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Rheological characteristics of mixture of raw primary and thickened excess activated sludge: impact of mixing ratio, solid concentration, temperature and sludge age

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ABSTRACT

Wastewater treatment process generates large quantities of sludge from different operational steps. The rheological behaviour of sewage sludge at different steps of wastewater treatment plant is useful for the design, operation, optimization of polymer dosing, hydrodynamics and mixing of anaerobic digestion and for efficient sludge management. In this research work, the impacts of solid concentration, temperature, mixing ratio and ageing of sludge on the rheological behaviour of mixture of raw primary and thickened excess activated sludge (TEAS) (mixed sludge) were investigated. Solid concentration, temperature, primary to TEAS mixing ratio, and sludge age were found to affect the viscosity, yield stress, flow index and flow consistency of mixed sludge. The decrease in total solid (TS) concentration of mixed sludge from 30 to 20 g/L resulted in significant decrease of yield stress from 7.4 to 1.1 Pa (85% reduction). The decrease in mixing ratio of TEAS to raw primary sludge from 80 to 20% resulted in the decrease of yield stress from 10.2 to 1.2 Pa confirming the significant contribution of TEAS to the non-Newtonian viscoplastic flow behaviour of the mixture. Similarly, viscosity also showed a decreasing trend with decreasing TS concentration and percentage of TEAS in the mixture. In contrast, yield stress and viscosity generally showed reduction with increasing temperature. Low temperature storage duration (sludge age) also affected the rheology of mixed sludge. The applicability of various rheological models such as Bingham, power law (Ostwald), Herschel-Bulkley, Casson, Sisko, Careau and Cross models were tested by fitting the models with experimental rheological characteristic of mixed sludge under various physico-chemical process conditions. The rheological data from the best fitted Bingham plastic and Sisko models are also discussed here.

Keywords: Raw primary sludge; Rheological model; Rheology; Sludge mixing ratio; Sludge age; Thickened excess activated sludge

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1. Introduction

Rheology is the science that deals with the flow and deformation of materials and it has become an important tool in wastewater sludge characterization for sustainable sludge management. In a wastewater treatment plant (WWTP), knowledge on the rheology of different types of sludge at different steps helps to improve process performance and plant economics. This is because rheology plays a vital role in influencing pumping, hydrodynamics, mass transfer rates, sludge settling, filtration and several other processes in WWTPs [1]. In addition, water consumption, demand for water resources and safe habitable environment is steadily increasing with the rapid population growth, associated with the generation of increased amount of wastewater and sewage sludge [2]. Hence, understanding flow behaviour and rheological properties of sludge is becoming increasingly important for a sustainable and efficient sludge management [2–4].

The wastewater sludge treatment process influences sludge characteristics among which rheological characteristics of sludge depend on many factors such as source, solid concentration, temperature and sludge treatment methods [1,3,5].

The anaerobic digestion and sludge dewatering processes account for 70% of the overall operation cost of WWTPs and are vital areas where sludge flow analysis should be conducted [6,7]. The feed to anaerobic digestion process, a mixed sludge, is a mixture of raw primary sludge (RPS) and thickened excess activated sludge (TEAS). RPS comes from the underflow of primary sedimentation tanks and contains solids separated from sewage feed, while TEAS originates from dissolved air floatation thickeners and is generally thickened form of excess activated sludge (EAS) from the activated sludge treatment process.

Studies show that the complex nature of sludge necessitates intensive investigation to meet the specific needs of understanding the rheological properties and response to changes in different process parameters. Hence, understanding the characteristic of mixture of raw primary and TEAS under various process conditions will provide better knowledge, and will help to produce correct procedure and estimation method [1].

Solids existing within fluid is considered as a key factor that contributes to non-Newtonian flow behaviour. According to Einstein's Law of Viscosity shown in Eq. (1), the presence and the solid content within a fluid is the primary reason for the increase in fluid viscosity [8].

$$\eta/\eta_0 = 1 + 2.5\phi \quad (1)$$

where η is the viscosity of the dispersion, η_0 is the viscosity of the dispersion medium and ϕ is the volume fraction occupied by the particle. The effect of solids content on viscosity of sludge has been examined in a great number of studies [2]. It was found that the viscosity of sludge increases with increase of solid content [9–11]. Increasing solids content will lead to stronger inter-particle interactions which is caused by the size increase of particles in suspension, resulting in higher apparent viscosity within the mixed sludge.

Sludge generally behaves like a non-Newtonian and shear thinning material. Hence, proposing an empirical equation to model the effects of total solid (TS) concentration on rheological properties is necessary to understand the sludge behaviour [8,12]. Lotito et al. [4] confirmed that solid concentration is one of the major parameters that affects sludge rheology and proved that characteristic of sludge is dynamic in nature and one parameter alone is not sufficient to represent its behaviour. Hence, they recommended analysis of multiple parameters for better understanding of flow behaviour.

Baudez [13] found that the critical shear stress and shear rate increased with solid concentration depending on the fractal dimensions of the floc which implies that thixotropic effects change with sludge age and solid content. The behaviour of sludge gradually changes with time due to change in the composition of key components like protein, lipid and carbohydrate with the age of the sludge due to degradation and synthesis of volatile fatty acids [13]. Most of the studies on rheology are limited to activated sludge system, therefore rheological measurement on other types of sludge particularly on mixed digester feed sludge (mixture of raw primary and TEAS that is fed to the anaerobic digester) as a function of different parameters is essential [4,11].

According to Markis et al. [14], researches on raw primary and TEAS are very few, limited, inconsistent, and most literature focus on the changes of rheological properties of activated sludge and digested sludge. Bhattacharya [15] and Moeller and Torres [16] have conducted work on sludge rheology prior to the anaerobic digester. Although there are interesting results on sludge characteristics and its implications in a WWTPs, most of the studies are limited to synthetic sludge system, and rheological behaviour depends on complex nature of sludge [3]. Furthermore, to the best of our knowledge, there are only few published studies on the effect of primary to TEAS mixing ratio on sludge rheological properties, and there are some inconsistencies on the findings and conclusion of these published literature [14–17]. Operating at optimum mixing ratio can enhance flow hydrodynamics, methane production, effluent sludge quality, dewaterability, pathogen removal and overall plant economy [6,7]. Hence, thorough investigation on the effect of operational parameters like TS content and primary to TEAS mixing ratios is essential for all different sludge type.

Khalili Garakani et al. [18] applied seven different rheological models such as power law, Bingham plastic, Herschel-Bulkley, Casson, Sisko, Carreau and Cross models to investigate the rheological behaviour of non-Newtonian activated sludge. Lau et al. [19] also reported the application of various rheological models in sludge conditioning and dewaterability. Nevertheless, there are very limited studies on the applicability of such rheological models to analyze the behaviour of mixed sludge that consists of both primary and TEAS. Besides, the choice of rheological model was found to be very subjective and highly dependent on experimental conditions and type of sludge [2]. Hence, this particular study has the objectives of investigating the rheological behaviour of mixed sludge under the influence of temperature, TS concentration, primary to TEAS mixing ratio, sludge age and applicability of various rheological models and determination of model parameters. The current study is based on a mixture of primary and TEAS collected from Beenyup Wastewater Treatment Plant of Water Corporation, Perth, WA.

2. Material and method

2.1. Sludge sampling

Raw mixed sludge sample was collected from Beenyup Wastewater Treatment Plant of Water Corporation, WA, Australia and carried in sealed containers. Mixed sludge was collected from the sampling point before the anaerobic digesters. Mixed sludge is mostly used in anaerobic digesters instead of primary sludge or activated sludge alone to enhance the rate and extent of biodegradation [20]. Besides RPS, EAS, and TEAS samples were collected from primary gallery and dissolved air floatation tanks from the same WWTP. The unmixed RPS and TEAS samples were used to investigate the effect of mixing ratio and the characteristics of each of these sludge types on mixed sludge rheological properties and the performance of the anaerobic digestion process. Fresh mixed sludge samples were used in all the experimental investigations to prevent changes in the rheological properties, due to the fermentation and other microbial activities. Samples of mixed sludge were stored in a refrigerator at 4˚C and reheated to 42˚C (temperature of sample at collection point) with the Peltier Concentric Cylinder Temperature System for the investigation on effect of sludge age.

2.2. Sludge characterization

Intensive characterization was conducted on each of the collected samples. The characterization study included determination of total solids content (TS), total volatile solids (VS), chemical oxygen demand (COD), temperature and pH. Such parameters influence the flow behaviour and the performance of anaerobic digestion and dewatering process. Hence, the effects of TS concentration and temperature were investigated in order to determine the optimum conditions for better anaerobic digester performance and improved digested sludge quality.

The procedures to obtain these physico-chemical and biological parameters were based on standard method described in "Standard Methods for the Examination of Water and Wastewater" provided by the American Water Works Association [7,8,21,22].

TS and VS were determined by employing the standard method (gravimetric method). COD was determined by using oxidation method with HACH COD reagent and colorimetric analysis on ORION UV–vis spectrometer. pH was measured with WP-90 and WP-81 conductivity/TDS-pH/temperature metre equipped with a glass electrode. Temperature of mixed sludge was measured during collection and again at the beginning of each experiment and is expressed in degree centigrade (˚C) and obtained by using a standard thermometer.

2.3. Rheology measurement

In this study, a Discovery Hybrid Rheometer G-2 (DHR-2) equipped with TRIOS analysis tool was used. The rheometer was fitted with a standard Vane concentric cylinders, Peltier Steel Geometry (30 mm diameter, 4,000 μm gap). A shear rate range of 0–1,000 s^{-1} was used and temperature was controlled between of 25 to 55˚C with intervals of 5˚C. The rheological measurement cycle consists of four major steps: (a) conditioning step of 60 s at shear rate of 5 s^{-1} at each desired temperature, (b) An equilibration phase of 30 s, (c) linear flow Sweep test until maximum shear rate of 1,000 s^{-1} with a maximum of 40 data points and (d) shear rate was reduced to zero. An average volume of 35 ml of mixed sludge was mounted into the concentric cylinder (sample holder) which is equipped with Peltier heating and cooling system. The initial temperature of each of the samples was adjusted to the temperature recorded at collection point before commencing the measuring cycle.

2.4. Rheological modelling

In rheological studies, flow measurement are conducted to obtain viscous and viscoplastic properties by making use of different rheological models where shear stress, yield stress, flow index, infinite and zero rate viscosities and flow consistency index of the sludge can be quantified. Shear stress models like Bingham, Ostwald and mainly Herschel–Bulkley, shown in Eqs. (2)–(4), respectively, have been used extensively with viscoplastic fluids like sludge which show shear thinning behaviour [12,18]. Viscosity models including Sisko, Careau and Cross models, shown in Eqs. (5)–(7), respectively, were used to characterize sludge rheology [18,23,24].

$$\tau = \tau_y + \eta_B \dot{\gamma}^n \tag{2}$$

$$\tau = K\dot{\gamma}^n \tag{3}$$

$$\tau = \tau_y + K\dot{\gamma}^n \tag{4}$$

$$\mu = \mu_\infty + K\dot{\gamma}^{n-1} \tag{5}$$

$$\frac{\mu - \mu_\infty}{\mu_0 - \mu_\infty} = (1 + (\lambda\dot{\gamma})^2)^{\frac{n-1}{2}} \tag{6}$$

$$\frac{\mu - \mu_\infty}{\mu_0 - \mu_\infty} = \frac{1}{1 + (\lambda\dot{\gamma})^m} \tag{7}$$

Generally, these equations are used to model the shear stress (τ is the shear stress in Pa) profile and viscosity (μ is the viscosity in Pa s) profile where τ_y is yield stress (Pa), η_B is the high shear limiting viscosity (Pa s), $\dot{\gamma}$ is the shear rate (s^{-1}), n is the flow index, K is the consistency index (Pa s^n), μ_∞ is the infinite rate apparent viscosity (Pa s), μ_0 is the zero shear apparent viscosity (Pa s), λ is the time constant (s) and m is the Cross rate constant. Published rheological information on different types of sludge is very specific and limited to the narrow solid concentration, temperature range investigated in the respective studies. In this study, the model which fits best to the experimental data was used to determine rheological parameters such as yield stress, infinite and zero-rate viscosities, and flow indices. The rheological parameters determined from the model analysis will have practical implications that help to optimize operational conditions of processes in a WWTPs.

3. Result and discussion

3.1. Sludge characterization

The major characteristic properties of each of the mixed sludge samples collected are given in Table 1. It can be observed from Table 1 that the mixed sludge properties fluctuate from time to time in terms of TS content, volatile solid content, COD, pH and temperature. This justifies the need for the investigation of the effect of these parameters on the overall rheological behaviour of mixed sludge, the anaerobic digestion process and dewatering performance. It appears that TS content does not change significantly, it remained constant around 28 to 30 g/L with the average TS concentration being 28 g/L. In addition, the volatile solid content was found to be between 20.3 and 26.4 g/L with the average being 24.6 g/L. While the COD varied from 28,250 to 43,200 ppm, the pH of mixed sludge ranged from 5.6 to 6.4. The temperature of mixed sludge varied from 25 to 42℃ due to the ambient weather on sampling day, with the average temperature being at 33℃.

The characteristics of RPS, EAS and TEAS samples are shown in Table 2. The TS content, volatile solid content, COD, pH and temperature data are also shown for each of these sludge types. The characteristics of various ratios of raw primary to TEAS are shown in Table 3.

Table 1
Characteristics of mixed sludge samples

Mixed sludge sample (MS)									Average
Total solid content (g/L)	29	30	29	28	27	29	23	30	28
Volatile solid content (g/L)	24.7	25.7	26.0	24.7	23.2	25.4	20.3	26.4	24.6
Chemical oxygen demand (ppm)	35,850	43,200	40,800	33,400	30,900	41,600	28,250	37,600	36,450
pH	6.4	6.1	5.7	6.0	6.2	6.1	5.6	6.0	6.0
Temperature (℃)	25	29	28	29	42	42	37	35	33

Table 2
Characteristics of raw primary, excess activated and TEAS

Sludge sample	Raw primary sludge (RPS)	Excess activated sludge (EAS)	Thickened excess activated sludge (TEAS)
Total solid content (g/L)	27	8	37
Volatile solid content (g/L)	24.3	6.4	30.4
Chemical oxygen demand (ppm)	20,100	1,800	27,500
pH	6	7	7
Temperature (℃)	24	25	24

Table 3
Characteristic of mixture of raw primary and TEAS for different mixing ratios

Mixed ratio (RPS:TEAS)	80:20	70:30	60:40	50:50	40:60	20:80
Total solid content (g/L)	29	30	26	28	30	32
Volatile solid content (g/L)	25.6	26.4	22.1	24.4	26.0	26.9
pH	6.5	6.5	7	7	7	7
Temperature (℃)	24	24	24	24	24	24

3.2. Effects of TSs concentration on mixed sludge rheology

To study the effects of TS concentration, samples of mixed sludge were thickened using vacuum filtration technique and diluted by the addition of deionised water to obtain various TS concentration [1,14,22,25]. The effect of TS concentration was investigated for mixed sludge sample with TS content of 20, 25 and 30 g/L. The mixing ratio of RPS to TEAS in the collected mixed sludge sample was 60:40% and the temperature during sampling was 25℃. The rheological behaviour of mixed sludge at different solid concentrations was presented by plotting shear stress–shear rate flow curves shown in Fig. 1(a) where shear stress shows an increasing trend with increasing shear rate indicating non-Newtonian pseudo-plastic flow behaviour [26]. Such flow behaviour of primary and TEAS was also previously reported by few researchers [25,27]. The experimental data were fitted to various rheological models discussed in Eqs. (2)–(7). The various fitted model parameters are presented in Table 4. The high values of linear correlation coefficient (R^2) indicate the applicability of most rheological models to represent mixed sludge system. However, Bingham model was selected for further analysis due to its practical significance and simplicity [3]. The increase in TS concentration from 20 to 30 g/L increased the

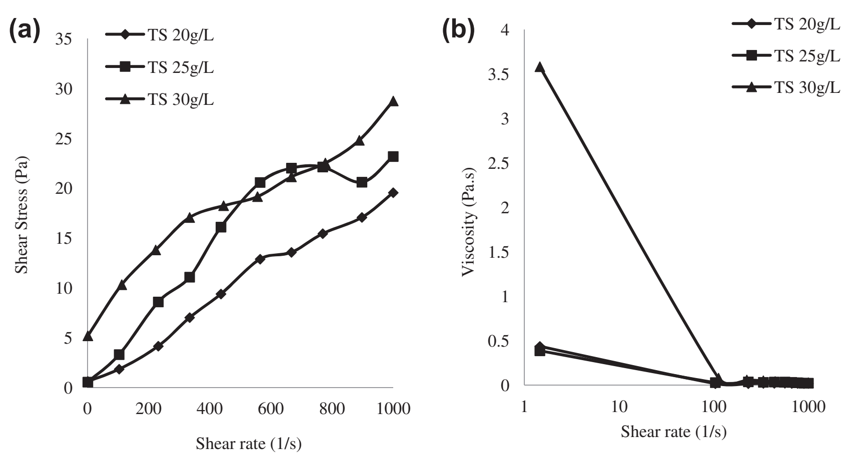

Fig. 1. (a) Shear stress–shear rate curves and (b) viscosity–shear rate curves for different solid concentrations of mixed sludge sample.

Table 4
Yield stress and viscosity of mixed sludge for varying TS content for various rheological models

Total solid concentration (g/L)	Rheological model	Yield stress (Pa)	Viscosity (Pa s)	Flow index	R^2
30	Casson	4.6	0.010	–	0.99
	Bingham	7.4	0.021	–	0.98
	Power	–	1.100	0.46	0.94
25	Casson	0.8	0.017	–	0.99
	Bingham	2.1	0.024	–	0.97
	Power	–	0.154	0.73	0.99
20	Casson	0.3	0.015	–	0.98
	Bingham	1.1	0.018	–	0.98
	Power	–	0.061	0.83	0.99

shear stress significantly as shown in Fig. 1(a). Markis et al. [1] also reported similar trends but for a different sludge type. Moreover, viscosity showed some reductions with decreasing solid concentration as shown in Fig. 1(b).

The rheology of mixed sludge shows non-Newtonian shear-thinning behaviour with yield stress of 1.1 Pa at TS concentration of 20 g/L which increased to 7.4 Pa at 30 g/L as shown in Table 4. An increase of TS concentration by 33% resulted in substantial increase of yield stress by 85% which reflects on the pseudo-plastic flow behaviour and power required during pumping and mixing of sludge. The viscosity on the other hand deceased from 0.021 Pa s for a TS content of 30 g/L to 0.018 Pa s for a TS content of 20 g/L as shown in Table 4 while the infinite rate viscosity does not change significantly with increasing TS concentration as shown in Table 5. The increase of TS concentration has also resulted in increasing non-Newtonian flow behaviour. This is due to larger and denser units of suspension resulting in higher apparent viscosity [2]. Inter-particle interaction also increases with increasing solid concentration [12], which is because of stronger network of sludge floc structure with the increase of solid concentration where colloidal and hydrodynamic forces between sludge particles change [1,25].

3.3. Effects of temperature on mixed sludge rheology

The effect of temperature on rheological properties of mixed sludge was studied for temperature conditions of 25, 30, 35, 40 and 55°C for a TS content of 29 g/L and a mixing ratio of 60% RPS to 40% TEAS. The samples were heated by utilizing the Peltier Concentric Cylinder Temperature System which is attached to the Rheometer with a typical temperature heating rate of 10°C/min [25]. Experimental results show that temperature has a significant effect on the rheological properties of mixed sludge in the temperature range of 35–55°C as shown in Fig. 2(a) and (b), the rheological properties in the temperature range of 25–35°C are not very different from each other. The increase in temperature from 25 to 35°C showed an increasing trend in yield stress from 6.8 to 8.0 Pa based on best fitted Bingham model while a decreasing trend from 8.0 to 4.5 Pa for a temperature range of 40–55°C as shown in Table 6. Furthermore, shear stress decreases with increasing temperature as shown in Fig. 2(a), the thermal energy resulted in change of the shape and size of flocculated particles, and the degree of dispersion of the soluble organic content of the sludge. These changes directly influenced the rheological properties of the mixed sludge [8]. The viscosity generally showed reduction with increasing

Table 5
Infinite-rate viscosity of mixed sludge for varying TS content based on Sisko model

Total solid concentration (g/L)	Infinite-rate viscosity (Pa s)	Flow consistency index (s)	R^2
30	0.02	5.0	0.99
25	–	12.5	0.95
20	0.02	0.9	0.97

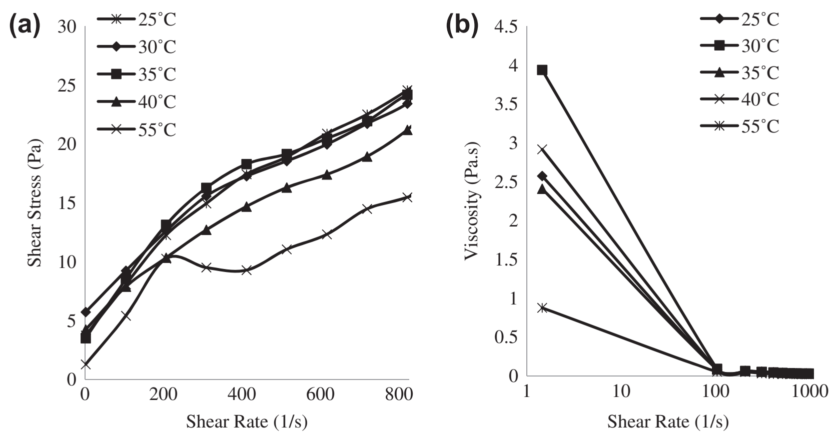

Fig. 2. (a) Shear stress–shear rate curves and (b) viscosity–shear rate curves for different temperatures of mixed sludge sample.

Table 6
Yield stress and viscosity of mixed sludge for different temperature conditions based on Bingham model

Temperature (℃)	Yield stress (Pa)	Viscosity (Pa s)	R^2
25	6.8	0.02	0.97
30	7.9	0.02	0.98
35	8	0.02	0.93
40	5.8	0.02	0.98
55	4.5	0.01	0.97

temperature and shear rate as shown in Fig. 2(b); similar trend was also reported by many authors [2,28,29]. The decrease in viscosity with increase in temperature is due to the weakening of inter-molecular cohesive forces which result in the reduction of shear stress and viscosity [25].

Viscosity reduced from 0.02 Pa s for temperature of 25℃ to 0.01 Pa s for a temperature of 55℃ for Bingham plastic model when shear force is applied to the system as shown in Table 6. As shown in Table 7, the viscosity of sludge at different temperatures for higher shear rate range (infinite rate viscosity) is similar to the viscosity determined from the shear stress-rate models. It can be concluded that increase in the temperature of mixed sludge would improve flow behaviour for the temperature range investigated which in turn enhances mixing and mass flow in the anaerobic digesters [6,7].

3.4. *Effects of RPS to TEAS mixing ratio on rheological properties of mixed sludge*

The experiments on the effect of sludge mixing ratios were conducted for RPS:TEAS mixing ratios of 80:20, 70:30, 60:40, 50:50, 40:60 and 20:80, respectively. In the actual industrial operations, mixing ratio usually ranges between RPS: TEAS ratios of 70:30–50:50 [6,7]. The mixing ratios investigated for the rheology tests were selected taking the operational conditions into account. The rheological behaviours of different sludge such as RPS, EAS, TEAS and mixture of PRS and TEAS are presented in Fig. 3. As shown in Fig. 3, the shear stress–shear rate plot for TEAS shows a shear force requirement that is much higher when compared to the other three types of sludge. This is associated to the presence of significant amount of bio-polymeric material (polysaccharides and proteins) and higher TS content of TEAS [2,7,17,27]. Moreover, the shear stress shows a significant jump from 43.2 to

Table 7
Zero-rate and infinite-rate viscosity of mixed sludge for varying temperature based on Sisko model

Temperature (℃)	Infinite-rate viscosity (Pa s)	Flow consistency index (s)	Flow index	R^2
25	0.02	3	0.2	0.99
30	0.02	5	0.1	0.99
35	0.01	3	0.2	0.99
40	0.02	4	0.1	0.99
55	0.01	2	0.2	0.99

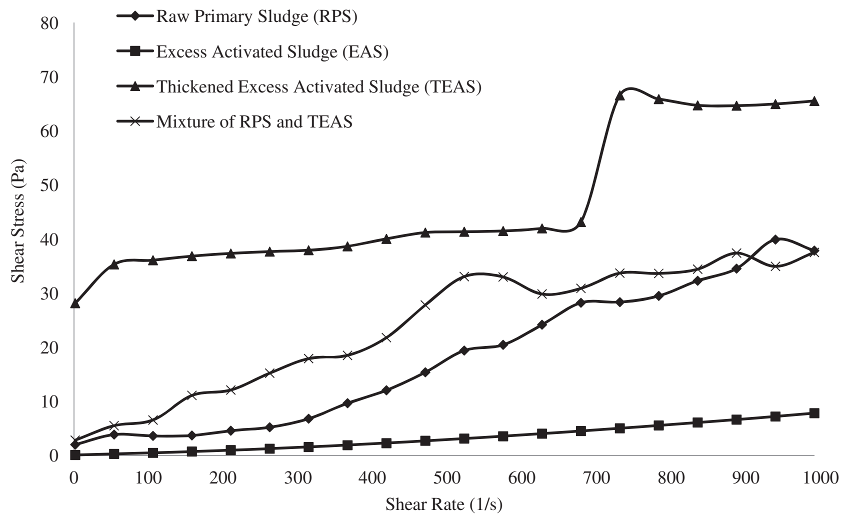

Fig. 3. Shear stress–shear rate curves for different sludge types.

Table 8
Yield stress and viscosity of different sludge types based on Bingham model

Sludge type	Yield stress (Pa)	Viscosity (Pa s)	R^2
Thickened excess activated sludge	33	0.02	0.82
Raw primary sludge	–	0.04	0.91
Mixture of RPS and TEAS	2.9	0.05	0.92
Excess activated sludge	–	6.5E−03	0.98

66.6 Pa between shear rate ranges of 680–740 s^{-1}. At the experimental temperature condition of 25℃ and TS content of 37 g/L, 680 s^{-1} is the shear rate at which significant change in floc structure of TEAS occurred. The various rheological fitted model parameters generated from the shear stress–shear rate rheograms are shown in Table 8.

Mixture of RPS and TEAS showed overall rheological behaviour that is partially similar to those of RPS and TEAS, where the yield stress, (2.9 Pa) viscosity (0.05 Pa s) and shear stress–shear rate profiles falls in between those of RPS and TEAS. The reduction in yield stress and viscosity in the mixed digester feed sludge has significant implications on mixing hydrodynamics, mass transfer and power requirement in the anaerobic digester's performance [23,30–32].

RPS exhibits lower yield stress and un-thickened excess activated sludge directly coming from the activated sludge treatment process has extremely low yield and behaves like a Newtonian fluid (Fig. 3) as the TS content is very low. The mixing ratio between RPS and TEAS is an essential process parameter that affects flow hydrodynamics and the biochemical methane production capacity, digestion kinetics, volatile solid removal and overall performance of anaerobic digestion process and dewaterability of the digested sludge that comes out of this process [6,7]. Hence, the rheological investigations for different sludge mixing ratios between the two sludge types showed that with increasing percentage of TEAS yield stress and viscosity significantly increased as shown in Fig. 4(a) and (b), respectively. This is also supported by rheological model parameters, which are tabulated in Tables 9 and 10, respectively. Yield stress decreased from 10.2 to 1.2 Pa for Bingham plastic model when the percentage of TEAS was reduced from 80 to 20%. Table 10 also shows that the viscosity at higher shear rate consistently decreased from 0.052 Pa s for RPS: TEAS of (20:80 V/V) to 0.027 Pa s for a composition of 80:20 V/V according to Cross models [33].

Previous studies show that greater percentage of RPS in the mixed digester feed sludge enhances anaerobic digester performance [6,7]. The findings of this study on the rheological behaviour of different mixing ratios support this finding that greater percentage of RPS not only favours digester performance, but also enhances sludge hydrodynamics and rheology with the significant decrease in yield stress and viscosity.

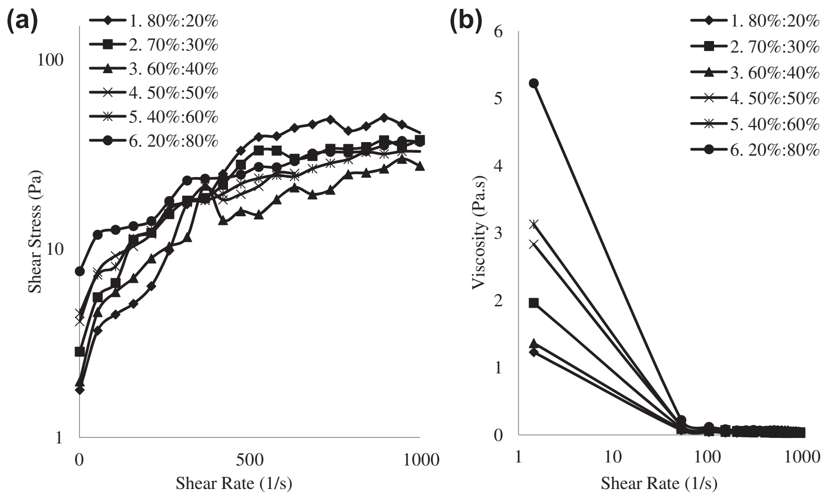

Fig. 4. (a) Shear stress–shear rate curves and (b) viscosity–shear rate curves for different mixing ratio of RPS to TEAS.

Table 9
Yield stress and viscosity of different raw primary: TEAS mixing ratio based on Bingham model

RPS:TEAS mixing ratio (%)	Yield stress (Pa)	Viscosity (Pa s)	R^2
80:20	1.2	0.05	0.88
70:30	5.9	0.04	0.92
60:40	3.7	0.03	0.93
50:50	5.8	0.03	0.94
40:60	6.8	0.03	0.98
20:80	10.2	0.03	0.97

Table 10
Zero-rate and infinite-rate viscosity of different raw primary: TEAS mixing ratio

RPS:TEAS mixing ratio (%)	Infinite-rate viscosity (Pa s)	Flow consistency (s)	Flow index	R^2
80:20	0.052	2.33	–	0.88
70:30	0.040	2.65	0.07	0.98
60:40	0.024	1.83	0.14	0.98
50:50	0.029	3.91	0.10	0.99
40:60	0.028	4.26	0.09	0.99
20:80	0.027	7.33	0.07	0.99

3.5. Effects of sludge age on rheology

The effect of sludge age on the rheological properties of mixed sludge was also investigated. Sludge undergoes chemical and microbiological ageing process during storage which resulted in changes of the apparent viscosity and other rheological parameters [27]. Hence, investigating the impact of mechanical ageing with time on the rheological behaviour is important. The experiments on the effect of low temperature storage time on rheological properties of mixed sludge are shown in Fig. 5(a) and (b), where sample MS1, MS2 and MS3 are samples of mixed sludge at different day of storage of day 1, day 15 and day 32, respectively. Table 11 shows that TS and VS content decreased over time. Samples of mixed sludge at an initial TS content of 29 g/L and volatile solid content of 25.4 g/L degraded to 25 and 21.65 g/L, respectively, after a period of 30 d. It can be seen that the changes within the first 15 d were insignificant, with the TS reduction of 3.5% while the total volatile solid reduce by 2.0% in the following 15 d due to hydrolysis and organic degradation as shown in

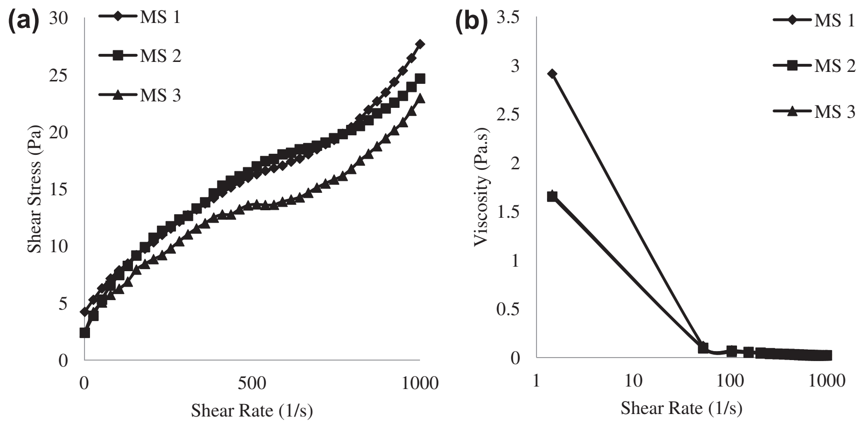

Fig. 5. (a) Shear stress–shear rate curves and (b) viscosity–shear rate curves for mixed sludge at various ageing stage.

Table 11
Effects of mixed sludge age on TS and volatile solid content

Mixed sludge (MS)	MS1	MS2	MS3
Day	1	15	32
Total solid content (g/L)	29	28	25
Volatile solid content (g/L)	25.4	24.9	21.65

Table 11. The results showed that within a period of a month, the yield stress has decreased from 5.8 to 4.9 Pa, as shown in Table 12 for Bingham plastic model, which is caused by slow hydrolysis of extra cellular polymeric substances, deflocculation and degradation of organic matrix [27]. Similar trend was observed in viscosity tests, as days of storage progress, the viscosity of the mixed sludge decreased from a value of approximately 0.02 to 0.016 Pa s for Bingham plastic model as shown in Table 12. The flow index shown in Table 13 supports the non-Newtonian flow behaviour which generally decreases with increasing storage time.

It can be concluded that mixed sludge samples degrade during storage and the rheological properties change significantly with time. All the sludge samples according to shear stress–rate curves in Fig. 5(a) show Bingham pseudo-plastic shear thinning behaviour up until shear rate of 600 s^{-1} and this trend is reverted with further increase in shear rate until 1,000 s^{-1}. Fig. 5(a) and Table 12 show that the yield stress and viscosity showed an increasing trend during storage in the first 15 d and later decreased after 30 d of storage.

Fig. 5(b) and Table 13 show that the viscosity at higher shear rate shows a decreasing behaviour with the increase in storage time. Generally, the biodegradation of organics enhances the shear thinning

Table 12
Yield stress and viscosity of mixed sludge for different sludge age based on Bingham model

RPS:TEAS mixing ratio	Yield stress (Pa)	Viscosity (Pa s)	R^2
MS1	5.8	0.020	0.98
MS2	6.1	0.019	0.96
MS3	4.9	0.016	0.96

Table 13
Zero-rate and infinite-rate viscosity of mixed sludge age based on Sisko model

RPS:TEAS mixing ratio	Infinite-rate viscosity (Pa s)	Flow consistency (s)	Flow index	R^2
MS1	0.02	3.9	0.1	0.99
MS2	0.01	1.9	0.3	0.99
MS3	0.01	2.2	0.2	0.99

behaviour; yield stress and viscosity reduce gradually over time which is because of the change in composition of key components like protein, lipid and carbohydrate with the age of the sludge and due to synthesis of volatile fatty acids [13]. This implies that in the course of the anaerobic digestion process, the viscosity of mixed sludge significantly decreases with time favouring better mass transfer and mixing.

4. Conclusion

The rheological behaviour of mixed sludge was observed to be affected by several physico-chemical factors including TS concentration, temperature, RPS to TEAS mixing ratio and sludge age. The decrease in TS concentration for mixed sludge from 30 to 20 g/L resulted in the reduction of yield stress by 85.4% proving the significant impact of suspended solids interacting together on the power required to disrupt the network and overcome the yield stress. In this study, it was also found that yield stress decreased from 6.8 to 4.5 Pa and viscosity decreased from 0.022 to 0.013 Pa s when temperature was increased from 25 to 55°C. Similar to the findings of other researchers the effect of temperature on shear stress and viscosity of mixed sludge in the temperature range of 25–35°C was limited compared to the effect at higher temperatures of 40 and 55°C where significant reduction in yield stress and viscosity was observed. The rheological investigations for different mixing ratios between RPS and TEAS show that with decreasing percentage of TEAS, from 80 to 20%, yield stress decreased from 10.2 to 1.2 Pa. Hence, greater percentage of RPS in mixed digester feed sludge not only favours digester performance but also enhances sludge hydrodynamics and rheology with the significant decrease in yield stress and viscosity. Furthermore, based on the investigation of anaerobic ageing over a period of a month, it can be concluded that although samples are stored under refrigerated condition under 5°C, the rheological behaviour changed gradually due to limited hydrolysis and release of extracellular polymeric substances and organic degradation as the storage time progresses and further investigation is required to better understand ageing of mixed sludge.

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