\text{TSS}} \quad R^2 = 0.00105 \tag{4}$$

For γ_c and G, the low R^2 values of the exponential regression equations demonstrated that they did not describe the relationships between these parameters and the TSS contents.

Figure 2b shows the variations in the four parameters as a function of the TSS contents in the conditioned ADS. The τ_y gradually increased with increasing TSS contents over the entire range of all tested values, while E_c gradually increased with increasing TSS contents except for 56.19 g/L. G showed an increasing trend at TSS contents between 56.19 and 74.72 g/L. γ_c decreased slowly with the increase in the TSS contents.

According to the definitions of the aforementioned rheological parameters, the variations in τ_y and E_c (Fig. 2b) indicated that the energy of cohesion of the conditioned ADS network increased with the increase in the TSS contents. The rigidity of the network sludge increased with higher TSS contents, which was in accordance with the results obtained by Khongnakorn et al. (2010).

The relationship between the four rheological parameters discussed above and the TSS contents in the conditioned ADS can be described by empirical power law regression equations (Eqs. (5)–(8)).

$$\log\tau_y = 2.6170\log\text{TSS} - 2.1224 \quad R^2 = 0.9765 \tag{5}$$

$$\log E_c = 1.4096\log\text{TSS} - 0.4708 \quad R^2 = 0.8529 \tag{6}$$

$$\log G = 0.1872\log\text{TSS} - 0.4891 \quad R^2 = 0.9376 \tag{7}$$

$$\log\gamma_c = -0.9903\log\text{TSS} + 3.6114 \quad R^2 = 0.9254 \tag{8}$$

The corresponding regression coefficients, which were higher than 80%, suggest that the empirical power law was able to describe the aforementioned relationships adequately. This observation was consistent in part with the results of Vreeker et al. (1992) for glycerol tristearate gel and those of Dong et al. (2011) for conditioned WTRs. In addition, a good correlation was found between τ_y and E_c, in accordance with the observations of Roche et al. (1996) and Mori et al. (2006).

Moreover, the relationship between the above four rheological parameters with the TSS contents of the conditioned ADS could be described by an empirical exponential law equation through regression (Eqs. (9)–(12)) and the corresponding regression coefficients were higher than 80% .

$$\tau_y = 16.9447e^{0.04774\text{TSS}} \quad R^2 = 0.9396 \tag{9}$$

$$E_c = 21.3253e^{0.0261\text{TSS}} \quad R^2 = 0.8741 \tag{10}$$

$$G = 0.5387e^{0.00445\text{TSS}} \quad R^2 = 0.8447 \tag{11}$$

$$\gamma_c = 463.5204e^{0.0363\text{TSS}} \quad R^2 = 0.9554 \tag{12}$$

Figure 2c and d shows the variations in these four parameters as a function of the TSS contents. For the raw WTRs, the τ_y increased with an increase in the TSS contents over the entire range of all tested values, whereas the E_c increased continuously, except when the TSS content was 63.72 g/L. In addition, both the γ_c and G values fluctuated as the TSS contents increased. When the WTRs were conditioned with polymer CZ8698 at optimum dosage, the G values gradually increased at higher TSS contents, and a general increasing trend was observed for the τ_y values, with lower values observed when the TSS content was 81.93 g/L. E_c increased up to a maximum value when TSS contents approach 71.87g/L, while fluctuated at the following higher TSS contents. A slight increase in the γ_c values was observed as the TSS contents increased from 57.49 to 63.72 g/L, and this increase was followed by a decrease at higher TSS contents.

Compared with the raw WTRs, the conditioned WTRs exhibited much higher τ_y values at the same TSS contents. The E_c was also higher at the tested TSS contents, which indicated greater cohesive interactions among the flocs in the conditioned WTR network matrix. However, the approximately equal G values implied that conditioning at the optimum CZ8698 dosage did not improve the rigidity of the flocs/aggregates network in the sludge system. These agree in part with the results of Khongnakorn et al. (2010). In addition, higher γ_c values were observed for the conditioned WTRs than for the raw samples, but these differences were reduced as the TSS contents increased.

For the raw and the conditioned WTRs, the regression results of the exponential law relationships between each of τ_y, E_c, G, and γ_c with the TSS contents within the range of 57.49 to 95.82 g/L are given as Eqs. (13)–(20).

Raw WTRs:

$$\tau_y = 0.2765e^{0.02889\text{TSS}} \quad R^2 = 0.8164 \tag{13}$$

$$E_c = 2.4123e^{0.02534\text{TSS}} \quad R^2 = 0.8759 \tag{14}$$

$$G = 0.6081e^{0.00207\text{TSS}} \quad R^2 = 0.4268 \tag{15}$$

$$\gamma_c = 21.0151e^{-0.0576\text{TSS}} \quad R^2 = 0.6117 \tag{16}$$

Conditioned WTRs:

$$\tau_y = 1.1054e^{0.01714\text{TSS}} \quad R^2 = 0.4866 \tag{17}$$

$$E_c = 28.8469e^{0.00363\text{TSS}} \quad R^2 = 0.0460 \tag{18}$$

$$G = 0.6019e^{0.00234\text{TSS}} \quad R^2 = 0.7750 \tag{19}$$

$$\gamma_c = 100.8153e^{-0.02212\text{TSS}} \quad R^2 = 0.8096 \tag{20}$$

The strong empirical exponential law dependence of τ_y and E_c on the TSS contents of the raw WTRs could be observed, and these two parameters showed an exponential increase at higher TSS contents. The G value of the conditioned WTRs exhibited an exponentially increasing trend with the increasing TSS contents, whereas the γ_c of the raw and the conditioned WTRs exhibited an exponentially decreasing trend. Surprisingly, the τ_y and E_c values of the conditioned WTRs and the G values of the raw WTRs displayed a poor exponential relationship with the TSS contents ($R^2 < 50\%$).

A comparison between the raw and the conditioned sludge for AS, ADS, and WTRs indicated obvious differences in rheological properties. These results could be attributed to the sludge components (inorganics, organics, bacteria, and other components) and the properties of the suspended flocs in the sludge matrix (particle size distribution, shape and density, particle-particle interaction, flocculation ability, surface physico-chemical characteristics, etc.). In general, AS was found to have the highest organics and bacteria content, whereas WTRs had the least organics and bacteria content. In terms of inorganic matter, WTRs had the highest content. In addition, the properties of the suspended flocs also differed for these types of sludge, and some characteristics of three types of raw sludge are shown in Table 2. Therefore, additional studies have to be conducted to examine further the above discrepancies attributed to sludge components and to suspended flocs.

3 Conclusions

The CSS test indicated that the critical point for yield stress determination cannot be observed at specific TSS contents, particularly for raw AS and ADS. In most cases, the yield stress and the cohesion energy of the sludge networks were improved with the increased TSS contents.

For the conditioned AS, the exponential law was observed in the relationships between E_c or τ_y and the TSS contents. For the conditioned ADS, both good power law and exponential law relationships were observed between τ_y, E_c, G, or γ_c and the TSS contents. For the raw WTRs, an exponential law relationship was observed between the parameters of E_c or τ_y and the TSS contents, whereas for the conditioned WTRs, only exponential law dependence

Table 2 Characteristics of the raw WTRs, AS and ADS

Raw sludge	MLSS (g/L)	CST (sec)	pH	Zeta potential (mV)	Median diameter (mm)	Fractal dimension (D2)	Reference
WTRs	12.53	22.27	7.30	−10.2 ± 3.6	33.76	–	Dong et al., 2011
AS	6.77	56.50	7.21	−19.3 ± 2.8	62.45	1.07	Li et al., 2012
ADS	16.02	193.60	8.34	−10	132.68	1.35	Feng et al., 2011

was found between the parameters of G or γ_c and the TSS contents. The differences in the above rheological parameters between the raw and the conditioned WTRs were reduced gradually as the TSS contents increased.

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