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The viscoelastic behaviour of raw and anaerobic digested sludge: Strong similarities with soft-glassy materials

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ABSTRACT

Over the last few decades, municipal and industrial wastewater treatment activities have been confronted with a dramatically increasing flow of sewage sludge. To improve treatment efficiency, process and material parameters are needed but engineers are dealing with vast quantities of fundamentally poorly understood and unpredictable material Thus, accurate prediction of critically important, but analytically elusive process parameters is unattainable and is a matter of grave concern. Because engineers need reliable flow properties to simulate the process, this work is an attempt to approach sludge rheological behaviour with well-known materials which have similar characteristics. Sludge liquid-like behaviour is already well documented so, we have focused mainly on the solid-like behaviour of both raw and digested sludge by performing oscillatory measurements in the linear and non-linear regimes. We have shown that the viscoelastic behaviour of sludge presents strong similarities with soft-glassy materials but differences can be observed between raw and digested sludge. Finally, we confirm that colloidal glasses and emulsions may be used to model the rheological behaviour of raw and anaerobic digested sludge.

1. Introduction

Sewage sludge production is the residue of wastewater treatment and by definition can't be avoided. In the EU it is produced at more than 30,000 tonnes (dry matter) per day and will increase by at least 10% in 2020 (EUREAU, 2012). These volumes have to be treated and reused.

Slatter (1997, 2001, 2003, 2004 and 2008) has consistently shown that sludge rheology plays a fundamentally important role in analysing the hydrodynamic behaviour of the sludge, as it flows in pipes or in tanks and reactors, such as anaerobic digesters. However, sludge properties continuously evolve due to the ongoing biochemical reactions, and for this reason it cannot be used as a reference material for the design of industrial processes: engineers need reliable and repeatable flow properties to simulate the process. Thus, various researchers attempted to use model fluids instead of sludge, such as kaolin suspension for the yield stress determination (Spinosa and Lotito, 2003), polymeric gels (Legrand et al., 1998), polyvinyl chloride (PVC) suspensions (Bongiovanni, 1998), polystyrene latex (Sanin and Vesilind, 1996), but none of these was particularly successful because each of these model fluids was only representative of a particular application. To model the flow properties of sludge, mainly in its liquid regime,

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kaolin suspensions are often used (Héritier et al., 2010) because it shows shear-thinning behaviour with a yield stress, modelled with a Herschel–Bulkley model (Masalova et al., 2006). Even if this model fluid can be used to simulate high velocity flows, it is not suitable for simulating the liquid-like behaviour at intermediate shear rates, nor the solid-like behaviour at low shear rates, which appears to be crucial in order to avoid – or at least minimise – dead zones in reactors, such as anaerobic digesters or aeration basins.

Because of its fundamental nature, sludge is a very complex mixture of unknown composition and its rheological behaviour is highly dependent of the treatment processes: accurate prediction of critically important, but analytically elusive, process parameters is unattainable and is a matter of grave concern.

For sake of simplicity, in the following we will only distinguish between activated (raw) and anaerobically digested sludge, respectively representative of the outlet of sludge treatment when no tertiary treatment is applied and when anaerobic digestion is implemented. Both are temperature-dependent (Dieudé-Fauvel et al., 2009; Baudez and Slatter, submitted for publication), present viscoelastic properties at low shear stress and a shear-thinning behaviour at high shear stress (Baudez and Coussot, 2001; Baudez et al., 2011), but at intermediate shear stresses, raw sludge is a thixotropic material (Tabuteau et al., 2006; Baudez, 2008) with ageing effects (Baudez, 2008) while anaerobic digested sludge highlights shear banding (Baudez et al., 2011).

Raw and digested sludge are mainly composed of water (more than 95%) and the remaining part is made of organic matter and bacteria which tend to aggregate forming flocs. That is the usual 'chemical' definition of sludge: organic flocs suspended in water. However, physically, sludge can also be visualised as interacting particles in a suspending medium: bacteria form extra polymeric substances (EPS), finally presenting a three-dimensional gel-like biofilm matrix (Wingender et al., 1999). EPS are highly charged polymers that interact with water in a manner similar to gels (Keiding et al., 2001; Sutherland, 2001). They interact with divalent metal ions to form sludge flocs in both aerobic and anaerobic treatment systems (Higgins and Novak, 1997). Flocs in activated sludge usually carry negative charge at neutral pH. It has been found that the extracellular polymeric substances (EPS) contribute to the negative surface charge of the sludge flocs (Jia et al., 1996; Liao et al., 2001). As regards the influence of the anaerobic digestion, Jia et al. (1996) also observed that during batch tests both surface charge and EPS content change significantly.

Polysaccharides and proteins were found to be the most significant surface polymers in activated (raw) sludge (Forster, 1983), and the two types of binding mechanisms between water molecules and the EPS structure are considered to be electrostatic and hydrogen bonds (Flemming, 1996).

Digestion leads to the transfer of bigger flocs into smaller ones (Mahmoud et al., 2006) and disintegration of the organics brings the solids to a homogeneous grain structure, with an increase of the quantity of colloidal particles (Turovskiy and Mathai, 2006) and a decrease of EPS (Karapangiotis et al., 1998). The anaerobic digestion data showed strong correlations between soluble protein generation and ammonium production (Park et al., 2006). The most important constituents in digested sludge are proteins and lipopolysaccharides (Forster, 1983), which are amphiphile lipids with both hydrophilic and hydrophobic heads. Novak et al. (2003) found the protein concentration was 3–5 times greater than the polysaccharide concentration in anaerobic systems compared to aerobic ones. They also noticed an increase of monovalent cations.

From a physical point of view, anaerobic digested sludge appears to be a stable suspension with low settling ability (Námer and Ganczarczyk, 1993) and low surface charge (Forster, 2002) indicating that interactions are more steric than electrostatic.

Moreover, Mikkelsen and Keiding (2002) showed that the ratio between protein and polysaccharides are more or less of the same order between activated and (mesophilic) digested sludge, but the degree of dispersion is 20 times higher after anaerobic digestion, indicating that sludge structure is strongly affected by anaerobic digestion.

In this paper, we intend to draw parallels between well-known materials and sludge. These well-known materials could then be used as model fluids to emulate the rheological behaviour of sludge for the investigation and design of treatment technologies. Because the liquid-like behaviour of sludge is well documented, we will intentionally focus on the solid-like behaviour of both raw and digested sludge by performing oscillatory measurements in the linear and non-linear viscoelastic regimes. We show that the viscoelastic behaviour of sludge presents strong similarities with soft-glassy materials but differences can be observed between raw and digested sludge. Stress and frequency sweeps were conducted at different temperatures to demonstrate that Brownian motion also plays a role in the build-up and break-down of sludge structure. Finally, we demonstrate that colloidal glasses and emulsions may be used to model the rheological behaviour of raw and anaerobic digested sludge.

2. Materials and methodology

Sludge was obtained from the Mount Martha wastewater treatment plant (Melbourne, Victoria, Australia) at the inlet (called raw sludge in the following) and the outlet (called digested sludge) of the digester number 1. The initial concentration of the raw sludge was found to be 45 g L^{-1} (this relatively high concentration was obtained after flotation thickening, without chemical conditioning) while the solid concentration of the digested sludge was found to be 18.5 g L^{-1}. The latter was also gently concentrated to 32 g L^{-1} (and 42 g L^{-1} after a second sampling for time sweep experiments) by using a Buchner vacuum. These concentrations were chosen to be representative of thickened sludge which is more often used in digesters. Digested samples were stored at 4 °C for 30 days before experiments were conducted to ensure no temporal variability, allowing us to use the same material for several days of testing. This technique was successfully used by Curvers et al. (2009).

On the other hand, because of their high degree of fermentation, raw sludge was stored only 5 days before experiments. Although storage implied changes in the composition of the raw sludge, considering the duration of rheological characterisation, especially the frequency sweep,