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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 preset 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.