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Rheological characterisation of primary and secondary sludge: Impact of solids concentration

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HIGHLIGHTS

- Primary sludge behaves as a colloidal suspension while secondary sludge is a more gel-like material.
- In the steady state flow, sludge behaved as a shear thinning, yield stress materials.
- A master curve developed for prediction of sludge rheology independent of concentration.

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ABSTRACT

Predicting the rheological behaviour of sludge is essential in the design and optimisation of various unit operations of waste water treatment, most notably anaerobic digestion whereby the efficient mixing of sludge feed produces biogas and digested sludge. In this paper, the rheological behaviour of primary sludge (2.8%, 3.7%, 5.5%, 6.8% and 8.2% TS) and secondary sludge (2.8%, 4.0%, 5.0%, 6.5% and 9.2% TS) has been investigated. At low stress, below the yield stress, sludge behaved as a visco-elastic solid, whereby primary sludge yielded abruptly whilst secondary sludge flowed smoothly to steady state. In the steady state, both sludges behaved as shear thinning, yield stress fluids with primary sludge exhibiting highly thixotropic behaviour. The apparent viscosity, yield stress and fluid consistency of both primary and secondary sludge increase with increasing total solids concentration and followed the Herschel–Bulkley model. A master curve was developed based on the dimensionless form of the Herschel–Bulkley model allowing the rheology of primary and secondary sludge at any concentration to be determined.

1. Introduction

Due to increasing urban populations, urban land shortages and economics, waste water treatment plants are under considerable pressure to treat higher loads without increase in plant size. This results in the treatment of a more concentrated and complex sludge. Therefore, an understanding of the hydrodynamics of sludge is required for the process design and optimisation of waste water plants. Slatter [1] and Spinosa and Lotito [2] emphasised the importance of predicting the behaviour of sludge as it flows through various treatment processes such as pumping and transportation, chemical conditioning, mixing, storage and dewatering.

Baroutian et al. [3] defined sludge as the solid residue from the municipal waste water treatment process. There are three types of sludge: primary, secondary or activated sludge and digested sludge. Primary sludge has been defined by Bhattacharya [4] as a flocculated mixture of organic and inorganic matter with gas bubbles trapped within the suspension. It is the product of primary clarification during the waste water treatment process. Bhattacharya [4] explained that its flow behaviour can be altered dramatically due to concentration, composition and temperature and that it is almost impossible to determine the effect of dimension, shape, size distribution and surface nature of the solid particles in the flocs because the solid particles have no fixed structure. The bacteria in primary sludge are said to be held together through nonspecific Lif-shitz van der Waals forces as well as hydrogen and chemical bonds [5,6].

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Secondary sludge, or activated sludge as it is often named, is the product of the secondary treatment process whereby it is removed via flotation and sent to a sludge settler. It is made up of polysaccharide and protein rich bacteria and micro-organisms that form extracellular polymeric substances (EPS). According to Wingender et al. [7], the EPS form a three dimensional gel like structure with a negative surface charge [8]. Keiding et al. [9] and Sutherland [10] explained that secondary sludge behaves as a gel when interacting with water and forms flocs, whilst Flemming [11] stated that the structure is held together by electrostatic and hydrogen bonds.

Another difference between primary and secondary sludge is that they do not have the same density because the density of primary sludge is obtained from settling of coarse particles while the density of secondary sludge is obtained from flotation.

Digested sludge is the product of the anaerobic digestion process. It is a mixture of primary and secondary sludge [3] that has been stabilized through the anaerobic digestion process. We will not go further with the description of digested sludge as it is not the subject of this paper.

Spinosa and Lotito [2] explained that rheology can be applied in the design and optimisation of various unit operations of the waste water treatment process whereby the rheological properties influence the operating conditions and scale up calculations of various processing units such as tanks, settlers, pumping stations and transport lines as well as heat exchangers. As a result, the current literature on sludge focuses on the rheological characterisation of sludge in the liquid regime [1,12–15] whereby viscous forces are dominant.

Few studies have focused on the rheological behaviour of primary sludge. The pioneering work of Bhattacharya [4] and more recently Moeller and Torres [16] are the only two studies to date that address the rheology of primary sludge. Concentrated primary sludge (3.77–7.48% TS) has been described by Bhattacharya [4] as a shear thinning yield stress fluid whilst Moeller and Torres [16] modelled the flow properties of dilute primary sludge (1–3% TS) using the power law model, suggesting that no yield stress was detected. The inconsistency between the two studies is due to the solids concentration of the characterised sludges which emphasises that the yield stress depends on the solids concentration. The current literature focuses on the rheological characterisation of activated sludge which is usually described as a complex non-Newtonian, viscoelastic [17,18], shear thinning fluid [4,12,14] which exhibits temperature dependency [19,20]. Moreover, Tabuteau et al. [21], Baudez [22] and Tixier [23,24] illustrated that secondary sludge is thixotropic and undergoes aging as the solid structure is able to rebuild under shear. Baudez et al. [18] also studied the viscoelastic behaviour of secondary sludge and concluded that the observed behaviour resembles gel structure.

The complexity of sludge as well as a lack of uniformity associated with sludge rheometric techniques [25–27] have highlighted that sludge is a highly difficult material to characterise in order to design and optimise waste water treatment plants.

This study focuses on the comparison of the rheological behaviour of primary and secondary sludge as a feed for anaerobic digestion. Anaerobic digestion requires the constant mixing and degradation of the feed sludge. As stated earlier, whilst the current literature focuses on the rheological characterisation of activated sludge, the aim here is to get a better understanding of the sludge entering the digester (i.e. primary and secondary sludge) in order to understand how its rheological properties will influence the anaerobic digestion process instead of characterising sludge once it has been digested (i.e. digested sludge). Hence, the yielding properties, thixotropy and apparent viscosity of primary and secondary sludge will be investigated.

In this paper, we demonstrate that primary sludge behaves as a colloidal suspension while secondary sludge is a more gel-like material.

2. Materials and methods

2.1. Sample preparation

Samples of primary sludge were obtained from Bessay (Allier, France) and secondary sludge was obtained from Vichy (Allier, France).

Primary sludge with an initial total solids (TS) concentration of 2.8 wt% was thickened to 3.7%, 5.5%, 6.8% and 8.2% TS using the vacuum filtration technique such that the floc structure would not be altered. Secondary sludge was sampled at the outlet of the dewatered centrifuge step of a waste water treatment plant (its solid concentration was at 22%) and was diluted using tap water to various concentrations (2.8%, 4.0%, 5.0%, 6.5% and 9.2% TS) to reach the usual concentrations entering into a digester.

2.2. Rheometric technique

An Anton Paar physica MCR 300 dynamic stress rheometer equipped with the wide gap vane geometry (diameter of the cup, D_c = 39.0 mm; diameter of the vane, D_v = 25.0 mm, height of vane,

Table 1
Summary of applied increasing and decreasing steps of stress for each sample.

Solids concentration	2.8% Primary sludge	3.7% Primary sludge	5.5% Primary sludge	6.8% Primary sludge	8.2% Primary sludge	2.8% Secondary sludge	4.0% Secondary sludge	5.0% Secondary sludge	6.5% Secondary sludge	9.2% Secondary sludge
Applied stress (Pa)	0.014	0.73	0.72	2.91	72.76	0.03	1.46	0.72	2.91	101.86
	0.049	1.0	1.4	3.6	80.3	0.1	2.0	1.4	4.4	116.4
	0.064	1.3	2.2	4.4	87.0	0.3	2.6	2.2	5.8	120.8
	0.109	1.5	2.5	5.1	91.5	0.5	3.0	2.9	7.3	123.7
	0.154	1.5	2.9	5.4	94.7	0.6	3.1	3.6	7.7	126.7
	0.192	1.5	3.1	5.8	97.5	0.7	3.0	4.4	8.0	131.0
	0.215	1.5	3.4	6.3	100.4	0.9	3.1	4.8	8.3	135.3
	0.250	1.6	3.6	6.6	101.7	0.9	3.2	4.9	8.7	138.2
	0.263	1.8	3.9	6.8	109.4	1.2	3.5	5.4	10.2	141.1
	0.278	1.9	4.2	7.3	116.4	1.3	3.8	5.8	11.6	145.5
	0.301	2.0	4.4	8.7	123.8	1.4	4.0	6.5	13.1	160.1
	0.327	2.2	4.5	9.4	131.0	1.9	4.4	7.3	14.6	189.2
	0.361	2.5	4.8	10.1	145.4	2.2	4.2	8.8	18.9	218.3
	0.359	2.7	5.1	10.9	176.1	2.5	5.3	10.2	21.8	247.4
	0.429	2.7	5.4	11.6	202.3	2.7	5.5	12.9	24.7	276.5
	0.584	3.0	5.8	13.1	228.5	2.9	5.8	14.6	29.1	305.6