Rheological behaviour of anaerobic digested sludge: impact of concentration and temperature

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Abstract
Renewable energy is one of the cornerstones of sustainable energy. Biogas from the anaerobic digestion of organic waste materials can provide a clean, easily controlled source of renewable energy, replacing firewood and/or fossil fuels. In order to maintain the requisite constant homogeneous conditions within digesters, operating conditions must be regulated according to the rheological characteristics of the sludge. An accurate estimate of sludge rheological properties is required for the design and efficient operation of sludge pumping and digester mixing.
In this paper, we have determined the rheological behaviour of digested sludge at different concentrations and different temperatures, and highlighted common features. At low shear stress, digested sludge behaves as a viscoelastic solid, but shear banding can occur which modifies the apparent behaviour. At very high shear stress, the behaviour fits well with the Bingham model. Finally, we show that the rheological behaviour of digested sludge is qualitatively the same at different solids concentrations and temperatures, and depends only on the yield stress and Bingham viscosity: by normalising the shear stress with the yield stress and the shear rate with the yield stress divided by the Bingham viscosity, a master curve was obtained independent of both temperature and concentration. These two parameters (Yield stress and Bingham Viscosity) increase when the solid concentration increases but decrease when the temperature increases.
Furthermore, we show that the rheological behaviour is irreversibly altered by the thermal history. Dissolution of some of the solids may cause a decrease of the yield stress and an increase of the Bingham viscosity. This result suggests that the solid characteristics decreases with temperature and the usual laws used to describe the thermal evolution of the rheological behaviour of fluids are no longer valid with anaerobic digested sludge.

Keywords
Digested sludge, Bingham model, Herschel-Bukley model, rheology, Thermal history

INTRODUCTION

To maintain homogenous conditions in anaerobic digesters, operating conditions must be regulated according to the rheological characteristics of the sludge (Slatter 2011). Except the work of Monteiro (1997) who showed that anaerobic digestion induces a decrease of the rheological characteristics of sludge, most of sludge rheology researches were focused on activated sludge. No reliable data, at low shear rate (within the digester) or high shear rate (within recirculation pipes) can be found in the literature for digested sludge.

From a physical point of view, digested sludge appears to be a stable suspension with low settling ability (Namer and Ganczarczyk, 2003) and low surface charge (Forster, 2002) meaning interaction forces are more steric than electrostatic. The most important constituents in digested sludge are lipopolysaccharides (Forster, 1983) which are amphiphile lipids with both hydrophilic and hydrophobic heads. These molecules displayed a very intriguing rheological behaviour (Muñoz et al, 1989, 1991), showing viscoelasticy, non-Newtonian viscous flow and shear banding (Miller and Rothstein, 2007). Our recent study (Baudez 2011) highlighted a more complex behaviour with shear banding at low shear rates and a viscosity plateau at very high shear rates.

Furthermore, none of these studies focused on the temperature dependence of the rheology of digested sludge, which dramatically affect the flow properties and consequent operating conditions of the digester.

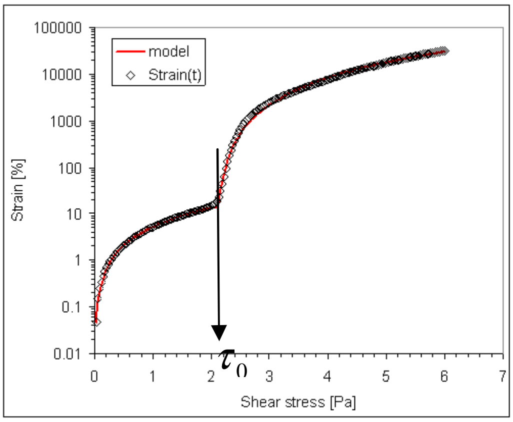
In this paper, we intend to underline the basic characteristics of the rheological behaviour of digested sludge, with the objective of industrial applications in digester mixing, pumping and pipe flows, meaning we only focus on short-term behaviours. As predicted by literature review of amphiphile rheology, we showed that digested sludge displayed viscoelastic behaviour at low shear stresses, followed by shear-banding phenomena at intermediate stresses, and finally a non-Newtonian flowing behaviour, modelled by a Herschel-Bulkley model at intermediate shear rates and by a Bingham model at very high shear rates. We also highlight the fact that the rheological behaviour is qualitatively the same at different solid concentrations and temperatures, allowing us to define a master-curve for which the dimensionless parameters are the yield stress and the Bingham viscosity. We also found that temperature irreversibly modified sludge structure. After being heated and cooled, digested sludge showed a lower yield stress but a higher consistency index than the initial material, at the same temperature. Such behaviour has to be taken into account for the practical design and operation of anaerobic digesters, especially heat exchangers and pipe flow.

MATERIAL AND METHOD

Digested sludge was obtained from the Mount Martha wastewater treatment plant (Melbourne, Australia).Stress sweep measurements at different concentrations and temperatures were carried out with a stress-controlled rheometer DSR200 from Rheometric Scientific, connected to a temperature controlled water bath. The rheometer was equipped with a cup and bob geometry (inner diameter: 29mm, outer diameter: 32mm, length: 44mm). Temperature was varied from 10 to 80°C.

RESULT AND DISCUSSION

Starting from rest, the shear stress sweep of digested sludge first shows a viscoelastic response up to a critical shear stress (τ_0) which above that sludge apparently starts to flow (Figure1). This behaviour can be modelled with the following Eq. $\gamma(t) = \tau \cdot \frac{1}{G} \cdot \left(1 - \exp\left(-(\lambda t)^m\right)\right) + b \cdot (t - t_0)^{1+\frac{1}{n}}$, where γ represents the strain, τ the stress and $\lambda = G/\mu$ with G and μ the usual parameters of a Kelvin-Voigt model, t_0 is the time that stress reaches to τ_0 , and n is the floe behaviour index.



Fitting experimental data using above equation is showing that sludge is shear thickening above τ_0 which is impossible since experimental results showed that viscosity is decreasing. The reason for this is apparent shear rate given by rheometer is calculated with the assumption of a full shear within the gap. However, the effective gap of shearing is smaller than what rheometer calculated due to shear banding.

Figure 1: Strain-stress behaviour of the 4.9% digested sludge. The dashed lined corresponds to the model of (1) with G=0.62Pa, λ=3.3.10-7s-1, m=0.34, b=0.35s-2, t_0=315.5s, corresponding to a stress equals to 2.13Pa and n=1.30.

Such behaviour (shear banding or in other word shear localization, and viscoelastic behaviour) has to be taken into in the digester design and operation, because shear banding means that there is coexistence of both sheared and unsheared zones (dead zone). At high shear rates, the whole gap is sheared and there is no shear banding effect observed. At high shear rate, a basic Bingham model is sufficient) while at low and intermediate shear rate, Herchel –Bulkley and power low models are more appropriate. Thus for pumping where shear rates are very high, a Bingham model would be appropriate since it deals with simple characteristic, ie. yield stress (τ_C) and a constant rheogram slope (k_2). Figure 2a shows the flow curve of different concentrations of digested sludge. As expected the higher the concentration, the thicker the sludge. We define the rheological behaviour of digested sludge as follows $\tau = \tau_c + k_1 \cdot \dot{\gamma}^n + k_2 \cdot \dot{\gamma}$, where k_2 is a plateau viscosity at high shear rate (in other word, Bingham viscosity) and k_1 is flow consistency behaviour. In our range of data (below 1000 s^{-1}), this model was successful and if $\dot{\gamma} << \sqrt[1-n]{k_1 / k_2}$, the Herschel-Bulkley model is sufficient to model the behaviour of sludge which Table 1 shows this limit shear rate.

Table 1: Limit Shear rate which below the Herschel-Bulkley model is suitable

Concentration [%]	Limit shear rate [s-1]
1.85	145
2.56	280
3.17	470
4.89	565

Since there is a similarity in the behaviour of different concentrations of sludge (Figure 2a) and different temperatures of sludge (Figure not shown), we developed a dimensionless of form of flow curves (Figure 2b).This similarity may be is the indication of similar network interactions within sludge at different concentrations and temperatures. This master curve can be described as the following, where" a" is parameter.

$$\frac{\tau}{\tau_c} = 1 + a\Gamma^n + \Gamma, with(\Gamma = \frac{k_2}{\tau_c} \cdot \dot{\gamma})$$

Since it is possible to represent a single master curve independent of temperatures and concentrations for flow curve of sludge, this indicates that (extrapolated) yield stress and the Bingham viscosity are the two key parameters to characterise the flowing behaviour of digested sludge. In our range of concentrations, yield stress and Bingham viscosity increase with the solid concentrations following a power law ($\tau_c = \alpha(\phi - \phi_0)^m$) and an exponential law ($k_2 = \mu_0 \cdot \exp(\beta \cdot \phi)$), where where ϕ_0 is the lowest concentration below which there is no yield stress and μ_0 is the viscosity of the liquid medium. We found that the value μ_0 is twice that of pure water, which can be explained by the large amount of dissolved matter present, which may increase the supernatant viscosity. Moreover, in the temperature range of 10-60°C, both yield stress and the Bingham viscosity decreased, and Bingham viscosity followed a linear relationship with water viscosity, meaning thermal agitation also had a major influence in the change of the liquid characteristics.

Temperature decreases rheological characteristics, but if sludge is heated and cooled before measurement, its rheological behaviour is irreversibly altered compared to its initial behaviour with no such thermal history (Figure 3a): the hotter the preheat, the smaller the yield stress and the higher the Bingham viscosity (Fgure3b). This may be due to a conversion of solid to dissolved constituents, a process which is irreversible. Because material composition changed with temperature, thus, the usual laws used to model temperature dependence are no longer valid due to the fundamental change in the sludge composition. It would be physically inaccurate to consider constant activation energies in Arrhenius equation for change of parameters with temperature. Such behaviour has to be taken into account in thermal process happening in the recirculation loops of heat exchangers, where head loss determination can be significantly affected.

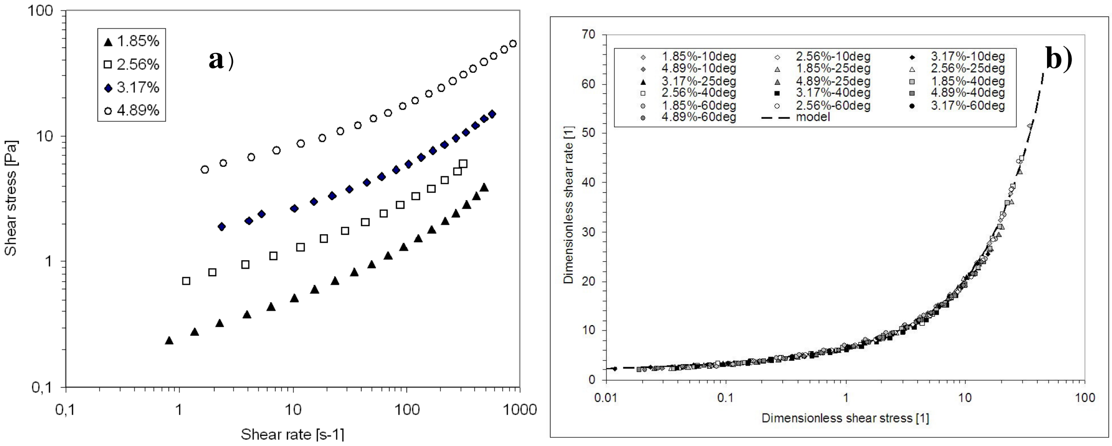


Figure2: a) Flow curves of the different concentrations of the digested sludge, b) Dimensionless flow curve of the digested sludge at different concentrations and temperatures with n=0.3,a=4.57 for the model.

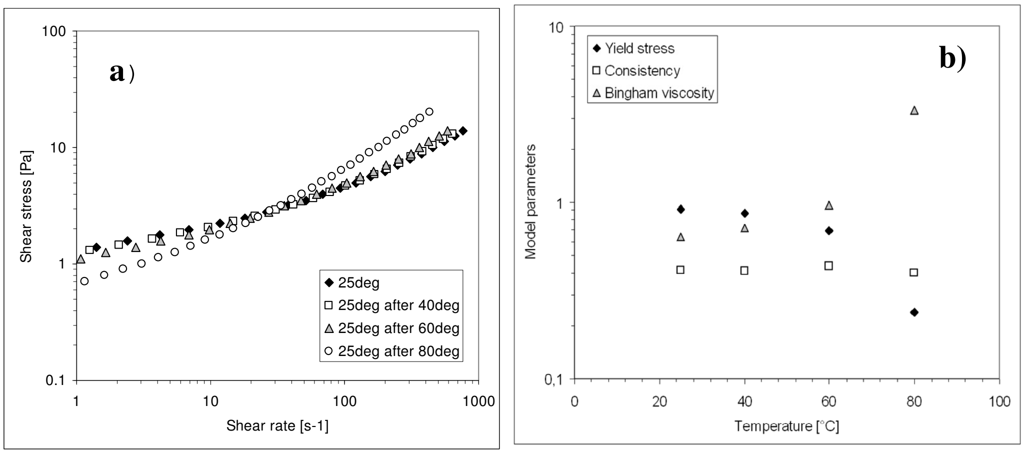


Figure3: a) Flow curve of the 3.2% digested sludge at 25°C after being heated at 40, 60 and 80°C, b) Change of yield stress and Bingham viscosity of 3.2% digested sludge at 25°C with respect to its thermal history

CONCLUSION

We showed that the rheological behaviour of digested sludge is qualitatively the same at different solids concentrations and temperatures, and depends only on the yield stress and Bingham viscosity. Also, digested sludge rheological behaviour is irreversibly altered by the thermal history.

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