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Rheological and fractal characteristics of granular sludge in an upflow anaerobic reactor

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ABSTRACT

The rheological and fractal characteristics of the granular sludge in an upflow anaerobic sludge blanket (UASB) reactor were investigated in this study. The influences of sludge concentration and temperature on the rheological properties of the granular sludge were evaluated, and the Bingham model was adopted to describe its rheology. In addition, image analysis was used to determine the sludge fractal dimension. The results indicate that the UASB granular sludge showed a shear-thinning behavior. The relationships between the limiting viscosity and the sludge concentration, as well as the limiting viscosity and temperature could be respectively modeled using an exponential equation and Arrhenius equation well. The Bingham model was able to adequately describe the rheology of the granular sludge. The fractal dimension of the granular sludge, 2.79 ± 0.03, was larger than that of some other aggregates, suggesting that the granular sludge were more compact and denser. Furthermore, the relationship between rheological and fractal properties of the granular sludge could be properly described with the model proposed by Shih et al. [1990. Scaling behavior of the elastic properties of colloidal. Phys. Rev. A 42, 4772–4779].

1. Introduction

Rheology is a powerful tool for characterizing the non-Newtonian properties of sludge suspensions, as it can quantify flow behaviors in real processes on a scientific basis (Dentel, 1997). In addition, fluid dynamic parameters have been found to be correlated to other material characteristics, such as particle size and distribution, surface charge, degree of hydratation, cohesion of sludge of agglomerated particles in suspension, and the dewaterability of sludges, i.e., their suitability for thickening, flocculation, centrifugation, etc. (Forster, 2003; Seyssiecq et al., 2003). A considerable number of studies have been conducted regarding the rheological characteristics of activated sludge. Rheological parameters have been found to be able to be employed as operating guides for conditioner assessment and control of sludge disposal (Abu-Orf and Dentel, 1999). The area of the hysteresis loop on the rheogram could be used as a parameter for indicating the overgrowth of filamentous bacteria species in activated sludge (Tixier et al., 2003a, b). The effects of surface physicochemical properties of activated sludge on its rheological parameters have been extensively studied (Forster, 2003).

On the other hand, natural aggregates such as those formed during water and wastewater treatment (Li and Ganczarczyk, 1989) have been characterized as fractal. Properties of sludge permeability, density, and porosity can be calculated from the fractal dimension (D_f) and have important implications for the aggregation kinetics, floc break-up, and settling velocities of sludge as a function of its fractal structure (Johnson et al., 1996). A powerful application of fractal geometry for describing sludge structure lies in its potential to relate formation processes to aggregate structure (Li and Ganczarczyk, 1989). Thus, the ability to measure the D_f of sludge is of considerable interest.

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In the past two decades, high-rate anaerobic treatment systems have been developed and are widely used. The methane production from anaerobic fermentation of organic wastes promises to be an economical and sustainable technology for both pollution control and energy generation (Lettinga et al., 1993). This anaerobic methanogenic process is greatly influenced by many factors, such as substrate composition, substrate concentration, hydraulic retention time, pH, and temperature (Holshoff Pol et al., 2004). The rheological and fractal characteristics of granular sludge in an upflow anaerobic sludge blanket (UASB) might also be significant factors influencing anaerobic production. They not only have an influence on the design and operation of an anaerobic reactor, but also impose a significant effect on the mass transfer of substrate and nutrition within granular sludge, as well as the release of generated methane from aqueous phase to gaseous one.

However, so far little information is available in the literature concerning the rheological and fractal properties of granular sludge in UASB reactors. Therefore, the main objective of this study was to explore the rheological and fractal characteristics of anaerobic granular sludge, in order to provide useful information for the design and operation of methanogenic reactors. The influences of sludge concentration and temperature on the sludge rheological properties were evaluated, and Bingham model was employed to describe its rheology. In addition, image analysis was performed to determine the fractal dimension of the granular sludge. Furthermore, the relationship between rheological and fractal characteristics of the granular sludge was established in the present study.

2. Materials and methods

2.1. *UASB granular sludge*

The granular sludge samples used in this study were obtained from a full-scale UASB reactor treating citrate-producing wastewater located in Benpu, China. This UASB reactor has a treatment capacity of 3000 m^3/d and a working volume of 2000 m^3. It is being operated at pH 6.8 and temperature of 35 °C. The specific methanogenic activity (SMA) of the granular sludge was 332 ± 50 mL-CH_4/g-VSS/d (volatile suspended solids: VSS), and its average size was 150–250 μm. The average VSS/TSS (total suspended solids: TSS) ratio of the granular sludge samples was 0.85 ± 0.05. Prior to use, the granular sludge samples were washed with tap water five times, and were then sieved to remove stone, sand, and other coarse matters.

2.2. *Analytical methods*

The rheological tests were carried out using a rotational viscometer (NXS-11A Rotational Viscometer, Chengdu Instrument Co.), a coaxial cylindrical measurement device with a gap of 0.8 mm. Fifteen different shear rates ($\dot{\gamma}$), which were defined as the changing rate of strain (γ), i.e., $\dot{\gamma} = d\gamma/dt$, were available at this viscometer. The rheogram of shear stress (τ)

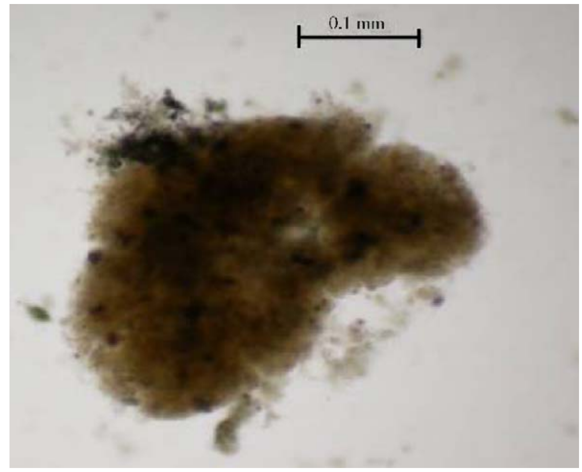

Fig. 1 – Image of the UASB granular sludge.

as a function of shear rate was recorded and analyzed for the sludge samples with the viscometer.

The D_f of the granular sludge was determined using image analysis (Motta et al., 2001). An Olympus CX41 microscope equipped with a digital camera (Olympus C5050 Zoom) and connected to a computer via a grabbing board was used for the image analysis. A drop of mixed liquor was carefully deposited and covered with a cover slip. No staining or fixation was done. At ambient temperatures of 20–25 °C, a series images with a resolution of 400 were obtained by a systematic examination of the slide: adjacent fields were grabbed by scanning the slide from the top right corner to the bottom left one. The pixel size calibration was done with a stage micrometer. Fig. 1 shows a typical image of the granular sludge. The image was then analyzed using a software of Fractal Image Process System developed by the University Science and Technology of China (Sun et al., 2003) and the analytical flowchart is illustrated in Fig. 2. The gray-level images (Fig. 2(a)) are automatically segmented, resulting in a binary image (Fig. 2(b)). Later, the Euclidian distance map (EDM) of images is generated (Russ, 1995) as shown in Fig. 2(c). In the EDM image, the gray-level b associated to each pixel is related to its distance to the nearest border. The gray-levels distribution $b(S)$ gives the number of pixels at each distance S. The perimeter $P(S)$ is calculated by dividing the number of pixels having a gray-level larger or equal to S by S:

$$P(S) = \frac{\sum_{i=1}^{S} b(i)}{S}. \quad (1)$$

If k is the slope of $\log P$ versus $\log S$, the D_f can be calculated with the following equation:

$$D_f = 2 - k. \quad (2)$$

The pH value of the sludge suspension samples was adjusted to around 7.0 using 4 mol/L HCl or NaOH solutions throughout the experiments. The TSS content of samples was adjusted by either diluting using the same sludge liquor or thickening by centrifuging at 1500g for 5 min. Thermostatic water bath was used to maintain the sample temperature