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Predicting the apparent viscosity and yield stress of mixtures of primary, secondary and anaerobically digested sewage sludge: Simulating anaerobic digesters

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A B S T R A C T

Predicting the flow behaviour, most notably, the apparent viscosity and yield stress of sludge mixtures inside the anaerobic digester is essential because it helps optimize the mixing system in digesters. This paper investigates the rheology of sludge mixtures as a function of digested sludge volume fraction.

Sludge mixtures exhibited non-Newtonian, shear thinning, yield stress behaviour. The apparent viscosity and yield stress of sludge mixtures prepared at the same total solids concentration was influenced by the interactions within the digested sludge and increased with the volume fraction of digested sludge – highlighted using shear compliance and shear modulus of sludge mixtures. However, when a thickened primary – secondary sludge mixture was mixed with dilute digested sludge, the apparent viscosity and yield stress decreased with increasing the volume fraction of digested sludge. This was caused by the dilution effect leading to a reduction in the hydrodynamic and non-hydrodynamic interactions when dilute digested sludge was added.

Correlations were developed to predict the apparent viscosity and yield stress of the mixtures as a function of the digested sludge volume fraction and total solids concentration of the mixtures. The parameters of correlations can be estimated using pH of sludge. The shear and complex modulus were also modelled and they followed an exponential relationship with increasing digested sludge volume fraction.

1. Introduction

Municipal sludge is the by – product of the municipal waste water treatment process. It is produced from human and residential waste, as well as industrial waste, farmland and landfill leachates and runoff from streets (Sanin et al., 2011). Sanin et al. (2011) describes sludge as an odorous mixture of organic flocs suspended in water whilst Bhattacharya (1981) and Baudez et al. (2013) have defined sludge as a suspension composed of mainly water (more than 95%), mineral particles, dead and alive bacteria (polymeric and dissolved). Two types of sludge are sent to the sludge treatment process – primary and secondary sludge whereby they are treated and stabilized to eliminate odour and remove suspended organic and inorganic matter and reduce pathogens and bacteria (Sanin et al., 2011). Anaerobic digestion is the most commonly used technique to stabilize sludge and reduce its volatile solids by about 40% (Sanin et al., 2011). During anaerobic digestion, the organic matter in primary and secondary sludge or a mixture of the two are degraded in the absence of oxygen with continuous mixing to produce methane gas (CH_4), carbon dioxide (CO_2) and anaerobic digested sludge. The methane gas is used as a source of heat or to generate electricity whilst the anaerobic digested sludge is dewatered (i.e. further treatment) to reduce its volume prior to disposal (Sanin et al., 2011). However, a UNESCO report (Nicklin and Cornwell, 2013) has shown that the amount of sludge generated globally is increasing at an exponential rate due to population growth so that the current sludge treatment plants including anaerobic digesters cannot handle the additional load of sludge without further innovative techniques or optimisation of current treatment plants.

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Anaerobic digestion requires efficient mixing of the primary and secondary sludge entering the digester to provide an optimum environment for digestion. Karim et al. (2004) explains that efficient mixing is necessary to transfer substrates to microorganisms, to maintain process stability, to maintain a uniform pH and temperature for bacterial growth, to prevent short circuiting and solids deposition in the digester bottom as well as to minimize scum and foam formation. However, the exponential production of sludge combined with the fact that anaerobic digesters are inadequately designed, has led to inefficient mixing (Eshtiaghi et al., 2012, 2013b). Karim et al. (2004) states that inefficient mixing of sludge leads to the formation of dead zones within the digester and poor microbial environment for biogas production. As a result, the anaerobic digesters fail (Karim et al., 2004).

Any changes to the flow behaviour of sludge entering the digester as well as the recirculated digested sludge through heat exchangers alters the performance of the digesters. As such, predicting the flow behaviour, most notably, the apparent viscosity and yield stress of mixtures of primary, secondary and digested sludge is essential to achieve efficient mixing. This is due to the fact that these two parameters have an impact of on the operating conditions and energy consumption of the digesters.

As mentioned earlier, primary and secondary sludge are fed to the digester where mixing is achieved by means of a constant recirculation of digested sludge in conjunction with gas injection. Primary sludge, also known as “raw sludge” is the product of the primary treatment process whilst secondary sludge, also known as “waste activated sludge” is the product of the secondary treatment process. Each sludge is biologically different, so that the interactions governing their network structure are also different. This means that primary, secondary and digested sludge flow differently. Bayoudh et al. (2009) and Cui et al. (2011) explained that the structure of primary sludge was governed by nonspecific Lif-shitz van der Waals forces as well as hydrogen and chemical bonds similar to highly colloidal suspensions such as bentonite (Coussot et al., 2002; Markis et al., 2014). Secondary sludge is composed of polysaccharides and proteins, bacteria and microorganisms which are governed by electrostatic and hydrogen bonds (Flemming, 1996) so that extracellular polymeric substances (i.e. EPS) are formed. Wingender et al. (1999) explained that the EPS form a three dimensional gel like negatively charged structure. Forster (1983) found that digested sludge contained proteins and lipopolysaccharides with both hydrophobic and hydrophilic heads. Furthermore, the structure of digested sludge was governed by steric interactions (Forster, 2002) and has been found to behave similar soft glassy materials such as O/W emulsions (Baudez et al., 2013).

The rheology of individual sludge has been studied extensively over the years (Dick and Ewing, 1967; Bhattacharya, 1981; Battistoni, 1997; Slatter, 1997; Baudez and Coussot, 2001; Seyssiecq et al., 2003; Baudez, 2008; Baudez et al., 2011a; Eshtiaghi et al., 2012, Eshtiaghi et al., 2013a; Markis et al., 2014; Baroutian et al., 2013), however, there is little to no information on the rheology, notably, on the apparent viscosity and yield stress of mixtures of primary, secondary and digested sludge. Markis et al. (2015) is the only study that investigates the impact of volume fraction and total solids concentration on the apparent viscosity and yield stress of mixtures of primary and secondary sludge. Mixtures of primary and secondary sludge as well as the individual sludge displayed non – Newtonian, shear thinning yield stress behaviour, consistent with the previous work on individual sludge. Markis et al. (2015) demonstrated that when mixtures of primary and secondary sludge are prepared at the same total solids concentration, the apparent viscosity and yield stress increases with increasing volume fraction of secondary sludge. Moreover, Markis et al. (2015) demonstrated that when thickened sludge is mixed with dilute sludge (regardless of being primary or secondary), the apparent viscosity and yield stress increased with increasing the volume fraction of the thickened sludge regardless of the sludge type. They explained that this was due to the strengthening of hydrodynamic and non-hydrodynamic interactions within concentrated sludge which was consistent with other studies (Markis et al., 2014; Baudez, 2008; Baudez et al., 2011b).

In the above mentioned studies, the impact of volume fraction of digested sludge on the apparent viscosity and yield stress of mixtures of primary, secondary and digested sludge was not investigated. This highlights the lack of research focusing on the rheological characterization of mixtures of primary, secondary and digested sludge over a wide total solids concentration and different volume fraction. Consequently, this study focuses on the rheology of sludge mixtures which will help understand the flow behaviour of sludge inside digesters. Correlations have been developed to estimate the apparent viscosity and yield stress of mixtures of primary, secondary and digested sludge as a function of total solids concentration and volume fraction of digested sludge. Additionally, the parameters of these correlations have been linked to the pH of sludge mixtures. The shear compliance and shear modulus of sludge mixtures are presented to highlight the changes in flow behaviour after digested sludge is introduced to the mixture of primary and secondary sludge.

2. Materials and method

Sludge was sampled in two different seasons and over two different years – summer (December to February 2014) and winter (June to August 2015). It was also sampled from two different treatment plants – the Mount Martha waste water treatment plant (Mornington Peninsula, Australia) and the Eastern treatment plant (Bangholme, Australia). Hence, any changes to the flow behaviour of sludge due to changes in environmental conditions experienced by sludge during different seasons (summer or winter) may be detected. Table 1 contains a summary of the different locations used to sample the sludge over the two different seasons. Table 2 contains a summary of the different total solids concentration required to prepare the different mixtures of sludge. Table 3 contains a summary of the volume required to prepare the different mixtures of primary, secondary and digested sludge.

2.1. Sample preparation

Dilute primary, secondary and digested sludge were thickened to the various total solids concentrations required and shown in Table 2 using the vacuum filtration technique. The total solids concentration was measured using a technique described elsewhere (Apha, 1992); this procedure was repeated five times to ensure the correct total solids concentration was measured. The samples were stored at 4 °C for 30 days prior to conducting the experiments. This ensured that the same material was always used throughout the experiments by reducing any changes to the composition (Curvers et al., 2009; Baudez et al., 2011b) without affecting the rheology.

First, mixtures of primary, secondary and digested sludge at the same total solids concentration were prepared. As such, the total solids concentration of the resulting mixture was equal to the total solids concentration of the individual primary, secondary and digested sludge. A 50–50 (V. %) mixture of primary and secondary sludge was prepared by mixing an equal volume of primary sludge with an equal volume of secondary sludge. Then different volume fractions of digested sludge were then added to this mixture, summarized in Table 3. For example, (refer to Tables 2 and 3), 3% primary sludge first was mixed with 3% secondary sludge; then 3%