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A rheological approach to analyze aerobic granular sludge

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ABSTRACT

Aerobic granular sludge is one promising biotechnology in wastewater treatment. Despite intensive researches on granular architecture and strategies to improve treatment efficiency, there are still some elusive material parameters needed to stimulate the granulation process. The main aim of this study was to evaluate aerobic granular sludge innovatively using the universal rheology methodology, in terms of processability or quality and texture. Steady shear and oscillatory measurements were performed. Basic rheological characterization showed that aerobic granular sludge was a shear-thinning Herschel–Bulkley fluid with yield pseudoplasticity. Meanwhile, granular sludge presented characterized viscoelastic behaviors in dynamic sweeps highlighting its superiority to flocculent sludge. Furthermore, a Wagner-type constitutive model incorporating a relaxation and damping function was introduced and able to describe the time-dependent and non-linear viscoelastic behaviors. This study could make a further step on predicting rheological properties, helping improve the actual sludge treatment process and the operation of sludge dewatering.

1. Introduction

Compared with conventional activated sludge system, granular sludge exhibits a more robust aggregate structure, better solid–liquid separation, higher biomass concentration and greater endurance to withstand shock loadings (Liu et al., 2009). Based on these advantages mentioned, granular sludge has been regarded as a promising technology in wastewater treatment. With decades of researches, predecessors have made plentiful micro- and macro-scale observations of the aerobic granular sludge, in terms of both structure and function, including settleability, morphology, permeability, porosity, thermodynamics, mechanical stability, surface hydrophobicity, and its practical applications in removal of phenol or heavy metals (Liu and Tay, 2004; Liao et al., 2001). The knowledge about its physicochemical characteristics and technological parameters has steadily improved to stimulate this technology. Nevertheless, there still exist some unanswered puzzles in the granulation process, for example, it is hard to give a precise qualitative or quantitative delimitation when granular sludge system comes to deterioration (Adav et al., 2008). To get a better understanding about granulation and achieve higher treatment

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efficiency, a deeper exploration of mechanism and a clearer definition of technological parameters are needed urgently.

Rheology is a subject describing the deformation of a body under influence of mechanical stress, and is a valuable tool for characterizing non-Newtonian and viscoelastic properties of the materials, e.g. sludge suspension (Chen et al., 2010; Wloka et al., 2004). As not only can it reflect the internal architectural features (Lin et al., 2013), but also can quantify flow behavior in actual process or sludge cake behavior during mechanical expression (Chang and Lee, 1998; Sozanski et al., 1997). These research fields about rheology applied in sludge system have already been proved successfully. Baudez et al. (2012) discussed these similarities of the viscoelastic behaviors of raw and anaerobic digested sludge with soft-glassy materials, and differentiated these two kinds of sludge in micro-rheology to a certain extent. To describe rheological parameters in sludge flow, Eshtiaghi et al. (2012) tried to use certain model fluids to emulate thickened digested sludge. And Stoodley et al. (1999) gave an in-situ investigation of bacterial bio-film rheology reflecting structural deformation caused by short-term fluctuations in fluid shear and concluded that bio-film viscoelasticity could increase fluid energy losses in pipelines. In brief, predecessors have given a fundamental inter-linkage between rheology and flocculent sludge, and that innovation makes it feasible to apply rheological analysis in a granular sludge system, as similarly implied by Mu and Yu (2006).

However, the understanding of rheological dynamics properties of granular sludge is rather limited because of fragmented studies on the whole. Most subtle researches have been concentrated on the study of extracellular polymeric substance (EPS) or its individual components (Ying et al., 2010; Seviour et al., 2009a; Lin et al., 2010). To our knowledge, the in-situ rheological characterization of aerobic granular sludge has barely been reported as a complete system, although important parameters, such as limiting viscosity and intrinsic viscoelasticity, play big roles in differentiating liquid-like from solid-like regime in granules (Seviour et al., 2009b). What's more, it is a challenge to match the viscoelastic response with steady-state flow behavior in sludge flow system, and limited attempts have been made. Mackley et al. (1994) extended an integral form Wagner equation originally developed for the description of polymer melts to test its applicability on an associative thickener, a kaolinite slurry, an oil-based paint and so on. Also Liang and Mackley (1994) adopted the same model, incorporating with a relaxation and damping function, to perform non-linear viscoelasticity and predict stress growth and steady-shear behaviors for polyisobutylene solutions. So Wagner-type model seems to be a promising solution.

In this paper, the aim was to elaborate the fundamental understanding of intrinsic rheological properties of aerobic granular sludge by performing basic rheological characterization and viscoelasticity measurement. Firstly, in steady shear measurement, shear deformation under the simple shearing flow was measured and shear stress was recorded to obtain its basic flow behaviors. Secondly, in oscillatory measurement, strain, frequency and temperature sweeps were conducted to obtain its viscoelastical response to external forces, and its granular configuration was highlighted in comparison with flocculent sludge reported by Baudez et al. (2012). Finally, to match the time-dependent viscoelasticity with the steady-state flow, a Wagner-type model, was established to predict the sludge flow preliminarily.

2. Materials and methods

2.1. Aerobic granules for investigation

The aerobic granules were sampled from a lab-scale granular enhanced biological phosphorus removal reactor treating synthetic wastewater with COD: N: P as 22: 1.6: 1. The reactor had a working volume of 8 L, operated with a cycle time of 6 h, and temperature was kept between 22 and 25 °C. Each cycle was consisted of a 130 min-anaerobic stage, a 190 min-aerobic stage, a 30 min-settling period and a 10 min-decant period. The suspended solid concentration (SS) was about 4 g/L, and the reactor was operated for over 3 months staying at a pseudo stable level. SS was measured following the Standard Methods (APHA, 1998).

Granules for rheological tests were collected at the end of aerobic period. Before tests, granules were gently concentrated to every objective concentration, and stored at 4 °C overnight in order to reduce temporal variability.

2.2. Extraction of extracellular polymeric substances

Granules with EPS extracted were obtained using a heat extraction method (Morgan et al., 1990). The sludge suspension was first dewatered by centrifugation in a 50-mL tube at 6000 rpm for 5 min. The pellet in the tube was re-suspended into 0.1 M NaCl solution and washed twice. Then sludge was diluted with NaCl solution to its original volume, and was heated to 60 °C in a water bath for 20 min. The supernatant collected after a centrifugation was regarded as EPS extraction, and the retained granules were used for following experiments to give a qualitative comparison.

2.3. Rheological tests

Rheological tests were carried out using a rotational ARES-G2 rheometer, a coaxial cylindrical measurement device, connected to a temperature controlled water bath. The rheometer was equipped with a cup and bob geometry. A 20-mL aliquot of granule sample in a certain concentration was poured into the cup and the bob was lowered until the space between bob and cup was fully wetted.

The temperature was kept at 25 °C through water bath. Before each rheological measurement was performed, granular sludge was pre-sheared for 5 min at a shear rate of 500 s^{-1}, which was to erase material memory and have reproducible results. Then granular sludge was left at rest for 10 min for different tests performed:

In the steady shear mode, shear stress (τ) was measured as shear rate ($\dot{\gamma}$) increased from 1 to 800 s^{-1} and then vice versa. The temperature was kept at 25 °C.

In the oscillatory shear mode, granular sludge was subjected to small and reversible periodic oscillations of frequency (ω) with shear strain (γ) and shear stress (τ) recorded. Strain, frequency and temperature sweeps followed the same