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Variation in rheological characteristics and microcosmic composition of the sewage sludge after microwave irradiation

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ABSTRACT

The objective of the presented investigation was to determine the effects of microwave irradiation (MV irradiation) on the rheological characteristics of sewage sludge, and tried to explain the variation of apparent behaviors from a viewpoint of microcosmic composition. The results revealed that, from a macroscopic perspective, several rheological characteristics of sludge, including the apparent viscosity, limit viscosity and rheogram, were markedly changed by MV irradiation, and four rheological models (**Power law**, **IPC Paste**, **Casson** and **NCA/CMA Casson**) were found to be quite suitable for describing the rheological behaviors of sewage sludge before and after MV irradiation. However, from a microscopic perspective, MV irradiation effectively disintegrated multi-pole macromolecules contained in sludge, which reliably reduced the size of sludge particles and narrowed the particle size distribution. Even though the concentration of total solids increased following MV irradiation due to the evaporation of water, the content of macromolecules such as protein and polysaccharides in the remaining solids actually decreased. The changes in water content, chemical composition and particle size of sludge lead to variations of the total solids and the absolute value of zeta potential, which may be an essential reason for changing the rheological characteristics, including yield stress, thixotropy and apparent viscosity.

1. Introduction

Building domestic wastewater treatment plants (WWTPs) and implementing stringent sewage discharge standards are very important for abating the pollution of the aqueous environment (Wang et al., 2015), in which, activated sludge (AS) process is the most widely used bio-treatment method. The operation of an AS process is an efficient way to positively affect the aqueous environment. However, the generated huge volumes of waste activated sludge (WAS) can have negative environmental impacts. These negative consequences have aroused serious environmental concerns globally, such that mitigating the harmful environmental impact of WAS is a new great challenge for running a WWTP (Cieślik et al., 2015). Most of the solids contained in WAS are biomass, the special composition and network of which makes WAS a non-Newtonian fluid. A deep understanding of the rheological behavior of WAS is very essential for the treatment and final disposal of this substance (Tang and Zhang, 2014).

Rheology is a very useful tool for describing the relationship between the internal structure and the macroscopic properties of a non-Newtonian fluid. Due to the obvious non-Newtonian characteristic of both activated sludge and WAS, the knowledge about the rheological behavior of these materials should be an essential aspect of managing and operating a WWTP (Lotito and Lotito, 2014). Traditional methods to dispose WAS include landfill and incineration, but before the final disposal, a dehydration process is required to maximally reduce the contained water. The processes of treating and disposing WAS generally involve concentrating, pumping, digestion, chemical conditioning, dehydration and transporting, whose costs may account for more than 50% in building and operating a WWTP (Zhang et al., 2007), and are closely related to the volumes and characteristics of the sewage sludge produced. Traditional methods and processes to pre-treat and dispose WAS need to consume lots of land and energy, which urgently require a new approach to optimize the whole system and achieve sustainable management. To reduce the negative environmental effect of operating a WWTP, and especially to achieve effective volume-reduction and safe disposal of WAS in a

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sustainable way, much research has been focused on physical WAS treatment methods, such as thermal and ultrasonic pre-treatment (Ruiz-Hernando et al., 2014; Serrano et al., 2015). The predominant merits of these physical methods are their effectiveness in destroying the stable structure of WAS and accelerating the subsequent anaerobic digestion without introducing any toxic chemicals (Tyagi et al., 2014).

Microwave (MV) irradiation refers to the application of electromagnetic waves having wavelengths ranging from 1 mm to 1 m. According to the reported literature (Eskicioglu et al., 2007), the consequences of treating WAS with MV irradiation include thermal and athermal effects, both effects change the physico-chemical properties of WAS and destroy its micro-structure (Eswari et al., 2016), which may positively affect the subsequent treatment and disposal of this very complex material (Tyagi and Lo, 2013). In the previous study (Tang et al., 2010), it was verified that the anaerobic digestion of WAS could be obviously improved after a certain dose of MV irradiation and further enhancing the biogas production performance (Kavitha et al., 2016).

Sustainable management is a comprehensive idea that optimizes the structure of a system for the purpose of achieving a minimal environmental impact and energy consumption, which can be applied to all aspects of human society. As the amounts of WAS increase constantly, the successful operation of WWTPs is facing a great challenge, which really needs a new technique to achieve effective and sustainable management and disposal of WAS. Considering the importance of rheological behaviors of sludge in so many aspects relating to the managing, handling, and disposing of WAS, the effects of MV irradiation on the rheological characteristics of sewage sludge should be paid more attention. In the present investigation, the aim was to study the effects of MV irradiation on the rheological characteristics of sewage sludge, which included two main aspects: (1) the variation of the rheological characteristics of sewage sludge in terms of apparent viscosity, yield stress, thixotropy after MV irradiation; (2) the effects of MV irradiation on the microcosmic physico-chemical characteristics of sewage sludge in terms of particle size and distribution, zeta-potential, total solids (TS), and the polysaccharide and protein content of TS. In addition, we attempted to quantitatively describe various rheological behaviors using mathematical models.

2. Materials and methods

2.1. Sludge samples and experimental procedure

All sludge samples were obtained from the secondary sedimentation and the gravity concentration tank of a local WWTP (Lijiao municipal wastewater treatment plant, located in Haizhu District, Guangzhou, China). Table 1 lists the characteristics of the raw sludge samples:

Immediately after sludge samples were received in the laboratory, each was totally mixed and analyzed for the basic physico-chemical characteristics, which included TS, volatile solids (VS), total COD (TCOD), soluble COD (SCOD) and other chemical components (proteins and polysaccharides). All the analyses were performed according to the Standard method (APHA et al., 2005), and after these analyses, each sample was divided into two equal sub-samples. One sub-sample was subjected to a series of direct tests, including a rheological test and tests of other physico-chemical characteristics (TS, particle size, size distribution, zeta potential, content of proteins and polysaccharides in the solids). The other sub-sample was treated with MV irradiation under pre-set time intervals and powers inputs, followed by similar tests performed on the first sub-sample, which were carried out under the same conditions unless stated otherwise.

A domestic microwave oven (power, 0–1250 W; frequency, 2450 MHz; maximum temperature, 260 °C; G8023 CTL-K3, Galanze, Guangdong, China), was used to irradiate all samples. In each experiment, about 10–30 mL sludge sample, after being totally mixed, was put into a special polyfluortetraethylene container and placed in the cavity of the microwave oven. Samples were exposed to MV irradiation for 30–300 s (30, 60, 120, 180, 240, and 300 s) at power settings of 400–800 W (400, 600 and 800 W). An index, E_s (J/mL), defined as specific energy was used to evaluate the energy consumption during MV irradiation (Tang et al., 2010).

2.2. Measurement of rheological behavior

A viscometer with an ultra-low viscosity adapter (DV-III ULTRA, Brookfield, Massachusetts, USA) was used to carry out all the rheological measurements. Each sample was analyzed before and after MV irradiation. All rheology tests were conducted under ambient conditions to control the influence of temperature (Baudez et al., 2013). The water content of the sludge samples was adjusted to 95–99 wt% by centrifuging or diluting them with the supernatant. Under a steady mode, a 16 mL-sample was put into the viscometer, and at shear rates from 10 to 300 s^{-1}, viscosity and shear stress were recorded automatically using a computer connected to the viscometer. Mathematical models were fitted to the rheological data using the software integral to the viscometer. The thixotropy of the sludge samples was determined using a hysteresis loop method by first gradually increasing the shear rate from 10 to 300 s^{-1}, and then decreasing the shear rate from 300 to 10 s^{-1}. The resulting data were used to automatically construct a rheogram for each sample.

2.3. Measurement of basic physico-chemical characteristics

Particle size analysis: a laser particle size analyzer (Mastersizer

Table 1
Characteristics of the raw sludge.

	Secondary sedimentation tank	Gravity concentration tank
pH	6.85 ± 0.01	6.91 ± 0.02
TS (g/L)	21.16 ± 3.77	41.08 ± 0.64
VS (g/L)	10.92 ± 0.83	14.07 ± 1.43
TCOD (mg/L)	20,867 ± 333	26,067 ± 467
SCOD (mg/L)	4724 ± 54	9800 ± 67
Zeta potential (mV)	−20.76 ± 2.15	−15.40 ± 0.41
Protein (mg/mL)[a]	0.019 ± 0.003	0.001 ± 0.0002
Polysaccharide (mg/mL)[a]	0.006 ± 0.001	0.011 ± 0.0006
Protein (mg/g)[b]	16.503 ± 0.014	20.243 ± 0.005
Polysaccharide (mg/g)[b]	11.916 ± 0.067	10.602 ± 0.009

[a] Concentration in the supernatant of the sludge samples.
[b] Content in the solids of the sludge samples.

2000, Malvern Instruments Ltd., Worcestershire, UK), capable of detecting particle sizes in the range of 0.02–2000 μm, was used to analyze the sizes of particles and their distribution of all sludge samples. Before and after being treated with different power levels of MV irradiation, approximately 10 mL of the sludge samples was used to carry out a particle size analysis.

Proteins and polysaccharides: the protein content of sludge solids was determined by the Coomassie Brilliant Blue G-250 method with using casein as the standard. The content of polysaccharides in the sludge solids was measured using the Phenol-Sulfuric Acid method.

Zeta potential: the zeta potential of sludge samples was measured before and after MV irradiation using a zeta potential analyzer (Zeta PALS, Brookhaven, New Yorks, USA). Samples (1–1.5 mL each) from both the secondary sedimentation and the gravity concentration tank were tested.

All of the above measurements were repeated for at least three times with parallel samples. Based on the obtained data, the standard errors could be calculated.

3. Results and discussion

3.1. Basic rheological behaviors of the raw sludge samples with different water contents

Viscosity measurements, rheogram and rheological model-fitting were used to describe the basic rheological behavior of samples from the secondary sedimentation tank of a WWTP. Comparisons were made on the basis of sludge water content. A shear rate range of 10–300 s^{-1} was used to observe the full rheological behavior from a low-shear rate to high-shear rate. The results are shown in Fig. 1.

To a non-Newtonian fluid, only "apparent" viscosity is meaningful. As shown in Fig. 1, water content is an important factor influencing the rheological behavior of sludge. The apparent viscosity of the sludge samples decreased exponentially as the increase of shear rate (Fig. 1(a)) except for sludge samples with 99 wt % water content, which showed a shear-thinning behavior. At a high water content, the sludge samples had an apparent viscosity that was nearly constant as the shear rate increased, exhibiting a Newtonian-like behavior.

Rheogram (Fig. 1(b)) from the samples in our experiment shows that after a brief, sharp rate of increasing in the values of shear stress (approximately after the shear rate is beyond 50 s^{-1}), the relationship between the shear rate and the shear stress developed in all sample curves gradually became linearity, except for sample with 99 wt% water content. The near-linear relationship between the shear rate and the shear stress was apparent when samples contained 99 wt% water, which (as did apparent viscosity) indicated a Newtonian-like behavior of sludge having a high water content.

3.2. Fitting with rheological model before and after MV treatment

Commonly used rheological models include the following: **Herschel-Buckley** model (Eq. (1)), **Bingham** model (Eq. (2)), **Power law** (Eq. (3)) and **IPC Paste** model (Eq. (4)), **Casson** (Eq. (5)) and **NCA/CMA Casson** model (Eq. (6)) as listed below.

$$\tau = \tau_0 + K\gamma^n \quad (\tau_0 > 0) \tag{1}$$

$$\tau = \tau_0 + \mu\gamma \quad (\tau_0 > 0) \tag{2}$$

$$\tau = K\gamma^n \tag{3}$$

$$\tau = KR^{\mathrm{n}} \tag{4}$$

$$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu\gamma} \quad (\tau_0 > 0) \tag{5}$$

$$(1 + \alpha_1)\sqrt{\tau} = 2\sqrt{\tau_0} + (1 + \alpha_1)\sqrt{\mu\gamma} \quad (\tau_0 > 0) \tag{6}$$

where τ is the shear stress ($N \cdot m^{-2}$); τ_0 is the yield stress ($N \cdot m^{-2}$); μ is the viscosity (mPa•s); γ is the shear rate (s^{-1}); α_1 is the ratio of the principal axis radius to the radius of inner cup of the used viscometer; K is the consistency index (mPa•s^n); R is the rotate speed (s^{-1}); n is a dimensionless parameter to represent the flow behavior, when n is close to 1, the material gradually tends to behave as a Newtonian fluid.

The measured rheological data from our experiments were regressed with the listed rheological models. The results are shown in Table 2, which reveal the rheological behavior of sludge samples with different water contents and MV irradiation doses.

The confident-of-fit, with a value ranging from 0 to 100%, is a parameter used to evaluate the adaptability of rheological models (Pham et al., 2010). As shown in Table 2, the values of confident-of-fit for all rheological models evaluated generally decreased with the increasing of MV dose. The **Herschel-Bulkley** and **Bingham** models exhibited very high confident-of-fit values, but predicated negative yield stresses in some cases, which were nonsensical and implied these models are not the adaptable models. The confident-of-fit values of **Power law** and **IPC paste** (extension of the **Power law**) models range from 87.1% to 96.8%, which indicated the high adaptability of these two models to describe the rheological

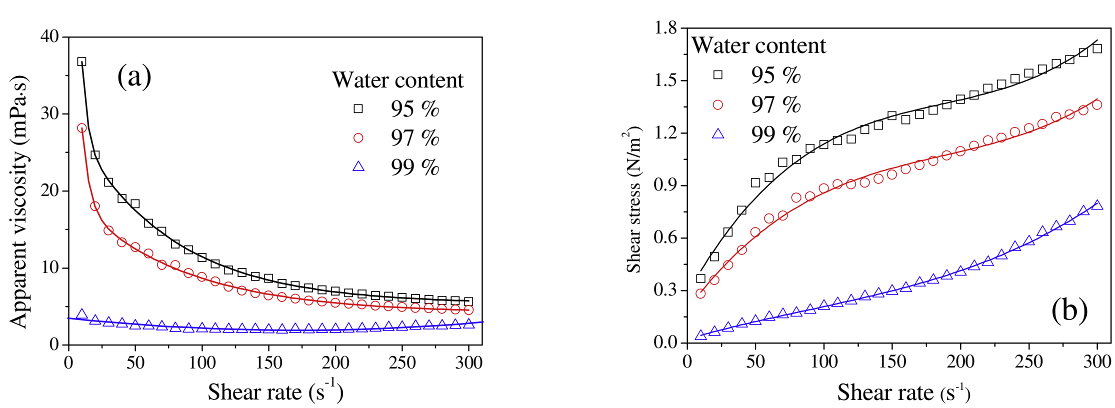

Fig. 1. Rheological behavior of the raw sludge with different water content. (a) Apparent viscosity vs. Shear rate; (b) Shear Stress vs. Shear rate.

Table 2
Rheological behavior of the sludge samples before and after being treated with MV irradiation.

Water content	95 wt%				97 wt%				99 wt%			
Specific energy (J/mL)	0	1280	1920	2560	0	1280	1920	2560	0	1280	1920	2560
Herschel-Bulkley												
Yield stress (N/cm^2)	−0.87	−2.54	2.19	3.32	−0.17	2.58	2.37	−51.85	0.88	1.06	1.02	0.83
Confidence-of-fit (%)	97.9	89.5	89	74.3	98.5	95.7	93.7	47.3	99.4	98.7	98.8	99.6
Consistency index	217	852.1	384.2	708.6	108.9	91.5	137.6	4519	0.05	0.18	0.06	0.05
Flow Index	0.36	0.26	0.35	0.29	0.44	0.51	0.45	0.1	1.67	1.45	1.65	1.68
Bingham law												
Plastic fluid (viscosity, mPa•s)	3.72	6.65	5.91	6.92	3.24	4.27	4.56	6.77	2.36	2.38	2.49	2.4
Yield stress (N/cm^2)	6.21	17.8	14.2	21.7	4.29	7.08	8.25	12.7	−0.13	0.27	−0.02	−0.2
Confidence-of-fit (%)	92.5	91.2	90.7	88.4	92.3	92.3	91.4	82.9	85.6	91.9	87.8	84.5
Power law												
Confidence-of-fit (%)	96.3	92.8	91.9	89.3	96.8	93.9	93.1	87.8	88.5	90.6	90.8	87.1
Consistency index (mPa•s)	164.1	652.3	495.5	872.8	98	202	245.8	287	5.27	8.51	6.03	5.23
Flow Index	0.4	0.3	0.32	0.27	0.46	0.39	0.37	0.42	0.83	0.76	0.82	0.83
IPC Paste												
Confidence-of-fit (%)	96.3	92.8	91.9	89.3	96.8	93.9	93.1	87.8	88.5	90.6	90.8	87.1
10 rpm viscosity (mPa•s)	36.9	112.5	89.3	139.5	25.2	43.8	51	67.1	3.46	4.71	3.88	3.43
Shear sensitivity factor	0.6	0.7	0.68	0.73	0.54	0.61	0.63	0.58	0.17	0.24	0.18	0.17
Casson												
Plastic fluid (viscosity, mPa•s)	1.7	2.28	2.14	2.14	1.66	1.88	1.93	3.28	2.06	1.91	2.13	2.11
Yield stress (N/cm^2)	3.54	12.1	9.37	15.4	2.21	4.15	4.98	6.7	0.01	0.08	0.02	0
Confidence-of-fit (%)	97.3	96.2	95.9	94.7	97.6	96.9	96.4	93	94.4	95.9	95.4	93.9
NCA/CMA Casson												
Plastic fluid (viscosity, mPa•s)	1.7	2.28	2.14	2.14	1.66	1.88	1.93	3.28	2.06	1.91	2.13	2.11
Yield stress (N/cm^2)	3.23	11	8.55	14.1	2.02	3.79	4.54	6.11	0.01	0.07	0.02	0
Confidence-of-fit (%)	97.3	96.2	95.9	94.7	97.6	96.9	96.4	93	94.4	95.9	95.4	93.9

behavior of sludge samples having higher solids contents. As described by these two models, higher MV irradiation decreased the consistency index or the 10 rpm viscosity, which implies the interactions among the sludge particles were weakened by MV irradiation. **Casson** and **NCA/CMA Casson** models also demonstrated excellent adaptability, having their high confident-of-fit values ranging from 93% to 97.6%; these two models indicated that the yield stress increased markedly at a relatively low water content. It should be noted that the four models (Eqs. (3)–(6)) yielded a rather consistent result, specially, that the rheological characteristics of sludge samples were easier to be changed by MV irradiation under lower water contents than that under higher water contents. The significant change in the macroscopic rheological behaviors implies that the internal compositions of the sludge are altered by MV irradiation, which is an interesting finding needs to be explored.

Water molecule has a dipole structure, which can absorb MV irradiation and convert the energy to heat. In this meaning, the WAS with higher water content may consume more energy when being treated by MV irradiation. Combining the results of Fig. 1 and Table 2, it can be concluded that less energy is needed to change the rheological behavior under low water content in a practical MV treatment.

3.3. *Limit viscosity*

When the imposed shear on sludges lasts for a long period of time, the three dimensional structure of sludge flocs is totally destroyed, and the apparent viscosity gradually becomes constant, this final stable value of apparent viscosity is defined as a “limit viscosity”, or an equilibrium viscosity (Pevere et al., 2006; Tixier et al., 2003). In this regard, limit viscosity can be used to describe the overall rheological behavior of a sludge sample (Pevere et al., 2006). After MV irradiation, the physico-chemical composition and the internal micro-structure of the sludge samples were totally altered; this led to obvious variations in their macro-appearance. As reflected by the changes in the limit viscosity of samples (Fig. 2), the rheological behavior of sludge samples was one of the properties altered by MV irradiation.

As shown in Fig. 2, as the duration of shear time increased, the apparent viscosity (of samples both before and after MV irradiation) decreased to a constant value. The most obvious difference between the samples is the significant improvement in limit viscosity after MV irradiation; that is, subjecting samples to higher specific MV energy led to larger limit viscosities. Results in Fig. 2 also reflect the fact that the apparent viscosity decreases quickly initially (within approximately 50 s) in MV irradiated samples, and then gradually reached to a constant value. Further, higher MV energy was imposed on a sample, and more obvious decline was reflected in the rate of limit viscosity. The raw sludge sample did not exhibit such an obvious period of viscosity decline towards the limit viscosity.

From a macroscopic perspective, viscosity stands for the internal friction of a fluid, and reflects the relative difficulty of interaction

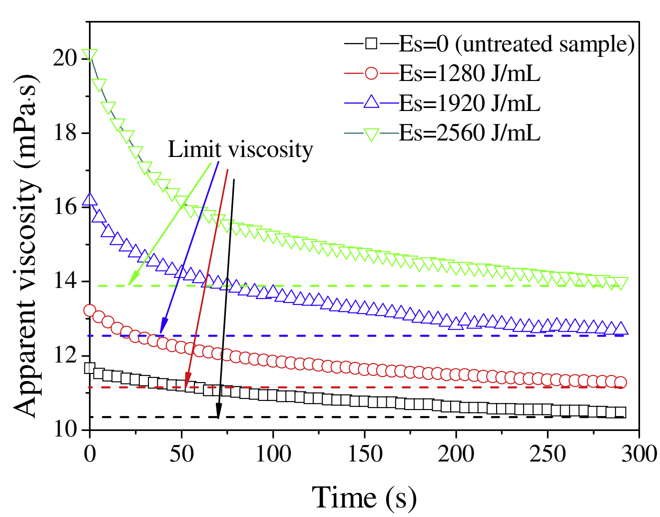

Fig. 2. Influence of MV irradiation on limit viscosity.

among different parts of the fluid. However, as a macroscopic property, the viscosity of a fluid such as sludge is influenced by many properties including, among others, the concentration of solid particles, their surface charge, and the content of biopolymers in sludge solids. Comparing with the reported literature, similar phenomena were observed (Mawioo et al., 2016), namely, increasing in the limit viscosity indicated an increase among the inter-particle interactions, and implied the above properties were heavily changed by MV irradiation.

3.4. Thixotropy

The internal structure of sludge flocs is heavily influenced by the force imposed on them. However, if the imposed force does not exceed the deformation limit of the sludge flocs, the internal structure of the flocs may recover to its original status after the imposed force is removed. Such a phenomenon is termed "thixotropy", which is generally used to describe the recoverability of the internal structure of a non-Newtonian fluid after being sheared. Apparently, the phenomenon of thixotropy results from the rate difference between the destruction and recovery of the internal structure of sludge flocs. In an engineering sense, self-recovery by the internal structure of a fluid after removal of an imposed force would indicate the network of the fluid was not destroyed, and that the imposed energy was stored in the elastic structure of the fluid network to be released during the recovery process. A commonly cited method, a hysteresis loop test (Ruiz-Hernando et al., 2013), was used to evaluate the effect of MV irradiation on the thixotropic property of sludge samples. In order to make comparisons, samples were analyzed from the secondary sedimentation and the concentration tank of the same WWTP. The results are shown in Fig. 3.

A larger area enclosed by the hysteresis loop generally exhibits an irreversible rheological behavior, which, for sludge flocs, implies a difficulty in recovering to the original structure of the sludge flocs. As observed in Fig. 3, the raw sludge from the secondary sedimentation tank did not show any obvious thixotropic phenomenon, whereas the raw sludge sample (non-irradiated) from the concentration tank showed a very weak thixotropic property. However, after MV irradiation, both types of sludge samples exhibited much larger areas enclosed by the thixotropic loop than did non-irradiated samples. This finding indicates the MV irradiation totally destroyed the internal structure of the sludge samples, and that the samples could not recover their original structural network even after the imposed shear force was removed.

The characteristics of limit viscosity and thixotropy have a close relationship with the fluid transportation and the dewatering of WAS. Higher value of limit viscosity and thixotropy means greater difficulty to transport the fluid and consume more energy to dewater the WAS. The results of Figs. 2 and 3 clearly indicate the dose of MV irradiation should be carefully calculated when involving in the subsequent processes as fluid transport and WAS dewatering.

3.5. Effect of MV irradiation on the particle size and its distribution of sludge samples

The influence of MV irradiation at various specific energies on the particle size and particle size distribution in sludge samples is shown in Fig. 4.

The results indicate that the size of the sludge particles was dramatically reduced by MV irradiation. Fig. 4(a) shows that the size distribution of sludge particles also decreased in response to MV irradiation, as did the maximum particle size. For further evaluating the effect of MV irradiation on the size of sludge particles, three "cutoff diameters" (10%, 50% and 90%) (Yu et al., 2010) were used to compare the particle size composition of samples, Fig. 4(b) indicates that the sludge particles with diameters less than 232.61 μm accounted for 90% of all particles in the raw sludge sample, but after MV irradiation, the particle size comprising this percentage was reduced nearly by half, as was the particle size that accounted for 50% of all particles. In contrast, the proportion of sludge particles with smaller sizes (<25 μm) was relatively unchanged by MV irradiation. The results shown in both Fig. 4(a) and (b) indicate the sludge particles with larger size were more sensitive to MV irradiation than relatively smaller particles, but no direct relationship was apparent between the size reduction effect and the specific energy of applied MV irradiation.

3.6. Effects of MV on the composition of sewage sludge

Proteins and polysaccharides are major components contained in sewage sludge; together these two types of macromolecules may account for more than 85 wt% of the biomass in the sludge solids (Baroutian et al., 2013) and usually dominate the characteristic of sludge samples. For this reason, total solids concentration (TS), and the protein and polysaccharide content in these solids were used to evaluate the effects of MV irradiation on the composition of sludge samples. The results are shown in Fig. 5.

After MV irradiation, sludge samples may experience two effects simultaneously: one is the dissolution of organic solids, and the

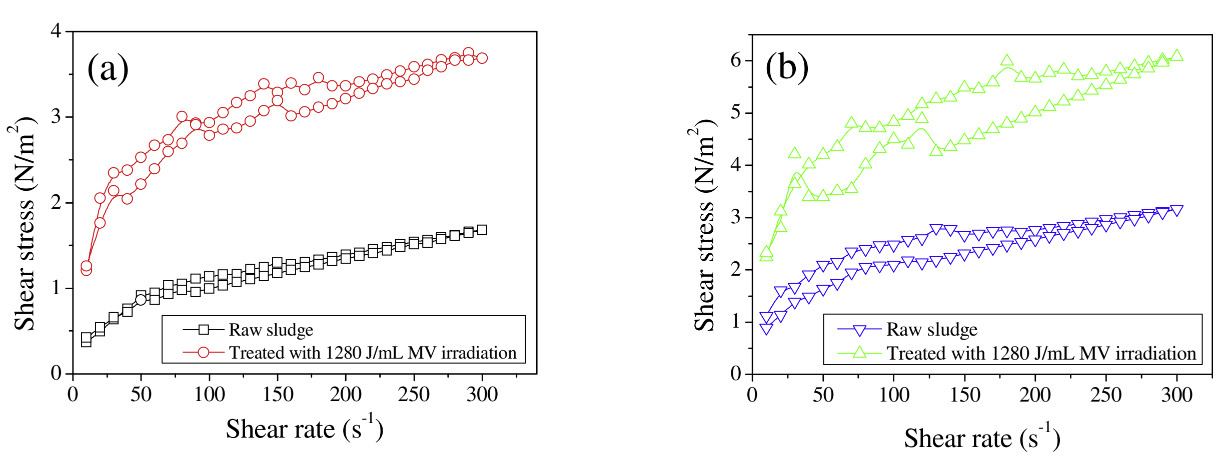

Fig. 3. Influence of MV irradiation on the thixotropic property of sludge samples from different origins: (a) samples from the secondary sedimentation tank; (b) samples from the concentration tank.

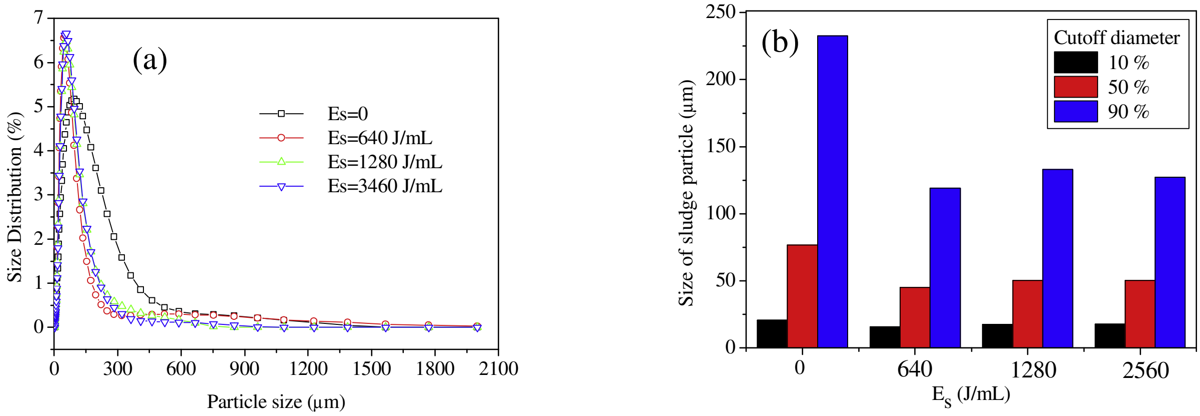

Fig. 4. Effects of MV irradiation on the particle size and its distribution of sludge samples. (a) Effect on size distribution; (b) Effect on different sizes of sludge particles.

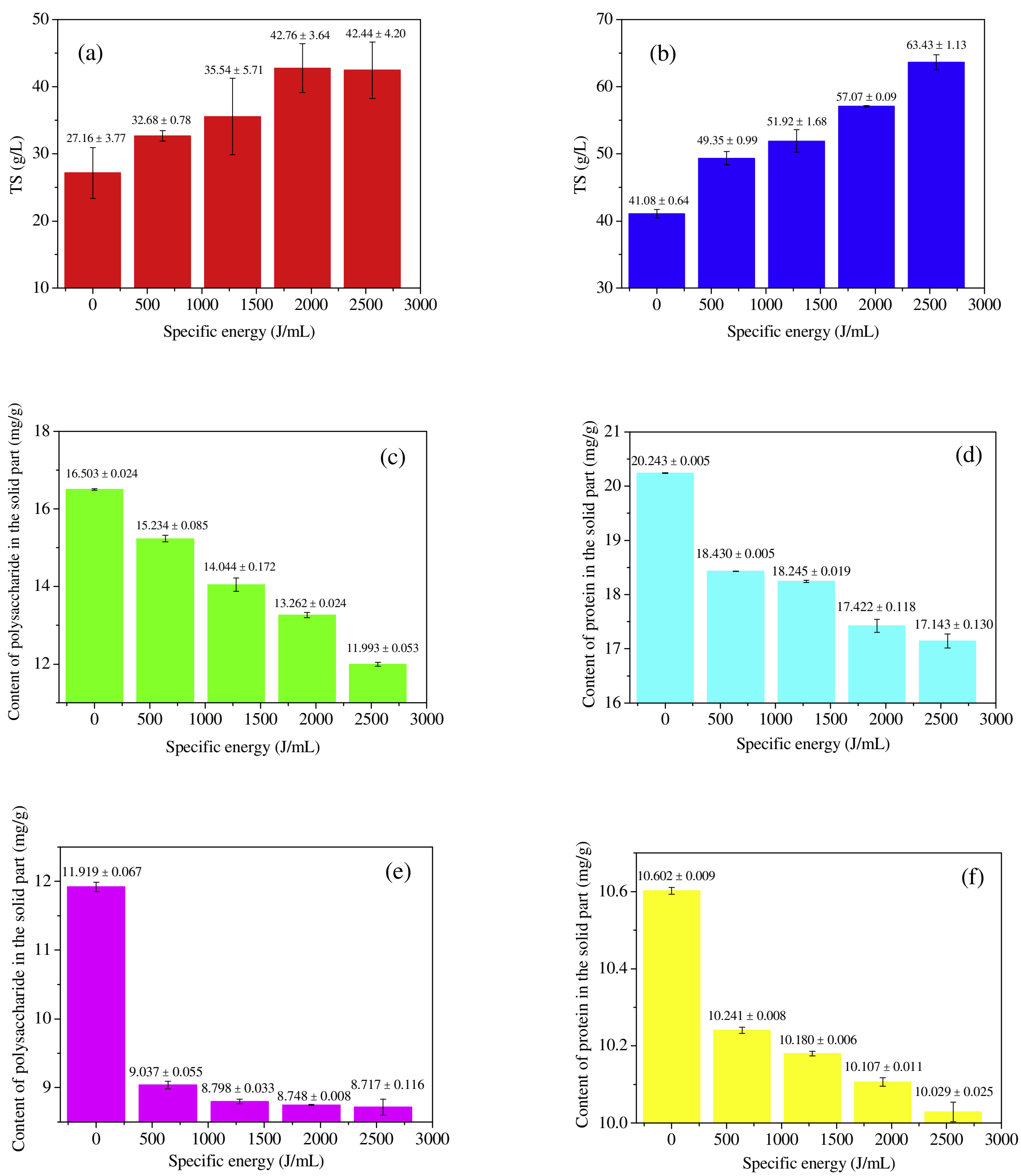

Fig. 5. Effects of MV irradiation on the composition of sewage sludge: (a), (c), (d) Samples from the secondary sedimentation tank; (b) (e) (f) Samples from the gravity concentration tank.

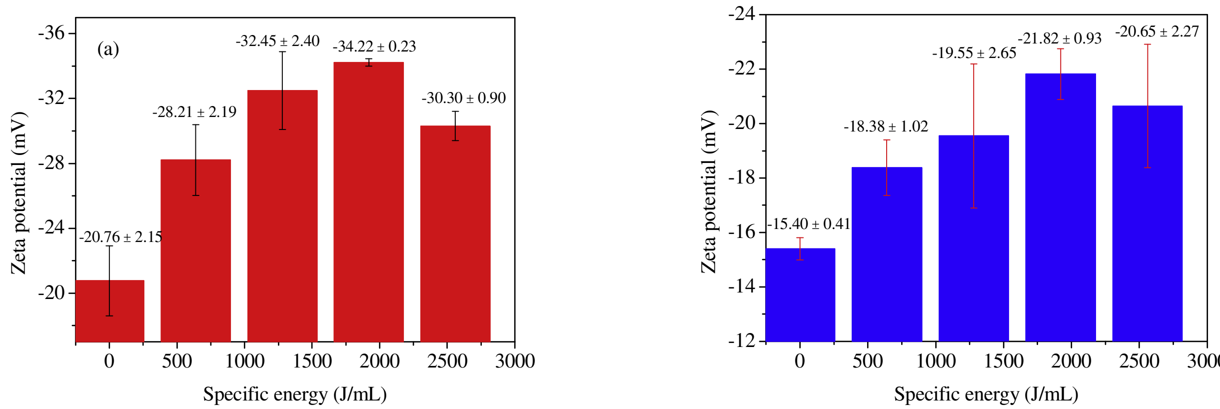

Fig. 6. Effect of MV irradiation on the zeta potential of the sludge samples from different origins: (a) samples from secondary sedimentation tank; (b) samples from concentration tank.

other is the evaporation of water. The former leads to a decrease in the TS concentration, while the latter may result in an increase in TS concentration. As shown in Fig. 5(a) and (b), the concentration of TS in all sludge samples increased markedly after irradiation, indicating that the water evaporation effect overwhelmed the dissolution of organic solids.

For further illustrating the effects of MV irradiation on the composition of sludge samples, the contents of protein and polysaccharide in the solids of the sludge samples were measured at various MV doses. The results in Fig. 5(c)–(f) demonstrate the contents of protein and polysaccharide in the sludge solids decreased as the MV dose increased, although the reduction of protein was relatively less than that of polysaccharide. Comparing with the composition and molecular structure of protein, polysaccharides are polymerized with many monosaccharide units, which generally have a long-chain molecular structure (linear- or branched-chain), they may be subject to more serious damage even under the same dose of MV irradiation (Ebenezer et al., 2015a). During a MV irradiation process, the thermal effect leads to evaporation of water and drying of sludge samples, but has very little impact on destroying the protein and polysaccharide in the sludge solids. However, organic matters that comprise the sludge solids are very complex, and only those macromolecules containing polar groups can be twisted and then broken by MV irradiation. Results in Fig. 5 indicate that these two effects (evaporation and physical destruction of macromolecules) actually occur simultaneously, which heavily change the basic components of sewage sludge. These changes caused by MV irradiation, including larger solid particles being broken into smaller particles, and macromolecules such as protein and polysaccharide cracked to smaller molecules, may be the essential reasons leading to the variation of apparent properties.

3.7. *Effect of MV irradiation on the surface charge of the sludge sample*

After MV irradiation, the sludge samples exhibited marked changes in particle size and chemical composition (Ebenezer et al., 2015b), and these changes altered the surface characteristics of the sludge particles. The effects of MV irradiation on the zeta potential of the sludge samples from the secondary sedimentation tank and the concentration tank are shown in Fig. 6.

The results in Fig. 6 show rather similar tendencies in the variation of the zeta potential of both sources of sludge following MV irradiation. The dominant component of sludge samples is water (approximately 95–99 wt%), and the solid fraction may include protein, lipid, polysaccharide and some ions (Jimenez et al., 2013). Water molecules absorb the energy of MV irradiation without damaging their molecular structure. With such an effect, the resulting temperature rise of the whole system would be reflected as an apparent behavior. However, more than 85 wt% biomass contained in sludge samples is protein and polysaccharide, each of which contains many polar groups in its molecular structure. Under an alternating magnetic field (such as MV irradiation), these macromolecules are twisted quickly and may be broken at the weakest chemical bond, which causes larger molecules to become smaller (Uma Rani et al., 2013). The broken chemical bonds are unsaturated, and must adsorb some negatively charged ions to achieve a stable state. Additionally, after being treated by MV irradiation, large sludge flocs are crushed into small particles, greatly increasing the surface area of the sludge system and stimulating the adsorption of additional negatively charged ions. As the applied specific energy increased, cations contained in sludge were released when the structural network of sludge was totally destroyed (Zhou et al., 2015), which neutralized the adsorbed negative charge and caused the decline in the absolute value of zeta potential. The macro-appearance of the above effects is first increase, and then decrease, and the absolute value of zeta potential, as shown in Fig. 6. The surface charge (zeta potential) is an essential index to stand for the stability of a dispersed system. With the results shown in Fig. 6, medium dose of MV irradiation caused a higher absolute value of zeta potential, which was not beneficial for the dewatering process of WAS.

4. Conclusions

The presented investigation focused on the effects of MV irradiation on the rheological behavior of sewage sludge. Results showed that MV irradiation obviously changed the microcosmic composition of sewage sludge, which was a direct reason leading to the variation of apparent rheological behavior. Water loss from the sludge samples resulted in an increased concentration of TS, and decreased the distance separating individual sludge particles. Together with the enhanced electrostatic interaction, these effects would greatly increase the interaction among the sludge particles when they were subjected to an external shear, and as a result, the apparent viscosity and the yield stress predicted by different rheological models would increase.

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