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Rheological characterization of digested sludge by solid sphere impact

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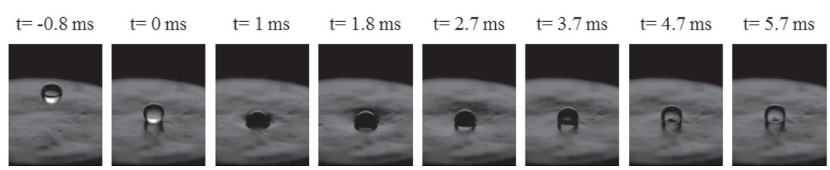
HIGHLIGHTS

- Impact method was applied to high-solids digested sludge.
- Crater diameter and depth depend on sphere diameter and fall height.
- Impact viscosity and elasticity were evaluated through a simplified force model.
- Elastic modulus and viscosity are in agreement with results of classical methods.

GRAPHICAL ABSTRACT

Impact process captured at 45° overhead leaned position (glass sphere diameter 4 mm; free falling height 500 mm).



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ABSTRACT

An impact method was applied to investigate the rheological characteristics of digested sludge and reveal its transient dynamics. A high-speed camera allowed visualizing the dynamic impact process and observing interaction between impacting sphere and targeted sludge. A damping oscillation was observed after the impact. The crater diameter followed an exponential function, while the crater depth varied as a logarithmic function of both sphere diameter and free fall height. Furthermore, the viscosity and elasticity of digested sludge were evaluated by establishing a simplified impact drag force model. The impact elastic modulus was consistent with the Young's modulus measured by a penetrometer. The impact viscosity was reasonable as the estimated impact shear stress was greater than the yield stress of digested sludge resulting in the formation of crater. The impact method offers an alternative way to reveal the viscoelasticity of digested sludge through a dynamic process.

1. Introduction

Rheological properties of soft matters are crucial for industrial applications (Chen et al., 2010). For instance, in anaerobic sludge digestion process, viscosity, elasticity and yield stress of digested sludge are closely associated with energy consummation, mass transfer and treatment efficiency (Slatter, 2011; Jiang et al., 2014a). In general, these rheological parameters can be obtained on a rheometer under steady state and dynamic modes. Nevertheless, it may encounter difficulties at high shear condition taking into account of its complex nature such as the phase separation between water and solid contents. The wall slip on the interface of geometry and sample usually affects the accuracy of rheological measurement. The impact method provides a possibility to overcome this defect and reveal further transient dynamics of soft matters. It could be applied to estimate the properties of materials such as impact resistance, mechanical strength and deformability (Edelsten et al., 2010; Salmi et al., 2012).

Impact was one of the most fundamental processes in nature and studied on diverse materials as a fascinating research subject in recent years (Marston et al., 2013; Lohse et al., 2004; Tanaka, 2006; Uehara et al., 2003). A solid sphere was widely used as an impactor. In the vicinity of impactor, viscoplastic target fluid behaved as a liquid-like or solid-like property depending on the magnitude between impact energy and yield stress (Tabuteau

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et al., 2011), which was largely comparable to the rheological behavior of digested sludge (Baudez et al., 2011). Within a viscoelastic fluid, a cavity appeared in the wake of impactor and underwent transitions from a smooth to fractured surface texture (Akers and Belmonte, 2006). The crater forms and penetration depths in a wet sand target were closely related to the water saturation, which changed the stiffness and yield stress of wet sand (Takita and Sumita, 2013). The phenomena and dynamics in the dry sand target were totally different (Ambroso et al., 2005).

Differing from solid sphere, deformation and eventual capillary effects play indeed an important role and can't be neglected for a soft impactor (Clanet et al., 2004; Nicolas, 2005; Pregent et al., 2009). The crater and crown reached the maximum size at almost the same time, then the crown fell down and a central jet was ejected for a single drop impacting onto a semi-infinite identical liquid (Bisighini et al., 2010). With immiscible target liquid, the drop flattened and spread at the surface of crater followed by a transient open and a maximum deformation in the target liquid accompanying potential fragmentation (Lhuissier et al., 2013; Yakhshi-Tafti et al., 2010). On a deformable surface such as granular layer, the crater shape varied with applied impact speed, grain size and liquid viscosity (Katsuragi, 2010, 2011).

In spite of recent advancements, the impact between a solid sphere and a complex viscoelastic matter is still scarce until quite recently (Ara and Katsuragi, 2013). As an effective way for sludge treatment, anaerobic sludge digestion involving complex viscoelastic matter attracts extensive attentions owing to a considerable amount of residual sludge produced from wastewater treatment plant (Duan et al., 2012; Hidaka et al., 2013). Rheological characteristics of digested sludge are closely related to the operation efficiency of a digester, in particular dealing with high solids content sludge (Dai et al., 2014; Eshtiaghi et al., 2012). Dynamic elasticity acts at the start-up of industrial application reactor, while dynamic viscosity under high shear rate appears in the pumping process. Both properties can increase operation difficulty and affect reactor design. Therefore, digested sludge was chosen as impact target to investigate its viscoelastic characterization of transient dynamics. With respect to existing impact targets in the literature such as granular sand media, digested sludge displays more heterogeneous behaviors. To our best knowledge, the impact experience was yet conducted in these complex media. In this study, crater dimensions and its formation process were characterized by means of a high-speed camera. In particular, a simplified impact drag force model was established to analyze the dynamic data. The viscosity and elasticity of digested sludge were estimated and then compared respectively with the result obtained by conventional rheometer and penetrometer.

2. Material and methods

2.1. Digested sludge

Anaerobic digested sludge was sampled at the municipal wastewater treatment plant of Nancy (France) at the outlet of mesophilic anaerobic digester and concentrated to 14.9% total solid (TS) content by centrifugation (Beckman Coulter, USA) with a wet bulk density ρ_s about 1200 kg/m^3. All of the digested sludge mentioned subsequently involving experiments possessed 14.9% total solid content. It is worth mentioning that recently, high-solids anaerobic sludge digestion (TS content >8%) attracted extensive attentions. It was advantageous over traditional anaerobic sludge digestion, such as smaller reactor volume, lower energy requirement for heating and less transportation cost. However, high TS content results in augmentation of viscosity and induces further difficulty of pumping and mixing, which will affect mass transfer process and anaerobic digestion efficiency. Thus, the digested sludge used in this work appears in high-solids anaerobic sludge digestion reactor.

2.2. Rheological properties

Rheological measurements were performed on an ARES rheometer (TA Instruments, USA) connected to a thermal bath. The rheometer was equipped with parallel plates geometry (diameter: 50 mm, gap: 2 mm) to allow reliable measurements. Both flow measurement and frequency sweep were carried out at 20 °C to characterize the rheological property of digested sludge.

2.3. Elastic modulus

The mechanical resistance of digested sludge was measured by a penetrometer (Instron, USA) equipped with a cylindrical needle of diameter 3 mm and a force sensor in the range of 0–10 N. The penetration velocity of the needle was set at 10^{-4} m/s. Experiments were repeated with similar samples about twenty times. Elastic modulus could be estimated according to the slope of curve at initial stage.

2.4. Impact experiments

A simple experimental apparatus was built up for free fall impact tests (Fig. 1). A glass container (diameter 40 mm, depth 25 mm) was overfilled with pressed digested sludge and then a straight edge was used to remove excess digested sludge and make the target surface flat and smooth. The dimension of container was large enough compared with that of used glass spheres, whose diameter d was respectively 3, 4, 5 mm and uniform density ρ_b was 2600 kg/m^3. In addition, the spheres stopped always in the center of shallow target surface. As a result, the effects of vessel's wall and base could be neglected with sufficient width and depth scales (Seguin et al., 2008). Experiments were completed by dropping sphere from a holder positioned at a certain height above the center of target surface. Impact velocity was controlled by free fall height h ranging from 150 to 500 mm, which was measured from the bottom of sphere to target surface by a height gauge. Because of negligible air drag effect under current experimental conditions, the free fall relation $v_0 = \sqrt{2gh}$ was accurate enough to calculate the impact velocity, where g was the gravitational acceleration (Range and Feuillebois, 1998). According to limited free fall height, impact velocity ranges from 1.7 to 3.1 m/s, much less than the terminal velocity (Table 1).

The impact process was visualized by a high-speed camera (Phantom v711, USA) at rate of 10,000 frames per second. An evident contrast for image capture was insured by a powerful LED

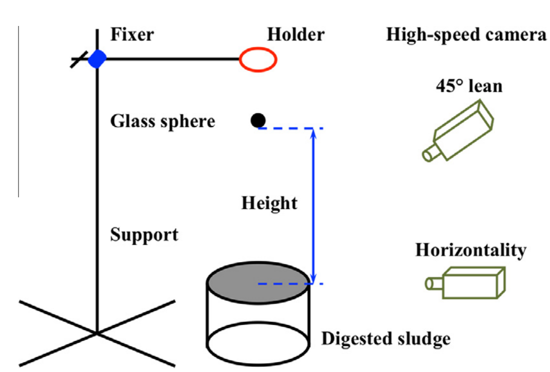

Fig. 1. Schematic illustration of experimental apparatus for impact method.