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The apparent viscosity and yield stress of mixtures of primary and secondary sludge: Impact of volume fraction of secondary sludge and total solids concentration

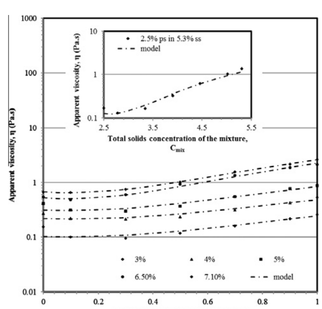
Flora Markis [a,b], Jean-Christophe Baudez [a,b], Rajarathinam Parthasarathy [a], Paul Slatter [a,c], Nicky Eshtiaghi [a,*]

[a] School of Civil, Environmental and Chemical Engineering, RMIT University, 3001 Melbourne, Australia
[b] Irstea, UR TSCF, F-03150 Montoldre, France
[c] ATC Williams, Mordialloc, VIC 3195, Australia

HIGHLIGHTS

- Mixtures of primary and secondary sludge prepared at same concentration ($C_{PS} = C_{SS}$).
- Dilute primary sludge mixed with thickened secondary sludge ($C_{PS} \neq C_{SS}$).
- The η & τ_c of sludge mixtures increases by increasing φ_{SS} if $C_{PS} = C_{SS}$.
- The η & τ_c of sludge mixtures increases by increasing $\varphi_{Thicker\ sludge}$ if $C_{PS} \neq C_{SS}$.
- The η & τ_c of sludge mixtures are predicted from η, φ_{SS} & τ_c of secondary sludge.

GRAPHICAL ABSTRACT



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ABSTRACT

Sludge rheology plays an important role in the design and optimization of anaerobic digesters. Organic matter such as primary and secondary sludge or a mixture of the two sludges enters the digesters for further digestion and stabilization. However, there is little information available on how the rheology of the mixed sludge changes. This paper investigates how the rheology of mixed primary and secondary sludge changes when the volume fraction of secondary sludge is altered. This will help predict the rheology of mixed sludge which is required for the design and optimization of pumping and mixing systems.

Mixtures of primary and secondary sludge between 2.5 and 7%TS behave as non-Newtonian, shear thinning, yield stress materials whereby the apparent viscosity and yield stress of the mixed sludge depends on the volume fraction of secondary sludge and total solids concentration.

The apparent viscosity of primary–secondary sludge mixtures (with same total solids concentration) increases with increasing secondary sludge volume fraction. This suggests that the weak flocs of primary sludge collapse such that the colloidal like particles of primary sludge become trapped and entangled in the gel-like network structure of secondary sludge. However, when dilute primary sludge is mixed with concentrated secondary sludge (and vice-versa), the apparent viscosity and yield stress of the primary–secondary sludge mixture increases with increasing volume fraction of the concentrated sludge

* Corresponding author. Tel.: +61 3 9925 9554.
E-mail address: nicky.eshtiaghi@rmit.edu.au (N. Eshtiaghi).

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regardless of sludge type. This is due to the strengthening of hydrodynamic and non-hydrodynamic interactions within concentrated sludge.

A master curve was developed to predict the flow behaviour of sludge mixtures. Consequently, correlations were developed to predict the apparent viscosity and a yield stress of sludge mixtures as a function of volume fraction and total solids concentration.

1. Introduction

Renewable energy is one of the key factors in sustainable sludge management. However, the production of biogas from the anaerobic digestion of waste water sludge is challenging because industry is dealing with large quantities of complex material that is not well understood [1].

Efficient mixing is a key factor influencing the anaerobic digester performance [2]. Good mixing is required 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, and also to minimize scum and foam formation [2]. As such, the processing of large volumes of sludge feed which consists of a mixture of primary and secondary sludge, combined with the fact that the current anaerobic digesters are not designed to process any additional concentrated loads leads to inadequate mixing [3,4]. Inadequate mixing of sludge feed leads to reduced digester efficiency due to the formation of dead zones. The dead zones are made up of the inactive volume within the digester which creates a poor microbial environment for biogas production [2].

Consequently, any changes to the sludge feed alters digester performance, as such the importance of predicting the flow behaviour, most importantly, the apparent viscosity and yield stress of mixtures of primary and secondary sludge as the sludge feed to the digester is essential. Any changes to the flow behaviour will have a direct impact on the operating conditions and energy requirements necessary to achieve efficient mixing.

In one of the most recent studies on sludge, Markis et al. [5] investigated the impact of total solids concentration (%TS) on the rheological behaviour of individual primary and secondary sludge. Markis et al. [5] demonstrated that at low stresses, below the yield stress, sludge behaved as a viscoelastic solid which was consistent with the literature on activated sludge [6–8]. Primary sludge yielded abruptly, a characteristic of highly thixotropic colloidal suspensions [9] that are governed by weak attractive forces (i.e. Van der Waals forces) [10,11]. The EPS (**E**xtracellular **P**olymeric **S**ubstance) rich structure of secondary sludge, which is held together by hydrogen and electrostatic forces [12], transitioned smoothly into the liquid regime, characteristic of gels [13]. As such, Markis et al. [5] demonstrated that primary sludge behaved like a colloidal suspension whilst secondary sludge behaved like a gel. In the liquid regime, sludge displayed shear thinning behaviour which was consistent with the pioneering works of Bhattacharya [14] on primary sludge and Slatter [15], Mori et al. [16] and Seyssiecq et al. [17] on activated sludge. The apparent viscosity increased exponentially with solids concentration whilst the yield stress followed a power law. This was consistent with Baudez [7], Sanin [18], Baudez et al. [8], Lotito and Lotito [19] and Jiang et al. [20]. However, these studies amongst others, focused on the rheology of one type of sludge-not a mixture.

The latest studies conducted by Baroutian et al. [21] as well as Lotito and Lotito [19] focus on the rheological characterization of mixed sludge at a fixed blend ratio. Baroutian et al. [21] studied the impact of solids concentration and temperature on the rheological behaviour of a fixed blend ratio of primary and secondary sludge. The mixed sludge consisted of 40% primary and 60% secondary sludge. The mixed sludge was prepared at 4.3, 4.5, 4.9, 7.3 and 9.8 wt.% solids content. Baroutian et al. [21] found that the yield stress increased with solids concentration. The Herschel–Bulkley model was employed to characterize the flow behaviour. Lotito and Lotito [19] conducted rheological measurements on different types of sewage sludge including anaerobic digested, raw mixed sludge, return activated sludge for pump design and found that for similar solids content, return activated sludge had the highest yield stress and Bingham viscosity followed by anaerobically digested and primary sludge. The yield stress and fluid consistency coefficient increased following a power law relationship with solids concentration [19]. Lotito and Lotito [19] demonstrated that raw mixed sludge was the easiest to pump whilst return activated sludge was the hardest to pump.

In the above mentioned studies, the impact of volume fractions of sludge constituents on the apparent viscosity and yield stress of mixed sludge was not studied. This highlights the lack of research on the rheological characterization of mixed primary and secondary sludge over a wide total solids concentration range and different volume fractions.

To study and understand the rheological characterization of mixed primary and secondary sludge, it is useful to consider the rheology of mixed colloidal suspensions and polymeric gels, which is similar to that of mixed sludge. Studies of Comba and Sethi [22], Hammadi et al. [23], Abu-Jdayil and Ghannam [24], Gómez-Díaz and Navaza [25], Eshtiaghi et al. [26] and Kelessidis et al. [27] focused on the rheology of mixed colloidal suspensions and polymeric gels. Comba and Sethi [22] studied the stabilization of highly concentrated suspensions of iron nanoparticles in xanthan gum solution and found that mixing a suspension with a gel led to the formation of a viscous gel with increased stability against aggregation and sedimentation. Comba and Sethi [22] explained that the suspension of iron nanoparticles was governed by colloidal forces whilst the xanthan gum solution was governed by hydrogen bonding and polymer entanglement leading to the formation of a gel network structure. Moreover, when iron nanoparticles were mixed with xanthan gum solution, the particles were integrated into the gel network structure of the polymer leading to the formation of a more viscous and stable dispersion [22]. Hammadi et al. [23] demonstrated that when polyethylene oxide (PEO) was added to bentonite clay, the yield stress and fluid consistency index of the mixture increased. Likewise, Hammadi et al. [23] explained that this trend was due to the interactions between clay particles and the viscous effect of the polymer solution.

Abu-Jdayil and Ghannam [24] studied the change in the rheological properties of a mixture when a low viscosity polymer such as carboxymethylcellulose, CMC (0.02–0.5 wt.%) solution is added to a highly thixotropic colloidal suspension such as bentonite. They showed that the dispersion viscosity increased significantly when the CMC solution was added to bentonite dispersions. This increase was attributed to the adhesion of CMC to the surface of bentonite particles leading to the formation of a network structure within the bentonite suspension [24]. Eshtiaghi et al. [26] studied the impact of adding glass beads suspension to carbopol gel. They prepared suspension–gel mixtures with different volume fractions by