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Rheology evolution of sludge through high-solid anaerobic digestion

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HIGHLIGHTS

- The operation performance of high-solid anaerobic reactors were investigated.
- The rheology evolution of sludge after high-solid anaerobic digestion was studied.
- The sludge rheology was characterized using the Herschel-Bulkley model.
- The sludge rheology exhibited a strong dependency on SRT and reactor's temperature.

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ABSTRACT

The main purpose of this study was to investigate the rheology evolution of sludge through high-solid anaerobic digestion (AD) and its dependency on sludge retention time (SRT) and temperature of AD reactor. The operation performance of high-solid AD reactors were also studied. The results showed that sludge became much more flowable after high-solid AD. It was found that the sludge from reactors with long SRT exhibited low levels of shear stress, viscosity, yield stress, consistency index, and high value of flow behaviour index. While the flowability of sludge from thermophilic AD reactors were better than that of sludge from mesophilic AD reactors though the solid content of the formers were higher than that of the latters, which could be attributed to the fact that the formers had more amount of free and interstitial moisture. It might be feasible to use sludge rheology as an AD process controlling parameter.

1. Introduction

The amount of sewage sludge has increased significantly due to the massive increase in human population size during the past few decades, which poses a serious threat to the environment. Anaerobic digestion (AD) is one of the most widely used methods to treat these sludge owing to its high-energy recovery and limited environmental impact. Comparing with the traditional AD for low-solid sewage sludge, high-solid AD, which is usually characterized by a high total solid (TS) content of the feedstocks, especially more than 15% (w/w) (Rapport et al., 2008), is more prevailing for its merits like higher loading, smaller reactor volume, lower energy consumption and so on. It was claimed that more than 80% of the sewage sludge in China has to be concentrated and dewatered before further disposal and treatment (Duan et al., 2012), and high-solid AD could be a favourable option to reduce the quantity of these dewatered sludge.

However, the viscosity of dewatered sludge is huge, and the rheological characteristics of sludge is one of the most important parameters when designing, selecting and operating AD equipments, such as pipe, pump, mixing devices, heat exchangers and so on (Baudez et al., 2011; El-Mashad et al., 2005). Moreover, rheology could also be used as a process control parameter to monitor the sludge's characteristics in AD reactors (Pevere et al., 2006). Thus, it is quite significant to study the variation of rheological behaviours of sludge through AD for the promoting of high-solid AD technology.

Generally, the rheology of Newtonian fluid could be described by the apparent viscosity, which is defined by the ratio between shear stress and shear rate. But it is well known that sludge is non-Newtonian fluid whose shear stress is not linearly proportional to the shear rate (Tang and Zhang, 2014). Therefore, sludge rheology can not just be determined by a single value of its viscosity (Seyssiecq et al., 2003). In previous studies, rheograms and various rheological models were used to describe the rheological behaviour of sludge, such as the Ostwald de Vaele model (or Power law model) (Lotito et al., 1997; Ruiz-Hernando et al., 2013), the Herschel-Bulkley model (Baroutian et al., 2013; Eshtiaghi et al.,

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2012), the Bingham model (Guibaud et al., 2004; Hasar et al., 2004), the Sisko model (Baudez, 2008), etc.

So far, most of the literatures about sludge rheology have only concentrated on the sludge itself, and no matter what kind the sludge is, TS content and temperature are critical parameters affecting its rheological characterisation (Baroutian et al., 2013; Baudez et al., 2011, 2013; Tixier et al., 2003). Additionally, it was reported that there was a great reduction in the apparent viscosity of sludge during AD (Guibaud et al., 2004; Monteiro, 1997). Nevertheless, there is no information available on the variation of dewater sludge rheology under a continuous high-solid AD. Moeller and Torres (1997) investigated the variation of sludge rheological parameters during the process of AD in batch reactors, and the TS content of the sludge studied was below 3%. Pevere et al. (2007) found that the apparent viscosity of the sulphidogenic sludge decreased after 30 days' fermentation in both membrane bioreactor and continuous stirred tank reactor, which were all operated at 33(± 2) °C, a hydraulic retention time of 8 h and a constant pH of 7.0 (± 0.1), but the feedstock studied was sulphidogenic sludge with a TS content less than 1.81 g l^{-1}. Aranowski et al. (2010) reported that the viscosity and pseudoplasticity of the mixture of primary and thickened excessive sludges decreased as AD proceeds in a semi-continuous reactor, which might be attributed to the changes of solids content, but the fermentation time studied only lasted for 17 days under a sludge retention time (SRT) of 20 days.

In this study, four single-stage completely mixed AD reactors were operated semi-continuously under different SRTs (20 d and 30 d) and temperatures (35 °C and 55 °C) using dewatered sludge (TS of 16.16%) as the feedstock. And the objective was to characterize the rheological properties of sludge taken from these high-solid AD reactors after running for more than 3 SRTs. The effects of SRT and temperature of reactor on sludge rheology and the operation performance of these reactors were also investigated. This provides useful information on the evolution of sludge rheology through AD treatment for the design, optimisation, operation and control of high-solid AD facilities as well as the promotion of high-solid AD.

2. Methods

2.1. Substrates and inoculums

Dewatered sewage sludge, which was obtained by collecting primary and excess sludge and dewatered with the aid of a cationic polyacrylamide (PAM) from Wangxiaoying WWTP (Hefei, China), was used as the feedstock in this study. The inoculum was collected from high-solid mesophilic anaerobic digesters of previous experiments with dewatered sludge as the feedstock. Characteristics of substrates and inoculums were listed in Table 1. The collected dewatered sludge was stored at 4 °C and heated to 35 or 55 °C before feeding.

2.2. Reactors and operation

Four identical reactors equipped with liquid working volume of 6.0 l and helix-type stirrers were utilized as the AD reactors in this work, and they were all set at a rate of 60 rpm (rotations per minute) with 3 min stirring and 7 min break continuously. These AD reactors were named as M30, T30, M20 and T20, in which M and T referred to mesophilic and thermophilic, while 30 and 20 referred to the values of SRT. The operation conditions of these reactors were presented in Table 2. At the beginning, 6.0 kg seed sludge was added to each reactor, then they were all operated semi-continuously (once-a-day drawing-off and feeding), and the organic loading rate (OLR) was increased stepwise to the setting data shown in Table 2.

Table 2
Operational conditions of the AD reactors.

Reactors	Temperature (°C)	SRT (d)	OLR (kg VS m^{-3} d^{-1})
M30	35 (mesophilic)	30	3.06
T30	55 (thermophilic)	30	3.06
M20	35 (mesophilic)	20	4.59
T20	55 (thermophilic)	20	4.59

2.3. Rheological measurements and modelling

Sludge rheology was determined by a rotational rheometer (Advanced Rheometer AR2000ex, TA instruments Ltd), which was fitted with a ST AL parallel plates geometry (40 mm diameter, 1000 μm gap). Before each measurement, sludge samples was pre-sheared for 10 min at a shear rate of 1000 s^{-1} then left at rest for 5 min, which aimed to erase material memory and to have reproducible measurements (Baudez et al., 2011). Then measurements were carried out for the first rheological testing mode by increasing shear rate from 10 to 1000 s^{-1} using a logarithmic ramp. The controlled shear rate (CSR) tests were performed at the temperature of 298.15 K using the temperature control system with a Peltier Plate. And during CSR tests, a shorter time span of 5 s for sludge response was employed to indicate the "network strength" of sludge at each shear rate.

Rheological data generated in this work were analyzed using the Herschel-Bulkley model, which is more efficient in describing the sludge rheological behaviour under rest and flow conditions, including the pseudoplastic or shear-thinning and the yield stress characteristics (Baroutian et al., 2013; Eshtiaghi et al., 2012):

$$\tau = k\dot{\gamma}^n + \tau_y \quad (1)$$

where, τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), τ_y is the yield stress (Pa), k is the consistency index (Pa·s^n), and n is the flow behaviour index (dimensionless).

2.4. Analysis methods

During the whole operation of these reactors, the daily yield of biogas was measured and recorded by the wet gas meter, while biogas and substrate samples were taken every 5–6 days to monitor the operation performance of reactors. It was observed that the performance data of each reactor were relatively stable after operating for more than 3 SRTs, which indicated that the reactors were at relatively steady state. Then all tests were undertaken in triplicate. Methane content of the biogas was measured by a gas chromatograph (GC-14B, Shimadzu, Japan) equipped with a thermal conductivity detector (TCD) and an da3 m stainless column. Volatile fatty acid (VFA) was analyzed by a GC (Agilent Technologies

Table 1
Characteristics of the substrate and inoculums.

Parameters	pH	TS (%, w/w)	VS/TS (%)	TAN (mg l^{-1})	FAN (mg l^{-1})
Dewatered sludge	6.85 ± 0.05	16.16 ± 0.09	56.85 ± 0.16	525.9 ± 2.1	2.1 ± 0.2
Inoculums	7.90 ± 0.03	13.76 ± 0.05	31.03 ± 0.23	3677.3 ± 10.4	298.7 ± 1.2