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Rheological characteristics of highly concentrated anaerobic digested sludge

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ABSTRACT

Highly concentrated anaerobic sludge digestion is a favorable way to treat a considerable quantity of sewage sludge and recover biogas from both environmental and energetic point of view. For enhancing mass transfer and ensuring efficient anaerobic digestion, pumping and mixing are crucial operations which are directly conditioned by the rheology of sludge. The present work aims at studying the rheological characteristics of highly concentrated anaerobic digested sludge with TS (total solid) content more than 8%. The dependence on both TS content and temperature is investigated, respectively, in dynamic and flow measurements. The results show a shear-thinning behavior with a yield stress under flow measurements and a viscoelastic property in dynamic measurements, comparable to a pasty material. The Herschel–Bulkley model can describe these experimental results and a master curve is then proposed. In addition, the yield stress as well as cohesion energy increase with TS content following a power-law. The effect of temperature is relatively smaller, as a consequence of pronounced internal interactions strengthening the interior structure after the digestion, in the form of networks and steric linking.

Nomenclature

G'	storage moduli (Pa)
G''	loss moduli (Pa)
G_c	critical moduli (Pa)
E_c	energy of cohesion (J m^{-3})
k	consistency (Pa s^n)
n	power index
γ_c	critical strain
η^*	complex viscosity (Pa s)
σ	phase lag between loss and storage moduli
τ	shear stress (Pa)
τ_c	yield stress (Pa)
$\dot{\gamma}$	shear rate (s^{-1})
ω	angular frequency (rad/s)
φ	total solid content

1. Introduction

Sewage sludge is an inevitable residue of wastewater treatment which needs to be treated. Otherwise it will cause huge environmental impact. In the European Union, production of sewage sludge exceeds 30,000 tons (dry matter) per day and would increase by at least 10% in 2020 [1]. The situation in China is more serious. Over 30 million tons dewatered sewage sludge (80% moisture matter) are generated every year and almost 80% of them do not reach necessary stabilization [2]. Anaerobic digestion is an effective way to realize the stabilization of sewage sludge, which has been widely used in Europe and America, being developed in many other countries. Moreover, it can recover biogas as a renewable energy for supplementing energy consumed in the plant.

Recently, highly concentrated anaerobic sludge digestion attracted a great deal of attention [3–5]. It was claimed to be advantageous over traditional lowly concentrated anaerobic sludge digestion for several reasons, such as smaller reactor volume, lower energy requirement for heating, higher net biogas yield ratio, less material handling, less transportation cost and so on [6]. However, high TS content results in tremendous augmentation of viscosity and induces then difficulty of pumping and mixing, which affects mass transfer and anaerobic digestion. Furthermore, dead zone may occur in the digester [7], which is usually not desired in practical operation. The energy consumptions of these essential operations

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which are necessary to be taken into account during digester design are closely associated with the rheology of digested sludge [8]. As a result, it is necessary to characterize and quantify the rheological behavior of highly concentrated anaerobic digested sludge.

There are already a number of studies on the rheology of sludge in the literature. Different kinds of sludge, such as sewage sludge, anaerobic granular sludge and anaerobic digested sludge, as well as diverse impact factors, such as concentration, temperature, extracellular polymeric substance, surface charge and original structure were investigated [9–17]. Baroutian et al. [15] revealed that the temperature and solid concentration affected largely the rheology of mixed primary and secondary sludge. The Herschel–Bulkley model was appropriate to describe its rheological behavior. Mori et al. [10] found viscoplastic and shear-thinning behaviors increased with total suspended solid and decreased with exopolysaccharides concentration within three used measuring geometries for liquid sewage sludge. Baudez and Coussot [17] studied the rheology of pasty sewage sludge as well as the effect of fermentation time and organic components. Yield stress behavior was revealed and the Herschel–Bulkley model described well the flow curve. Due to the absence of digestion, the dewatered sewage sludge fermented rapidly and continuously during the storage, which led to the increase of fatty compound and accordingly the decrease of apparent viscosity.

The digested sludge is relatively stable for physiochemical properties, but only a few attentions were paid to the rheology of concentrated anaerobic digested sludge. Baudez et al. [7] investigated the rheological property of lowly concentrated anaerobic digested sludge with TS content less than 5%, showing a shear-thinning and yield stress behavior. It obeys to Herschel–Bulkley and power-law models at low and intermediate shear rate. While at high shear rate, a Bingham model is sufficient to model it. Then Eshtiaghi et al. [18] found transparent model fluids to mimic the rheological behavior of digested sludge. They made use of carboxymethyl cellulose (CMC) in steady flow at high shear rate, Carbopol gel for short-time flow processes and Laponite clay suspensions for time-dependent behavior.

The present study aims at investigating the rheological characteristics of highly concentrated anaerobic digested sludge with TS content exceeding 8%. The dependence on both TS content and temperature is verified. As a pasty material, the concentrated sludge displays a solid behavior at rest, undergoes arbitrary deformations with enough applied force, and keeps final state when applied forces are withdrawn [19]. At rest, constituent components in the sludge interact each other to form connected microstructures, which are responsible for the solid character and ability to support weight. But these microstructures are devoid of particular order to resist deformation. When a threshold deformation is applied, they break-up and flow as a liquid [20].

2. Materials and methods

Anaerobic digested sludge was sampled at the municipal wastewater treatment plant of Nancy (France) at the outlet of the mesophilic anaerobic digester. Its original TS content was 3.6%, and then respectively concentrated to 8%, 10%, 13% and 16% by centrifugation (Beckman Coulter, USA). To obtain various concentrations, sludge was concentrated step by step under different rotation speeds at room temperature. TS content was determined by drying the sludge in a furnace (Memmert, Germany) at 105 °C during 24 h.

Rheological measurements were performed on an ARES rheometer (TA instruments, USA) connected to thermal bath. The rheometer was equipped with parallel plates geometry (diameter: 50 mm, gap: 10 mm) to investigate the effects of TS concentration and temperature on the rheological behavior of highly concentrated anaerobic digested sludge. Temperature was varied by the thermal bath at 35 °C, 50 °C and 70 °C, respectively, corresponding consecutively to typical temperature range for mesophilic anaerobic digestion, thermophilic anaerobic digestion and alternative temperature for hydrolysis pretreatment. To avoid evaporation during measurements, sludge was covered with a thin film of silicon oil that is immiscible with sludge. The viscosity of the silicon oil employed was 5 mPa s and then negligible with respect to the sludge. Both dynamic oscillatory measurements and steady flow measurements were carried out to gain insight into the internal structure. Dynamic oscillatory measurements lead to structural properties of the sludge, while steady flow measurements give useful information about viscous and viscoplastic properties as key processing parameters.

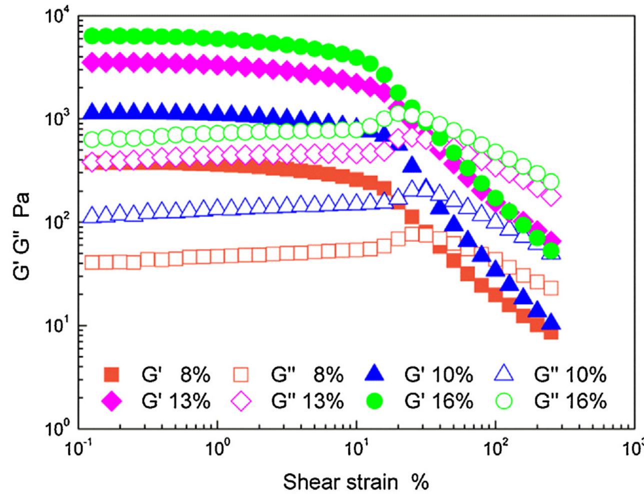

Fig. 1. Evolution of storage and loss moduli during strain sweep at 35 °C with different TS contents.

3. Results and discussion

3.1. Dynamic measurements

Generally, storage modulus G' represents the energy stored in a fluid and characterizes its elastic property, while loss modulus G'' represents the viscous dissipation of energy and the related viscous property. For highly concentrated anaerobic digested sludge, G' and G'' are nearly constant under a low strain, showing a linear viscoelastic behavior. The G' decreases drastically starting from 20% strain, while G'' passes through a peak before decreasing rapidly as well (Fig. 1). These synchronized phenomena: the beginning of a fast decline and the appearance of maximum in the curves of G' and G'', respectively, occur around the strain 20%, suggesting that there is a substantial modification of internal structure in digested sludge around this critical strain. This structural evolution could also be regarded to some extent as a transition from a solid characteristic to a liquid property. These observed phenomena are in agreement with the results of Baudez et al. [1], but the linear viscoelastic domain is much larger in the present work due to high TS content.

The effect of TS content on the elastic behavior of highly concentrated anaerobic digested sludge is clearly illustrated in Fig. 1, even though four pairs of curves have similar evolution of G' and G''. Critical modulus G_c is defined as the intersection of curves G' and G'' and the resulting stress at this point can be considered as the dynamic yield stress $\tau_{c\,dyn}$. It is worth noting that the end of the complex modulus G^* plateau in the strain sweep experiments was also used to corroborate the magnitude of the dynamic yield stress.