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Research article

Effects of the low-temperature thermo-alkaline method on the rheological properties of sludge

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ABSTRACT

Municipal sewage sludge (hereafter referred to as sludge) in increasing amounts is a serious threat to the environment and human health. Sludge is difficult to dispose because of its complex properties, such as high water content, viscosity, and hazardous compound concentration. The rheological properties of sludge also significantly influence treatment processes, including stirring, mixing, pumping, and conveying. Improving the rheological properties and reducing the apparent viscosity of sludge are conducive to economic and safe sludge treatment. In this study, the low-temperature thermo-alkaline (LTTA) method was used to modify sludge. Compared with the original sludge with an apparent viscosity at 100 s^{-1} (η_{100}) of 979.3 mPa s, the sludge modified under 90 °C–$Ca(OH)_2$-1 h and 90 °C–NaOH-1 h conditions exhibited lower η_{100} values of 208.7 and 110.8 mPa s respectively. The original sludge exhibited a pseudoplastic behavior. After modification, the pseudoplastic behavior was weakened, and the sludge gradually tended to behave as Newton fluids. The hysteresis loop observed during the shear rate cycle was mainly caused by the viscoelasticity of the sludge. The hysteresis loop area (Hla) reflected to a certain extent the energy required to break the elastic solid structure of the sludge. The larger the Hla, the more energy was needed. However, this result should be evaluated comprehensively by considering other sludge parameters, such as yield stress and apparent viscosity. Hla may also reflect the damage degree of the sludge structure after shearing action. The irreversible destruction of the structure during shearing may also increase Hla.

1. Introduction

Sludge is the deposit produced in each operating unit in a municipal wastewater treatment plant (MWTP). Sludge is very difficult to dispose. The high content of energy-containing matter renders sludge a potential candidate for recycling. At present, methods widely used to recycle sludge include anaerobic digestion (Appels et al., 2008; Hidaka et al., 2015), combustion or co-combustion with other fuels (Caneghem et al., 2012; Nadziakiewicz and Koziol, 2003), cement production (Xu et al., 2014), and sludge composting (Cukjati et al., 2012). Regardless of the method used, stirring, mixing, pumping, and conveying are inevitable processes. In addition, the rheological properties of sludge significantly influence these processes. Hence, understanding the rheological properties of sludge is important.

The primary and secondary sludges from an MWTP usually exhibit a high moisture content of up to 96%–99%. Sludge must to be thickened (>90% moisture) and mechanically dewatered (75–85% moisture) for follow-up technological processes. Dewatering can reduce the bulk of sludge significantly and consequently, the costs for sludge storage, transportation, and handling. Dewatering can also increase the caloric value (wet base) of sludge. Thus, the utility value of sludge increases when it is combusted as fuel or used as material to produce cement. However, dewatering decreases the fluidity and then significantly increases the viscosity of sludge. The Primary and secondary sludges have a low viscosity of approximate 10^1–10^2 mPa s at a shear rate of 100 s^{-1}, whereas thickened sludge has a viscosity of approximately 10^2–10^3 mPa s. However, mechanically dewatered sludge is likely to have a viscosity over 10^4 mPa s, which requires a large amount of power to stir and convey the sludge. Therefore, a low-cost method of sludge modification is needed to reduce the viscosity and increase the fluidity of sludge.

Common methods of sludge modification include thermal

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treatment (Appels et al., 2010), ultrasonication (Iritani et al., 2015; Ruiz-Hernando et al., 2014), chemical conditioning (Liu et al., 2012), mechanical disintegration (Ruffino et al., 2015), microwave irradiation (Appels et al., 2013), and wet oxidation (Baroutian et al., 2016). However, existing studies on sludge modification mainly focused on either increasing biogas production (Park et al., 2012; Rafique et al., 2010; Salsabil et al., 2010; Tyagi and Lo, 2011) or improving sludge dewatering (Neyens et al., 2004; Ruiz-Hernando et al., 2015).

Baudez et al. (2011) reported that the Herschel–Bulkley and power–law models are appropriate to describe the rheological properties of sludge at low and intermediate shear rates. The same researchers (Baudez et al., 2013) studied the impact of temperature (10–80 °C) and thermal history on the rheological properties of the solid and liquid fractions of anaerobically digested sludge. They found that the yield stress and high shear viscosity are the key parameters determining the rheological properties of sludge. Farno et al. (2014) focused on the changing trend of the viscosity and yield stress of digested sludge at different temperatures (20–80 °C). Liao et al. (2016) found that low-temperature thermal pretreatment (50–80 °C) decreases sludge viscosity and accelerates high-solids digestion. Urrea et al. (2015) reported that thermal hydrolysis (160–200 °C) reduces the sludge viscosity by two orders of magnitude and improves the fluidity of activated sludge effluent. Mori et al. (2008) investigated the effects of exocellular polymers on the rheological properties of sludge and reported that a decrease in excellular polymer concentration decreases both the viscoplastic and shear-thinning properties of sludge.

Thermochemical methods are commonly used to modify sludge, because of their effectiveness. Among them is the low-cost and facile low-temperature thermo-alkaline (LTTA) method developed using industrial waste heat and low-cost alkali reagents. The LTTA method combines the advantages of thermal and alkali conditioning methods, i.e., both the temperature in the thermal method and the alkali dosage in the alkali conditioning method are decreased; hence, the sludge treatment time is also shortened (Tanaka et al., 1997). The present study used the LTTA method to modify sludge and then analyzed the rheological properties, including apparent viscosity, rheology, thixotropy, and hysteresis loop of the modified sludge. The effects of LTTA modification on the rheological properties of the sludge were determined. The results of this study can serve as an experiment basis for the future design and operation of sludge handling processes.

2. Materials and methods

2.1. Materials

Sludge samples were collected from a wastewater treatment plant in Hangzhou City, China and then stored at 4 °C after slight dewatering. The total moisture content of the dewatered sludge was 86.5%. The proximate and ultimate analyses of the sludge are shown in Table 1.

2.2. LTTA modification of sludge

Sludge of 85 mg was sampled and poured into a 150 mL beaker. Then, an alkali reagent ($Ca(OH)_2$ or NaOH) was added at a dosage of 10% to the dry sludge. The sludge and alkali reagent were mixed well for 5 min and then sealed with a plastic film to prevent water loss. Afterward, the mixture was placed on a shaker operating at a speed of 150 rpm. Different temperatures (25 °C, 50 °C, 70 °C, and 90 °C) and modification times (1, 4, 8, and 24 h) were used in sludge modification. The modified sludge samples were labeled in the form of “Temperature–Alkali–Time”, e.g., 25 °C–Neutral-1 h, 50 °C–$Ca(OH)_2$–4 h, and 90 °C–NaOH–24 h. The 25 °C–Neutral–1 h sample was close to the original sludge and thus was considered as the “blank” reference.

2.3. Measurements and evaluations of the rheological properties of sludge

2.3.1. Rheological measurements

Rheological measurements were performed using a shear rate-controlled viscometer NXS-4C (Chengdu Instrument Factory, China) equipped with wide gap coaxial cylinders (inner radius, 15 mm; outer radius, 20 mm; height, 50 mm). The temperature test was regulated at 20 °C by a thermal water bath.

Before each measurement, the samples were first homogenized at a rotational speed of 500 rpm with an electric mixer for 2 min. Then, the samples were sheared in accordance with the following steps: a continuous shear rate ($\dot{\gamma}$) ramp was applied from 0 s^{-1}–100 s^{-1} in a linear manner within approximately 1 min. A constant $\dot{\gamma}$ of 100 s^{-1} was then held for 5 min. Subsequently, $\dot{\gamma}$ was linearly decreased from 100 s^{-1} to 0 s^{-1}. The shear stress (τ) and the corresponding $\dot{\gamma}$ were recorded online.

Each measurement was repeated for three samples that underwent the same modification scheme to determine the consistency of the results. The results were shown as the arithmetic mean of the three measurements.

2.3.2. Apparent viscosity

The apparent viscosity (η, a quotient of τ and $\dot{\gamma}$), calculated automatically from the shear stress and the corresponding shear rate, was also recorded online.

η is closely related to $\dot{\gamma}$; thus, selecting a certain $\dot{\gamma}$ condition is necessary to evaluate sludge viscosity. In the study, the $\dot{\gamma}$ of 100 s^{-1} was selected, and the corresponding η was expressed as η_{100}, which was used to study the sludge viscosity and the effect of LTTA modification on sludge viscosity.

2.3.3. Flow behavior

Flow behavior was analyzed as the relationship of τ–$\dot{\gamma}$ or η–$\dot{\gamma}$ on the shear rate decreasing ramp.

The Herschel–Bulkley model [Eq. (1)] was adopted to describe the non-Newtonian behavior of the sludge. The Herschel–Bulkley model was introduced by Herschel and Bulkley in 1926.

Table 1
Proximate and ultimate analyses of the sludge.

Proximate analysis (%)				Ultimate analysis (%)					Q_d
M_t	A_d	V_d	FC_d	C_d	H_d	N_d	$S_{t,d}$	O_d	(MJ/kg)
86.5	54.95	40.09	4.96	23.25	4.36	3.77	0.69	12.98	10.36

M_t refers to the total moisture; A_d, V_d, and FC_d respectively refer to ash, volatile, and fixed carbon on a dry basis; ultimate analysis was conducted on a dry basis; Q_d refers to the higher heating value.