Effects of temperature, polymer dose and solid concentration on the rheological characteristics and dewaterability of digested sludge of wastewater treatment plant (WWTP)

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Abstract

The rheology of digested sludge affects the flow hydrodynamics, dewaterability and the polymer consumption in wastewater treatment plants. The rheological characteristics of digested sludge are highly dependent on changes in total solid concentration, temperature and polymer dose. Hence, this study aims at investigating the impacts of total solid concentration, temperature and polymer dose on the rheological characteristics and the dewaterability of digested sludge. Investigating the relationship between rheological and physico-chemical characteristics of sludge can also serve as a tool to optimize essential process parameters. Different homogenised digested sludge samples were subjected to rheological measurement on rotational rheometer equipped with Peltier concentric cylinder system. The shear stress-shear rate and viscosity-shear rate curves were then developed before and after polymer conditioning at various temperatures and solid concentrations. Different rheological model were fitted to the shear stress-rate, and viscosity-shear rate rheograms, and the model with the best fitting and more practical significance was selected to determine key rheological parameters. The relationship between dewaterability and digested sludge rheology was also developed. The rheological characteristics of digested sludge during polymer conditioning and flocculation process was significantly affected by temperature and solid concentration; hence, polymer dose can be reduced by operating the dewatering process at optimum temperature condition and varying the poly dose as a function of the total solid concentration and viscosity of the digested sludge. The dewaterability as measured in capillary suction time (CST) improved with increasing polymer dose up to 12kg/t DS but further increase in polymer dose resulted in the deterioration of the dewaterability due to overdosing.

Key words: Dewaterability, digested sludge, polymer dose, rheology.

1. Introduction

The flow pattern and rheology of sludge in wastewater treatment plants particularly after anaerobic digestion process affects the pumping cost, mixing hydrodynamics, and the dewaterability of digested sludge. Rheological and fluid dynamic characteristics of sludge are also essential in the design and operation of processes in wastewater treatment plants due to their influence on heat and mass transfer and mixing (Baroutian et al. 2013; Bandrés et al. 2009). The rheological characteristics of digested sludge depend on many factors such as source, solid concentration, temperature, and sludge treatment method (Ratkovich et al. 2013; Abu-Jdayil et al. 2010; Hong et al. 2015; Hong et al. 2016). Total solid concentration is one of the major factors that affects the rheology and flow behaviour of digested sludge. Baroutian et al. (2013) and Farno et al. (2013) investigated the effect of total solid concentration on sludge rheology and observed that yield stress of digested sludge is directly related to total solid content of the system. The increase in shear stress with solid concentration was observed to be more noticeable at higher shear rates. The existence of solids within fluid are responsible for the shear-thinning flow behaviour. The existence of solids within a fluid is the major reason for the increase in the fluid viscosity (Sanin 2002). Sludge characteristic curve for low solid concentrations differ from that for high solid concentration where there is a strong interaction between solid particles. The apparent viscosity of sludge reflects the internal and external interactions and forces occurring within sludge flocs and fluid (Yang et al. 2009). Forster (1981) has shown the exponential relationship between total solid concentration and yield stress. Besides, rheological properties of digested sludge are known to mainly depend on the organic fraction and duration of the anaerobic biochemical degradation. By extracting the main solids components (minerals, proteins, lipids, carbohydrates) it was shown that the rheological behaviour is governed by the synthesis of volatile fatty acids (J.-C. Baudez and Coussot 2001).

Temperature is another factor that influences the rheological properties of digested sludge. Thermal energy results in change of the shape and size of flocculated particles, and the degree of dispersion of the soluble organic content of sludge. These changes directly influence the rheological properties of digested sludge during dewatering (Sanin 2002). Viscosity, generally lowers with higher temperature and shear rate, a similar trend was reported by many researchers (Farno et al. 2013; Eshtiaghi et al. 2013; Hasar et al. 2004; Yeneneh 2014; Hong et al. 2015; Hong et al. 2016).

Polymer dose is another very important parameter that significantly affects the rheology, the dewaterability of digested sludge and the operational cost of the dewatering unit. Campbell and Crescuolo (1983) observed the relationship between digested sludge conditioning for varying polymer dose with yield stress and overall rheological property of the sludge. Campbell and Crescuolo (1983) showed that the initial yield stress of sludge increased with increasing polymer dose. They also identified the critical point in the rheograms where the curve profile changes indicating point of optimum dose. The initial yield stress peak is associated to the elastic floc network that the polymer creates due to its bridging effect; it is at this yield point where this network also ruptures. The increase in viscosity with increasing polymer dose is also associated to the bridging effect of the conditioning polymer (Abu-Orf and Dentel 1999). Besides, rheological investigations for varying polymer dose provides more reliable result compared to characterization and dewaterability test on the digested sludge (Örmeci 2007). Yet, there are limited number of studies on the effects of polymer dose, other process parameters including temperature and solid concentration on digested sludge rheology, and on the role of rheological investigations to optimize polymer dose, dewaterability of digested sludge, and lower operating cost by avoiding excessive use of polymer.

Hence, this study focuses on investigating the influence of variation in polymer dose, temperature and total solid concentration on the rheological properties of digested sludge and its dewaterability. Besides, optimum polymer dose for better dewaterability was determined and the relationship between total solid content, temperature and polymer dose versus the rheological and physico-chemical characteristics of digested sludge were developed. The rheological models that best represents the rheological behaviour of digested sludge for varying temperature, total solid concentration and polymer dose conditions were selected.

2. Materials and methods

2.1 Sampling and characterization of digested sludge and conditioning polymer

In this study, digested sludge sample was collected from the dewatering centrifuges and the polymer samples were collected from the polymer mixing tank at Beenyup Wastewater Treatment Plant (BWWTP), Perth, Western Australia. The collected samples were used for rheological investigation on the same day to prevent the change in the rheological properties of the sludge samples except for the study on sludge age. All samples were refrigerated at 4˚C after use.

Intensive characterization was conducted on the collected digested sludge samples. The characterization of digested sludge involved determination of physico-chemical and biological parameters such as Total Solids Content (TS), Total Volatile Solids (VS), Chemical Oxygen Demand (COD), Temperature, and pH. Standard Methods for Examination of Water and Wastewater provided by the American Public Health et al. (2005) were used for the study. Total solids (TS) and total volatile solid (VS) content were determined by employing the standard method (gravimetric method) (Vincenzo Lotito and Lotito 2014). Total chemical oxygen demand was determined by using oxidation method with HACH COD reagent and colorimetric analysis on ORION UV/Vis spectrometer (Li et al. 2008). pH was measured with WP-90 and WP-81 conductivity/TDS-pH/temperature meter equipped with a glass electrode (Sanin 2002).

2.2 Rheological investigation of digested sludge and conditioning polymer

The rheology of untreated and polymer conditioned digested sludge samples and the conditioning polymer was investigated on a rheometer equipped with Peltier concentric cylinder system and vane rotor and shear stress-rate and viscosity versus shear rate curves were generated as a function of different parameters including temperature, solid concentration and polymer dose. Shear rate range was adjusted to 0 – 1000s^{-1}. Temperature was homogenised before each test and five equilibrium points were used to plot each data point in the rheograms. Effect of solid concentration on the rheological behaviour of digested sludge was varied between 1.0 - 2.0% TS, and the effect of temperature was investigated between 20˚C - 50˚C. Furthermore, the impact of polymer dose on digested sludge rheology and dewaterability was investigated for polymer dose range of 7kg/t DS – 18kg/t DS. Shear stress-shear rate and viscosity-shear rate rheograms were developed and the model with the best fit and practical significance was selected to determine the apparent yield stress, apparent viscosity and flow index of the digested sludge In addition, to further understand the rheological properties in a hysteresis cycles, hysteresis tests were conducted for the digested sludge sample (Piani et al. 2014). The digested sludge sample was homogenised before each test. During the test the shear rate was first increased from 0 – 1000s^{-1} and then decreased from 1000 – 0s^{-1} at a temperature of 25˚C in the cycle.

2.3 Rheological modelling

Ideal fluids (Newtonian fluids) exhibit linear rheological flow behaviour. Non-Newtonian fluids on the other hand involved complex structure and deformation effects and are non-linear in nature (Björn et al. 2012). Non-Newtonian fluids can be categorised into different classes such as pseudoplastic, viscoplastic, dilatant, and thixotropic fluids. Different rheological models can be used to represent non-Newtonian fluids and calculate important rheological model parameters such as shear stress, yield stress, flow index, infinite and zero-rate viscosities and flow consistency index (Sokolov 2013).

Shear stress and viscosity models such as Bingham, Ostwald, Herschel-Bulkley, Sisko, Careau, and Cross models, shown in equations (1), (2), (3), (4), (5), and (6) respectively, have been used extensively to characterize viscoplastic fluids like sludge which show pseudo-plastic shear thinning behaviour (Mori et al. 2006; Khalili Garakani et al. 2011; Ratkovich et al. 2013).

$$\tau = \tau_y + \eta_B \dot{\gamma}^n \quad (1)$$

$$\tau = K\dot{\gamma}^n \quad (2)$$

$$\tau = \tau_y + K\dot{\gamma}^n \quad (3)$$

$$\mu = \mu_\infty + K\dot{\gamma}^{n-1} \quad (4)$$

$$\frac{\mu-\mu_\infty}{\mu_0-\mu_\infty} = (1+(\lambda\dot{\gamma})^2)^{\frac{n-1}{2}} \quad (5)$$

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

where τ_y is yield stress (Pa), η_B is the high shear limiting viscosity (Pa.s), Υ 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, in equation (7) *T* is temperature (K), μ_0 is a coefficient usually termed as frequency factor (pre-exponent coefficient, *E* is the activation energy (J.mol^{-1}) and *R* is the universal gas constant (8.314J.$mol^{-1}K^{-1}$). Equations (1) to (6) are commonly used to model the shear stress (τ is the shear stress in Pa) profile and viscosity (μ is the viscosity in Pa.s) profile.

3. Result and discussion

3.1 Characterization of digested sludge

The total solid concentration, volatile solid concentration, pH, temperature and total chemical oxygen demand were determined for all collected samples as shown in Table 1. The total solid and volatile solid concentrations of the digested sludge samples varied from 1.6 – 2.0% and 74 - 82% respectively, depending on the composition of the feed and performance of the anaerobic digesters. The temperature of the digested sludge samples was about 31˚C on average but it fluctuated between 28 - 37˚C based on the temperature of the ambient environment and the operational temperature of the anaerobic digesters. The pH of digested sludge was mostly constant with average value of 7 over the period the investigation was conducted. Generally, the pH varied in the range of 6.9 - 7.3. The chemical oxygen demand for the digested sludge samples fluctuated in the range of 17400 - 25500 mg/L based on the performance of the anaerobic digesters. The polymer dose and its characteristics were maintained constant in the operation of BWWTP, despite the changes in the composition and characteristics of the digested sludge.

Table 1 Characterization of digested sludge samples collected at different days

Digested sludge Sample	Temperature (˚C)	pH	Total Solid Content (%)	Total Volatile Solids Content (%)	Chemical Oxygen Demand (mg/L)
S1	30	6.9	1.7	74.0	8800
S2	28	7.1	2.0	81.3	25500
S3	30	6.9	1.7	79.3	21300
S4	33	7	1.9	79.4	17400
S5	37	7.1	1.6	82.3	265550
S6	37	6.9	1.6	74.6	9740
S7	20	7.3	1.3	82.8	27640
Average	**30.7**	**7.0**	**1.7**	**79.1**	**18250**

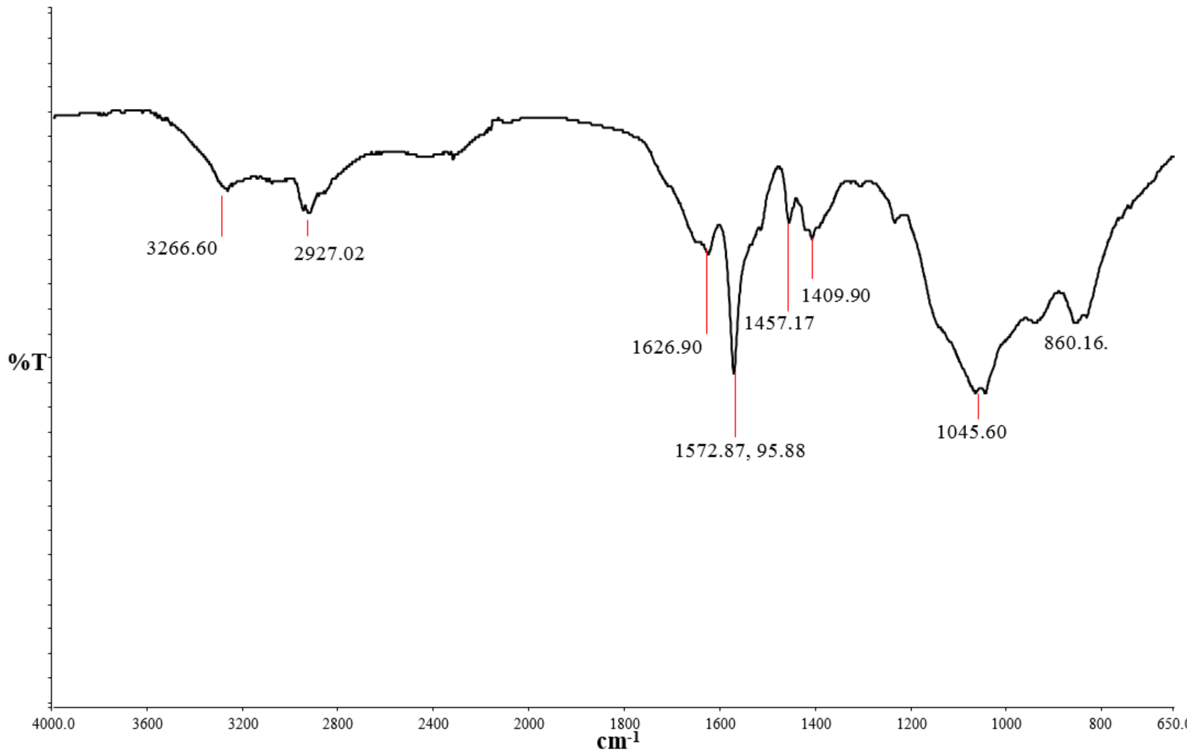


Fig. 1 FTIR spectra of typical digested sludge sample from BWWTP

Furrier transform infrared spectroscopic plots (FTIR) plots were also generated to understand the chemistry and flocculation behaviour of the digested sludge and its interaction with the conditioning polymer. Fig. 1 shows the FTIR spectra for digested sludge sample. FTIR bands around 1100 – 1000cm^{-1} represent the occurrence of polysaccharides or cellulose. Bands around 2925 - 2950cm^{-1} show the decomposed fatty acids and lipid components, bands of amide I, II, III around 1630-1650cm^{-1} come from proteins and amino acids. Bands of carbonyl groups and hydroxyl groups around 2920-2950 cm^{-1} and 3600-3200 cm^{-1} respectively represent proteins, carboxylic acids, phenols and water (Show et al. 2007; Lay et al. 1999; Yeneneh 2014). The poly saccharides and proteins shown by these bands are the biopolymers which play key role in the flocculation and dewatering of the digested sludge (Neyens et al. 2004; Yin et al. 2004; Raszka et al. 2006).

3.2 Characterization of polymer

The conditioning polymer sample collected from the primary polymer concentrate dilution tank was also characterized. The characteristics shown in Table 2 indicate that the total solid content was 0.4%. The pH was neutral in all the collected samples with an average value of 7.2. The FTIR spectra, as shown in Fig. 2, generated for moisture free dried polymer sample shows that the polymer constitutes an array of organic functional groups including OH^- (3600 cm^{-1}), stretching N-H and C-H group (2800 - 2900 cm^{-1}), $COOH^-$, C=O, P=O. The functional groups play important role in forming the network between the digested sludge particles enhancing flocculation and further separation of the biosolid from centrate (Yin et al. 2004).

Table 2 Characteristics of the conditioning polymer used in the study

Polymer Sample	pH	Total Solid (%)
EMA	**7.2**	**0.4**

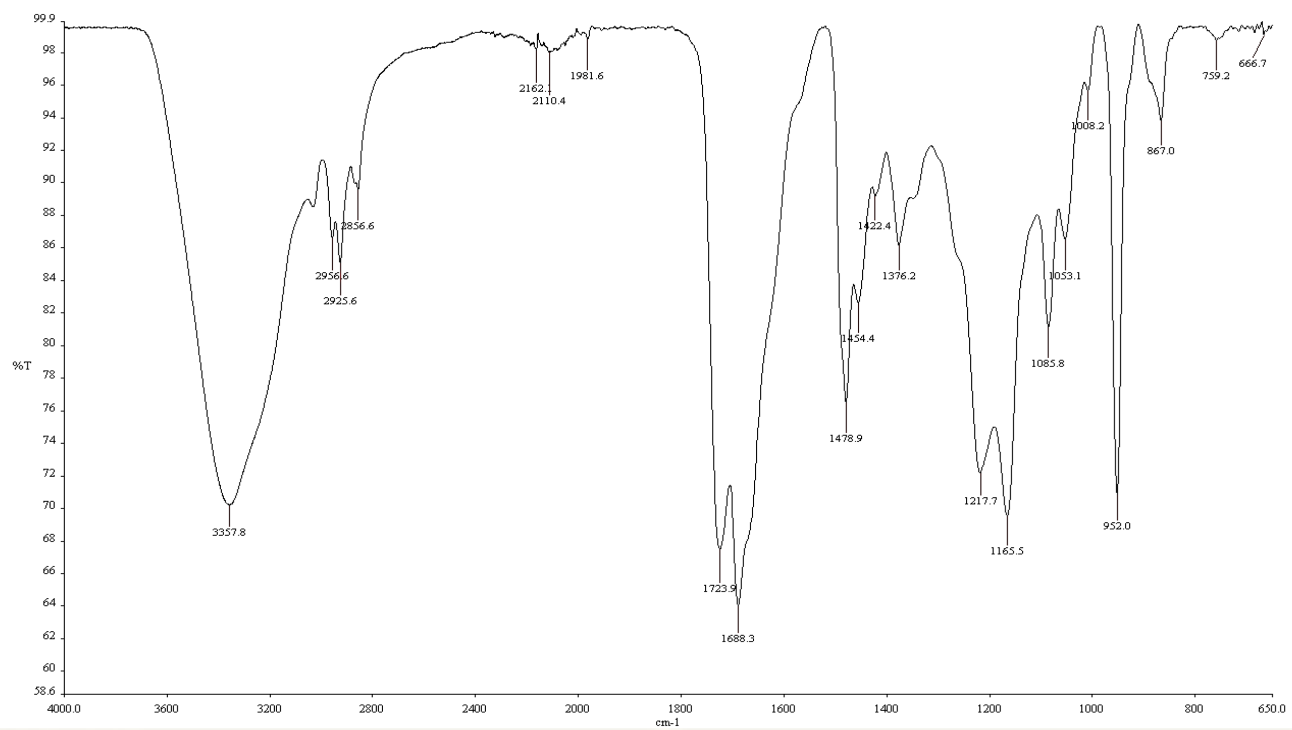
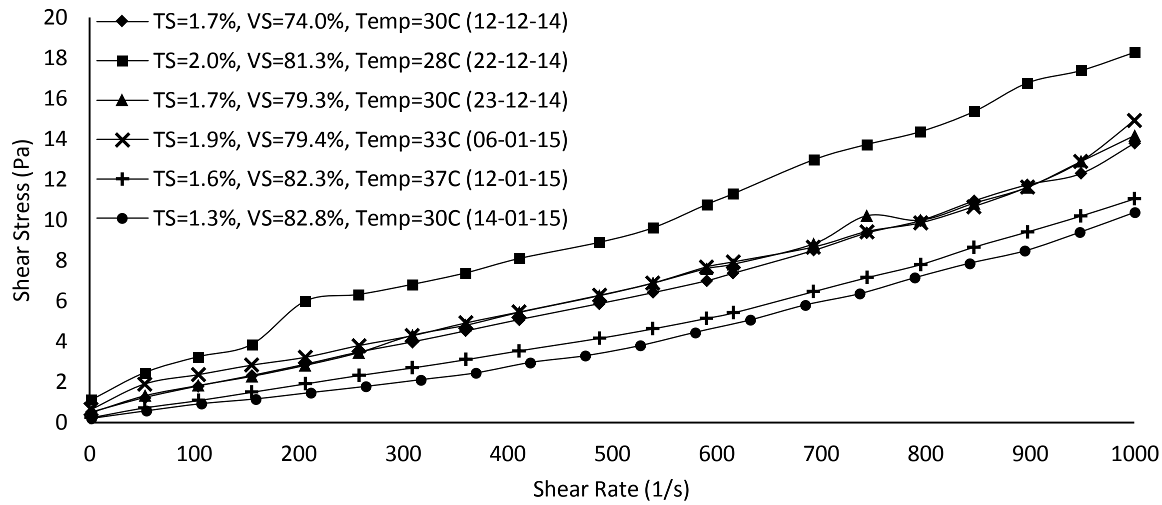


Fig. 2 FTIR spectra of the conditioning polymer

3.3 Rheological dynamics of digested sludge at BWWTP

Digested sludge samples collected from centrifuge of BWWTP were homogenised and used for rheological investigation on the same day of collection. The temperature during the rheological tests was adjusted to the temperature of the samples upon collection. The shear stress-shear rate and viscosity-shear rate curves of all the digested sludge samples were later generated as shown in Fig. 3(a) and Fig. 3(b). It can be observed that the effect of total solid concentration on the rheological behaviour of digested sludge is more significant than the effect of temperature or volatile solid concentration, this is because of stronger inter-particle interactions which is caused by the increase in total solid content and size of particles in suspension, resulting in higher apparent viscosity and yield stress (Eshtiaghi et al. 2013). The shear stress versus shear rate curves were fitted to different rheological models and Herschel-Bulkley model was selected as it fits best to the rheograms and better represents the complex shear thinning behaviour of digested sludge. The apparent yield stress ranges from 0.53Pa to 1.04Pa and the apparent viscosity ranges from 0.00012 – 0.002Pa.s as shown in Fig. 4(a). The viscosity versus shear rate curves were found to best fit to Cross model. Initial or zero-rate viscosity and infinite-rate viscosity values determined from this model are reported in Fig. 4(b). The presence of initial yield stress in shear thinning fluids like digested sludge is due to the resistance of the sludge flocs for shearing unless sufficient amount of stress is developed that overcomes the resistance which varies with floc size and structure (V. Lotito et al. 1997). Furthermore, hysteresis tests were carried out for digested sludge sample to have a better understanding of the rheological behaviour within the hysteresis loop. The upward and downward curves of the shear stress-shear rate and viscosity-shear rate plots of digested sludge show shear thinning thixotropic behaviour as shown in Fig. 5 (Piani et al. 2014).

(a)



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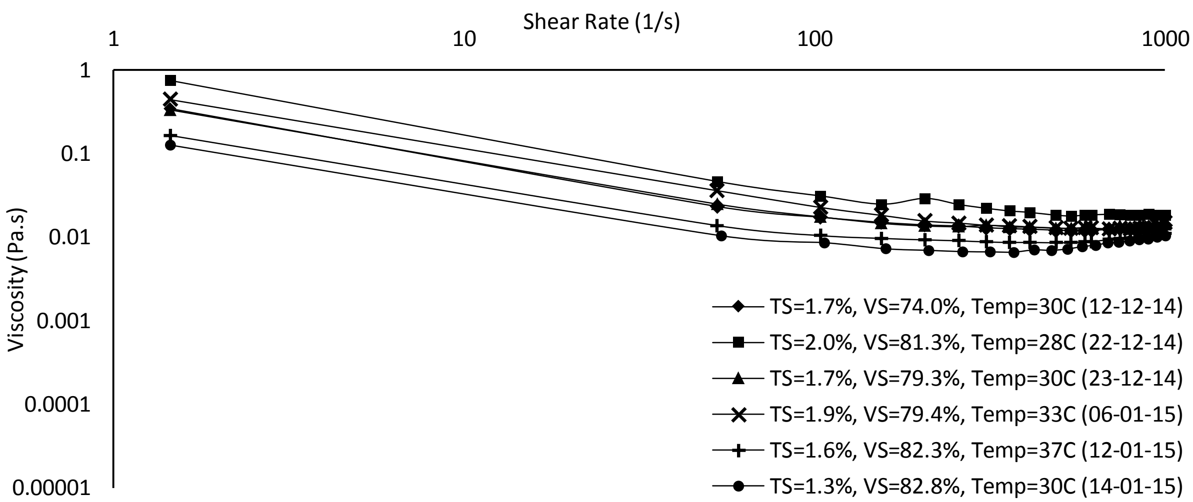
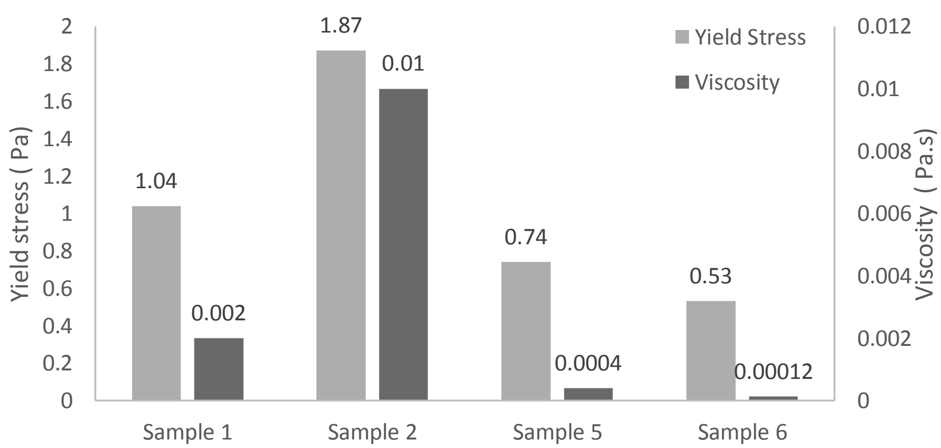


Fig. 3 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for digested sludge from different collection day

(a)



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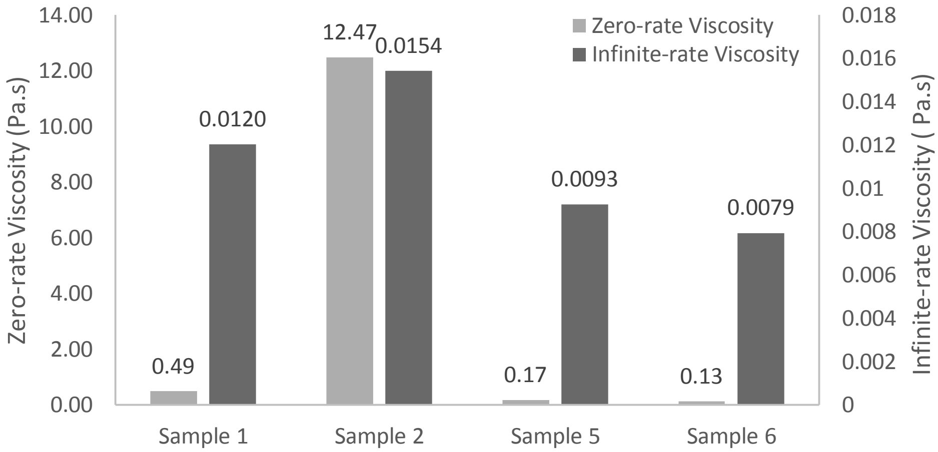
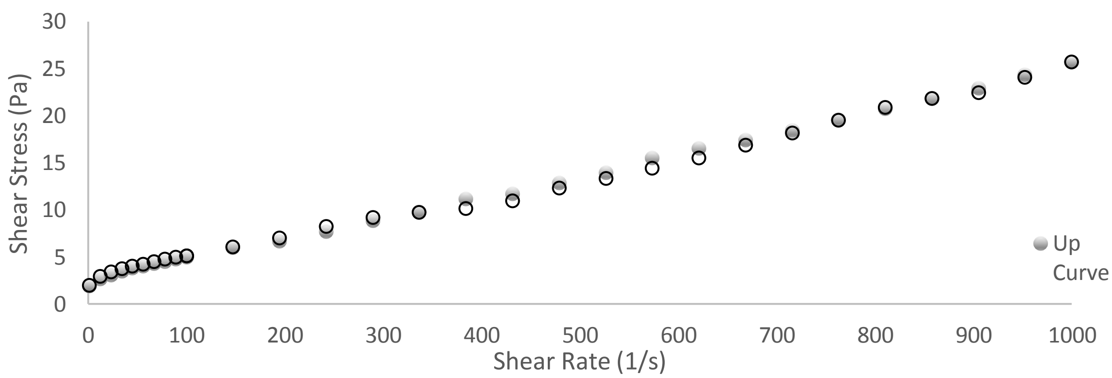


Fig. 4 Rheological model based parameters for digested sludge from different collection day (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

(a)



(b)

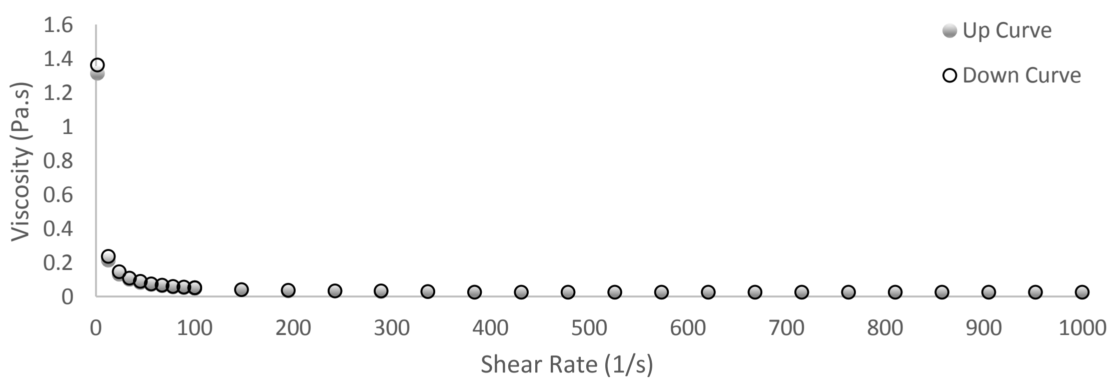


Fig. 5 Hysteresis test: (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for digested sludge sample with TS=2.3%, pH=6.6 and Temperature=25˚C

3.4 Effect of temperature on the rheological properties of digested sludge before and after polymer conditioning

The rheological characteristics of polymer conditioned and unconditioned digested sludge were also investigated for varying temperatures of 20˚C, 35˚C, 40˚C and 50˚C. Fig. 6(a) and Fig. 6(b) show shear stress-shear rate and viscosity-shear rate rheogram for digested sludge after polymer conditioning respectively. The shear stress-shear rate and viscosity-shear rate flow curves were plotted and the results show that the shear stress-shear rate flow curve of polymer conditioned digested sludge at 20˚C is relatively higher than the shear stress-shear rate curves for the range of 35˚C to 50˚C as shown in Fig. 6(a) which is due to the stronger bridging and networking effect and greater viscosity of the polymer at lower temperature of 20˚C. The apparent viscosity at the start of shearing, generally showed reduction with increasing temperature as shown in Fig. 6(b). The increase in temperature from 20˚C to 50˚C resulted in steady decrease of apparent viscosity from 0.0053Pa to 0.0011Pa based on Herschel-Bulkley model as shown in Fig. 7(a). Yield stress of polymer conditioned digested sludge also showed a decreasing trend with increasing temperature in the temperature range of 20-40 ˚C and it increased again at 50˚C as shown in Fig. 7(a). Infinite rate viscosity showed a decreasing trend with increasing temperature from 20-50˚C as shown in Fig. 7(b) as the thermal energy results in change of the shape and size of flocculated particles, and the degree of dispersion of the soluble organic content of the sludge (Abu-Orf and Örmeci 2005). Fig. 8(a) and Fig. 8(b) show shear stress-shear rate and viscosity-shear rate rheograms respectively for unconditioned digested sludge. The temperature range considered for this study is similar to the polymer conditioned digested sludge (20˚C - 50˚C) and the trends both for shear stress-shear rate and viscosity-shear rate rheograms are similar to the result obtained in the case of polymer conditioned digested sludge, yet, Fig. 9(a) and Fig. 9(b) show that apparent yield stress and apparent viscosity of unconditioned digested sludge are more consistent than the polymer conditioned one. Apparent yield stress showed an increasing trend in the range of 20-35˚C and it started to decrease again in the range of 35-50˚C, the viscosity on the other hand was observed to decrease from 20-50 ˚C as shown in Fig. 9(a). The addition of polymer resulted in the increase of the floc network strength contributing to the increase in yield stress and viscosities (Wang and Dentel 2010; Örmeci 2007).

(a)

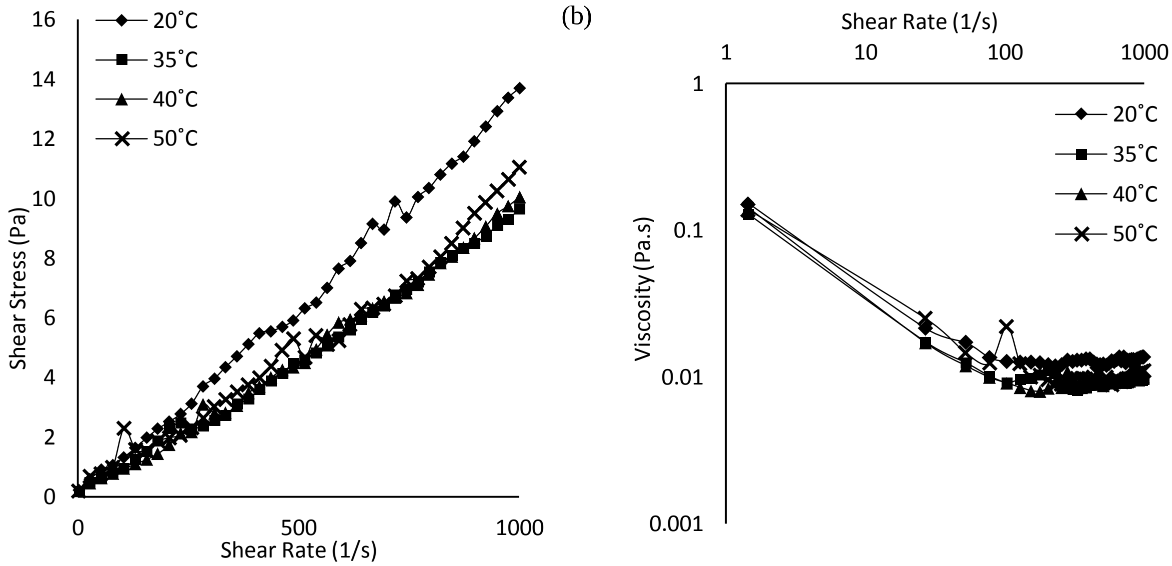
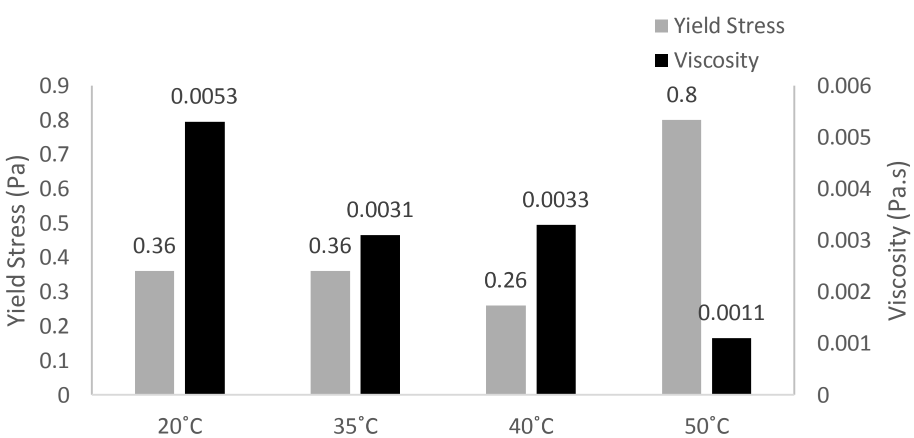


Fig. 6 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different temperatures of polymer conditioned digested sludge

(a)



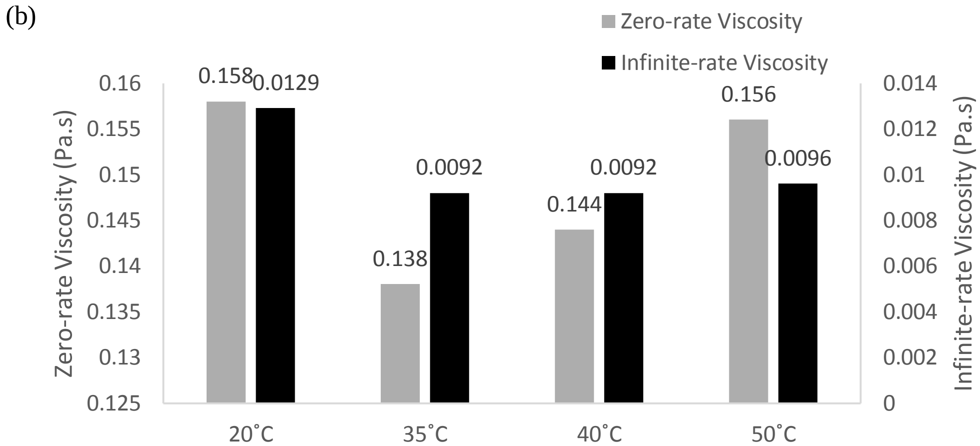


Fig. 7 Rheological model based parameters for varying temperature of polymer conditioned digested sludge (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

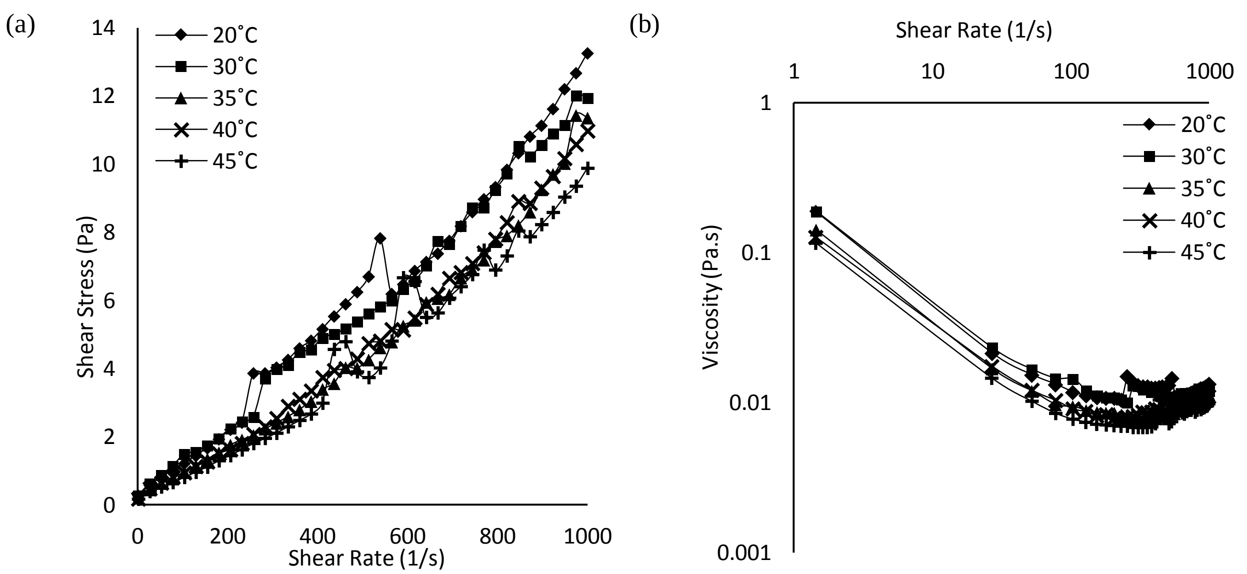


Fig. 8 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different temperatures unconditioned digested sludge

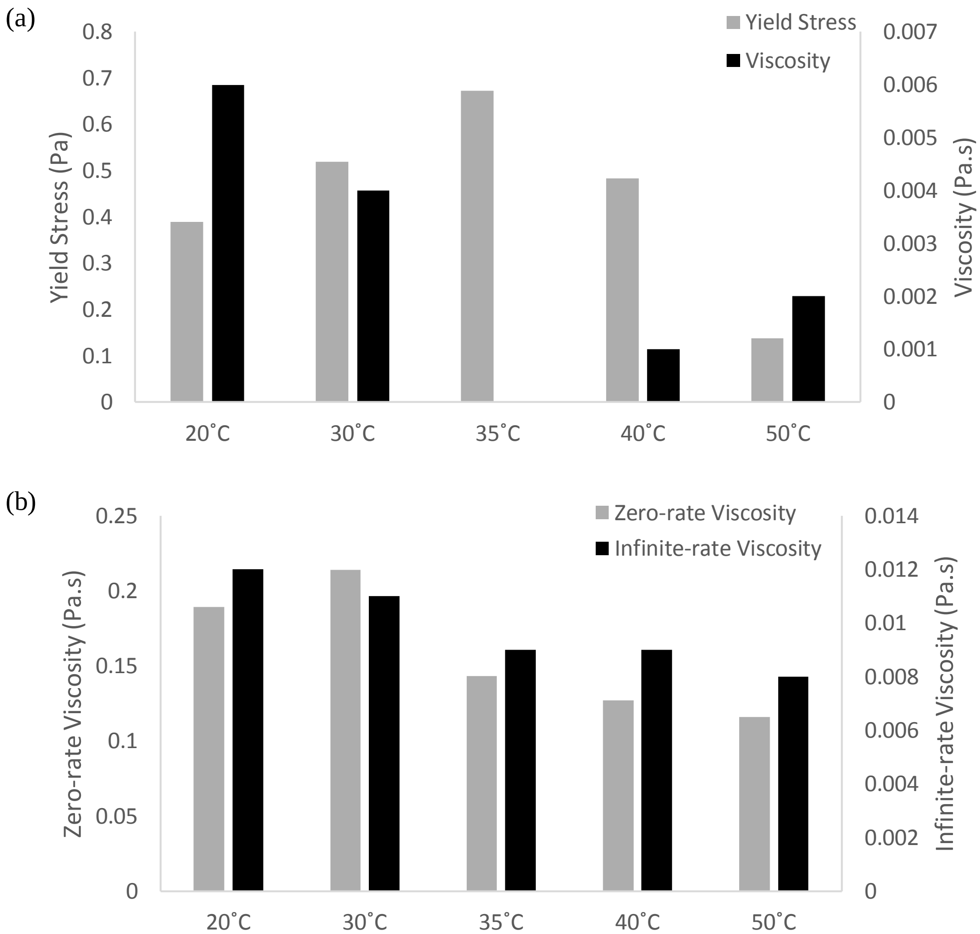


Fig. 9 Rheological model based parameters for varying temperature of unconditioned digested sludge (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

3.5 Effect of pre-shearing and temperature on digested sludge dewaterability

The effect of temperature on dewaterability of pre-sheared digested sludge was studied at different temperatures of 20˚C, 30˚C, 35˚C, 40˚C, and 50˚C respectively. The desired temperature and pre-shearing effect were achieved by using a rheometer equipped with concentric cylinder and vane geometry. Fig. 10 shows the effect of pre-shearing on digested sludge dewaterability under different temperature and polymer dose conditions. Pre-shearing resulted in significant improvement in the dewaterability of digested sludge as shown in Fig. 10(a). The dewaterability improved from 172s to 49s when the shear rate was increased from $0s^{-1}$ to $1000s^{-1}$. This is due to the destruction of floc network and release of bound water and decrease in floc network strength and viscosity that improves flow behaviour of the digested sludge (Yen et al. 2002). Higher temperature was observed to enhance dewatering performance for unconditioned pre-sheared digested sludge as shown in Fig. 10(b). In case of polymer conditioned digested sludge the optimum dewaterability was achieved for a temperature of 35˚C as shown in Fig. 10(c). The dewaterability of digested sludge showed a decreasing trend with increasing temperature in the range of 35-50˚C. This is an interesting finding that maintaining the temperature of the digested sludge at the digester operating condition of 35-36˚C is beneficial to the dewatering process.

(a)
(b)
(c)

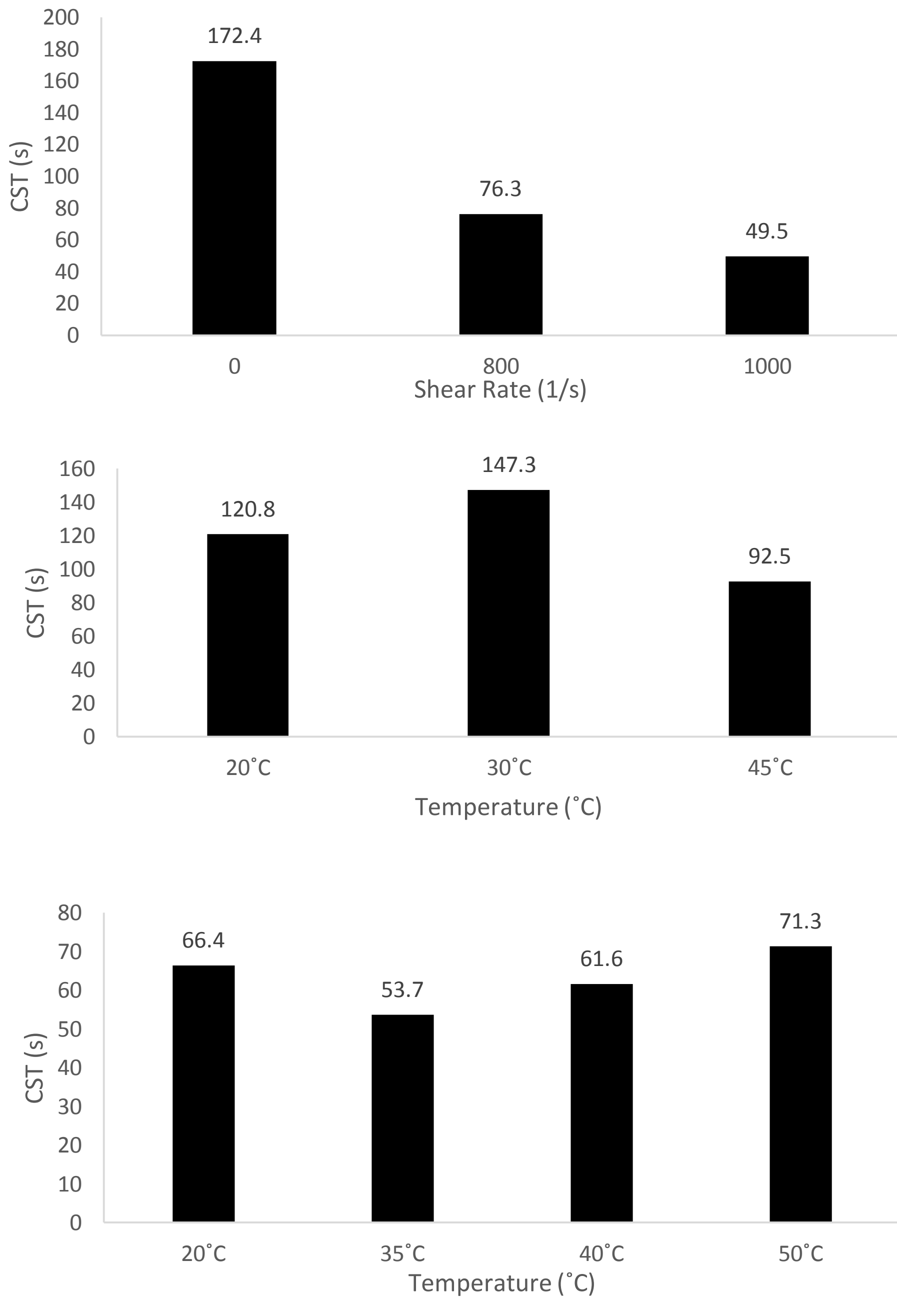
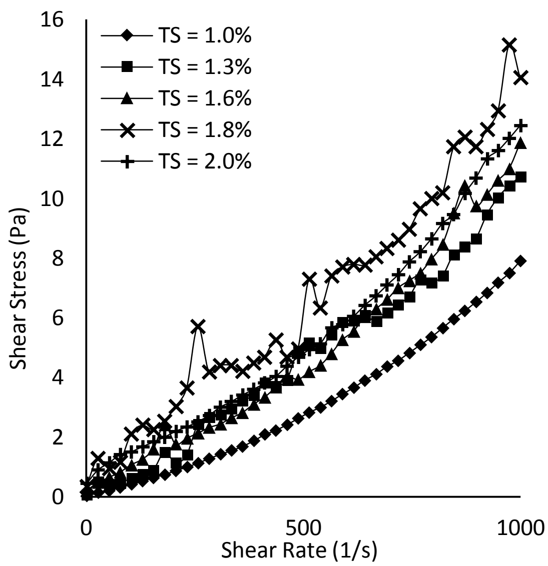


Fig. 10 Dewaterability of digested sludge due to the effects of (a) pre-shearing, (b) pre-shearing & temperature (c) pre-shearing and polymer conditioning at different temperatures

3.6 Effect of total solid concentration on digested sludge rheology and dewaterability

The effect of change in total solid concentration on digested sludge rheological properties and dewaterability was investigated for total solid concentrations of 1.0%, 1.3%, 1.6%, 1.8%, and 2.0%. The desired solid concentrations were achieved by using vacuum filtration technique and by dilution method using deionised water (Vincenzo Lotito and Lotito 2014; Baroutian et al. 2013; Markis et al. 2014). The rheological behavior of digested sludge at these solid concentrations was investigated by plotting shear stress-shear rate and viscosity-shear rate curves as shown in Fig. 11(a) and Fig. 11(b). The shear stress-shear rate and viscosity-shear rate rheograms were found to best fit to Herschel-Bulkley model. The yield stress and viscosity determined from the model fitting showed that digested sludge with higher total solid concentration have higher yield stress compared to digested sludge with lower total solid concentration. Fig. 12(a) shows that total solid content of 2.0% resulted in yield stress of 1.2Pa where as 1.0% total solid content showed significantly smaller yield stress of 0.2Pa. Similarly, the viscosity at the initial stage of shearing increased from 0.008Pa.s to 0.331Pa.s when total solid concentration of digested sludge was increased from 1% w/w to 2% as shown in Fig. 12(b). This is due to stronger network of sludge floc structure with the increase of solid concentration where colloidal and hydrodynamic forces between sludge particles change (Baroutian et al. 2013; Markis et al. 2014). The study on the relationship between sludge dewaterability and total solid concentration showed that smaller total solid concentration of digested sludge favours the dewatering process as shown in Fig. 13 (J. C. Baudez et al. 2011; Sanin 2002). This confirms that a significant improvement in sludge dewatering can be achieved by improving the performance of anaerobic digesters to enhance the total solid and volatile solid reduction.

(a)



(b)

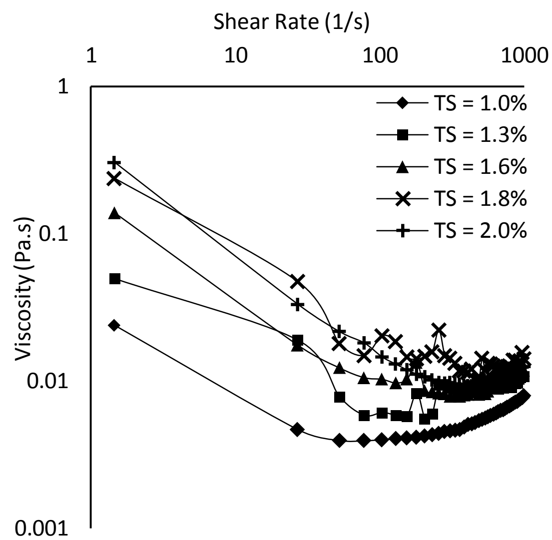
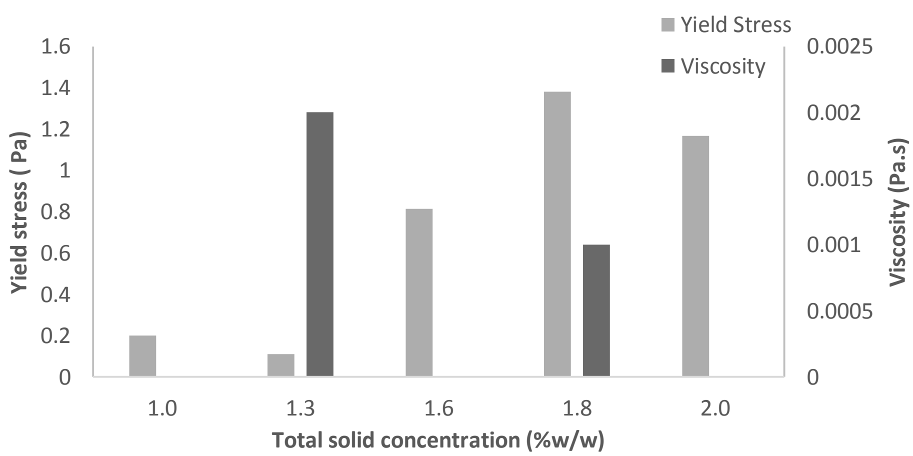


Fig. 11 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different total solid concentration of unconditioned digested sludge

(a)



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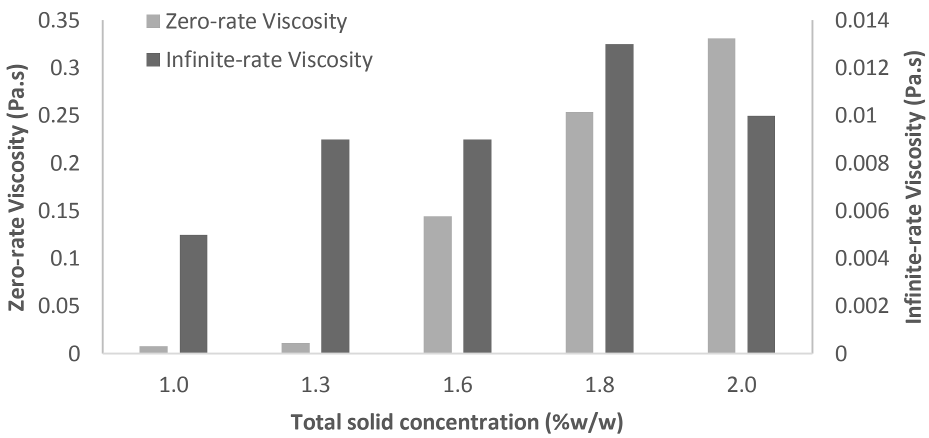


Fig. 12 Rheological model based parameters for different total solid concentration of unconditioned digested sludge (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

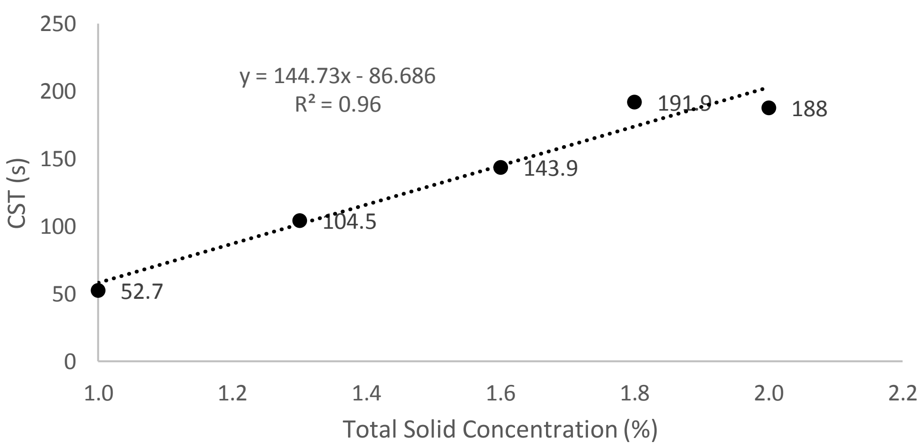


Fig. 13 Effect of total solid concentration on the dewaterability of digested sludge

3.7 Effect of polymer dose on digested sludge dewaterability and rheology

It is known that conditioning polymer added to digested sludge to enhance dewaterability is an important cost factor in the operation of the dewatering process. Different polymer dose of 18kg/day, 12kg/day, 9kg/day, 7kg/day and 5kg/day were selected for experimental polymer dose optimization test. These polymer doses were selected based on polymer consumption trend in BWWTP. Fig. 14 shows the effect of different polymer doses on the dewaterability of digested sludge. The dewaterability was measured in capillary suction timer (CST). It was observed that increase in polymer dose from 7kg/t DS to 18kg/t DS improved the dewaterability from 124.4s to 7s. The dewaterability of unconditioned digested sludge was 158s. In a separate jar test conducted on 500ml of digested sludge sample the dewaterability for polymer doses of 7kg/t DS, 9 kg/t DS, 12kg/t DS, 13kg/t DS, 14kg/t DS, 15kg/t DS, and 18kg/t DS was found to be 139.7s, 123.5s, 22.5s, 21.5s, 20.5s, 13.7s and 9.1s as shown in Fig. 15. The floc structure for polymer dose of 18kg/t DS showed that this is an over dose condition. The dewaterability measured for this condition was of pure water (very low) and does not realistically represent the flocculation that took place under this condition. Hence, polymer dose of 12kg/t DS provides reasonably acceptable separation of water (53.9s) and better dewatering performance.

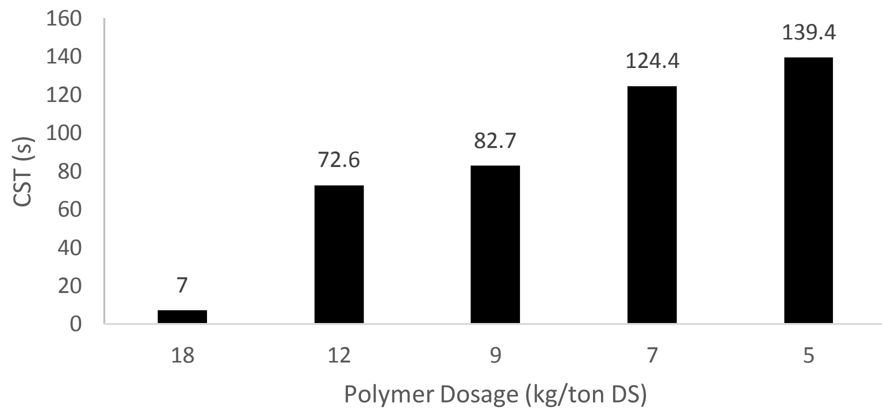


Fig. 14 Effect of polymer dose on digested sludge dewaterability

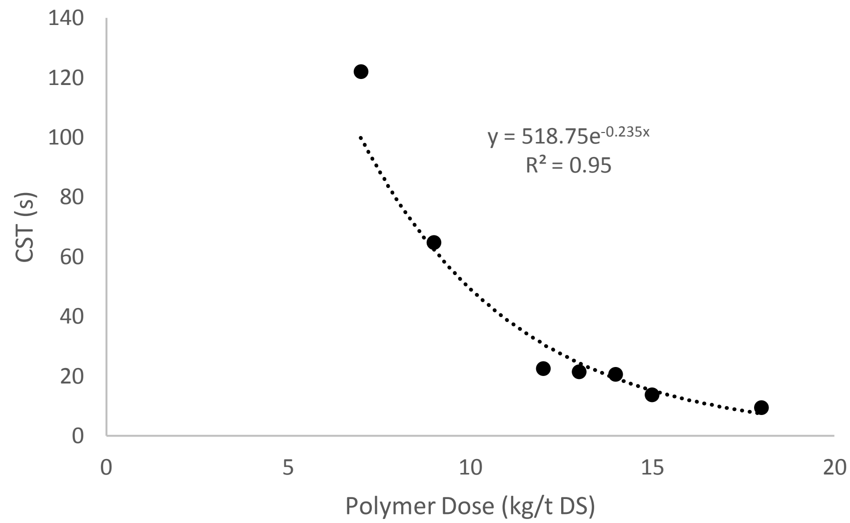


Fig. 15 Effect of polymer dose on digested sludge dewaterability

The effect of polymer dose on the rheological behaviour of digested sludge was also investigated for polymer dose in the range of 7kg/t DS to 18kg/t DS. Fig. 16(a) and Fig. 16(b) show the effect of different polymer doses on shear stress-rate and viscosity shear-rate profile of polymer conditioned digested sludge. The model fitting analysis showed that the shear stress-rate curves fit better to Herschel-Bulkley non-Newtonian rheological model whereas the Sisko model was selected to represent viscosity shear-rate rheograms. Fig. 17(a) and Fig. 17(b) show the rheological model parameters derived from Herschel-Bulkley and Sisko models respectively. It was observed that unconditioned digested sludge had an initial yield stress of 0.5Pa and as polymer dose was increased from 7kg/t DS to 18kg/t DS, the yield stress of digested sludge increased from 0.6Pa to 1.1Pa due to formation of bigger floc with increasing polymer dose as shown in Fig. 17(a) (Wang and Dentel 2010). However, polymer dose of 18kg/t DS can be considered as an overdose condition due to the very loose and big floc structure which negatively influenced dewaterability. It was found that, polymer dose of 12kg/t DS had the lowest yield stress value making this dose optimum both from dewaterability and rheological point of view. Similarly, the viscosity of unconditioned digested at higher shear rate was observed to increase from 0.008Pa.s to 0.02Pa.s when polymer dose was increased from 0kg/t DS to 18kg/t DS as shown in Fig. 17(b). The polymer dose tests were conducted for a fixed total solid concentration. However, the test on dewaterability of digested sludge as a function of varying total solid concentration confirms that the polymer consumption can be optimized based on the totals solid content of the digested sludge being conditioned. The model equation shown on Fig. 13 can be related to polymer dose test shown in this section for optimization purposes.

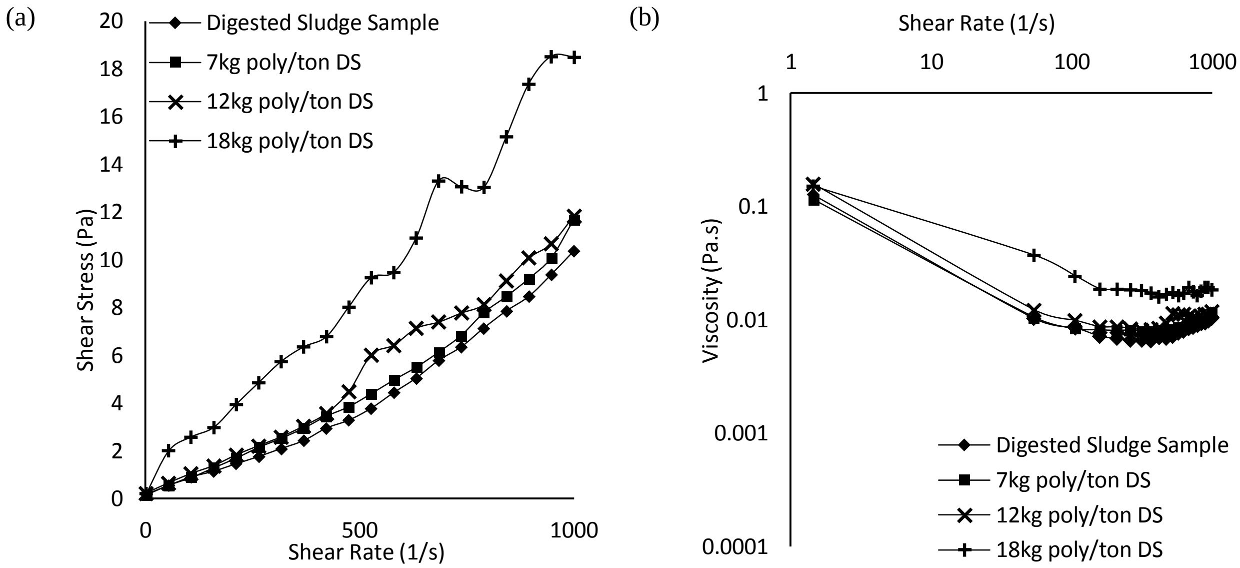
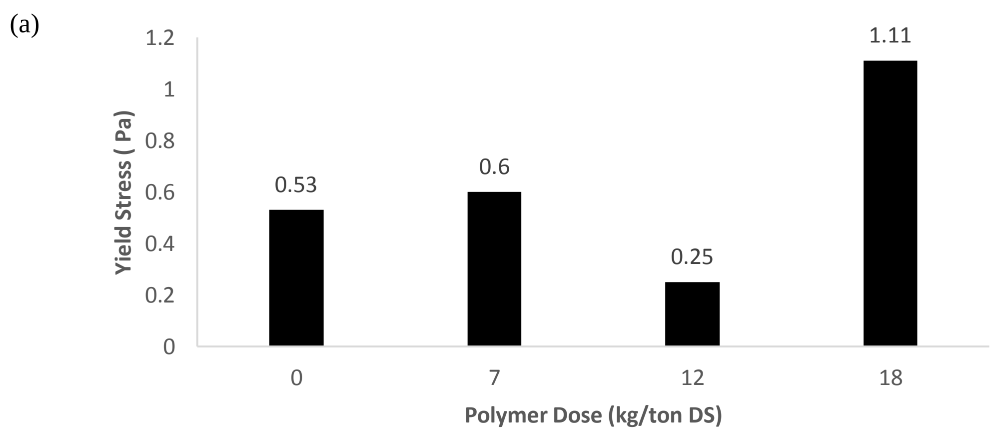


Fig. 16 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different polymer dose of digested sludge



(b)

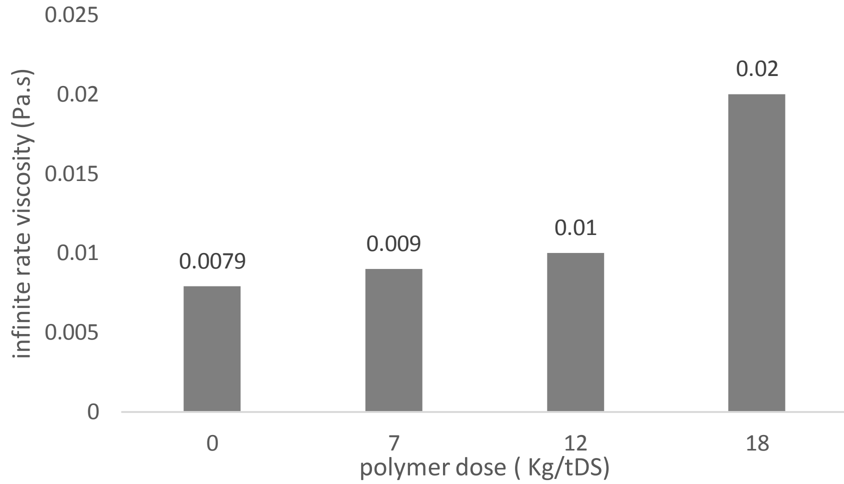
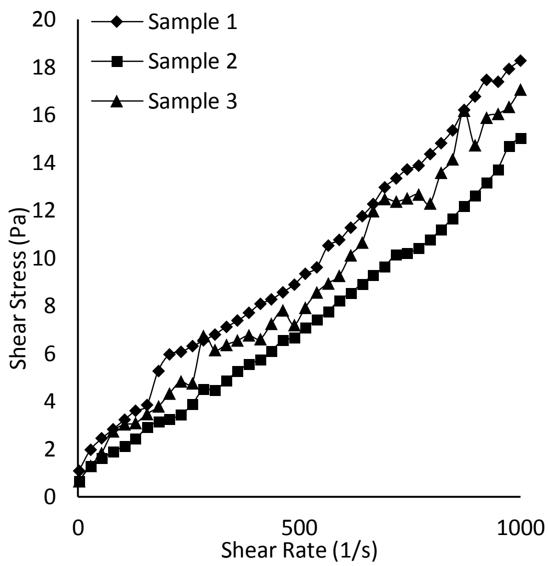


Fig. 17 Rheological model based parameters for different polymer dosage of digested sludge (a) yield stress & viscosity (Herschel-Bulkley), (b) infinite-rate viscosity (Sisko)

3.8 Effect of sludge age on the rheological characteristics of digested sludge.

The effect of storage time (age of sludge) on the rheological property of digested sludge was investigated over a period of 23 days. Rheological tests were conducted on digested sludge samples at the time of collection and after 8, and 22 days of storage in refrigerated environment at 4ºC. It can be observed that the degradation and change in rheological property of the digested sludge sample during the 22 days of storage was significant. The shear stress-rate profile showed a significant decrease in the first 8 days as shown in Fig. 18(a). Similar trend was observed in viscosity tests, as days of storage progresses, the viscosity of the digested sludge decreased as shown in Fig. 18(b). It can be concluded that digested sludge samples degrade during storage and the rheological properties change significantly with time. The shear thinning behaviour is generally enhanced by the biodegradation of organics within the sludge (Markis et al. 2014). Yield stress and viscosity also decreased over time as shown in Fig. 19(a) and Fig. 19(b) respectively due to biodegradation of important organic components such as protein, lipid and carbohydrate, and synthesis of volatile fatty acids which affect the rheology (J.-C. Baudez 2008). This implies that in the course of the anaerobic digestion process the viscosity of sludge significantly decreases as observed in this study, favouring better flowability mass transfer, mixing, and anaerobic degradation.

(a)



(b)

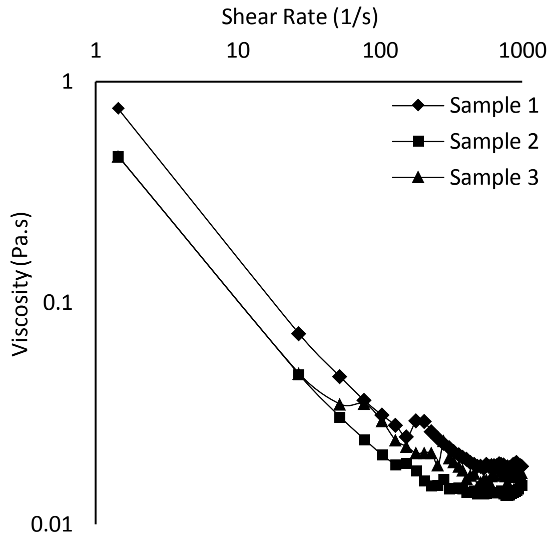
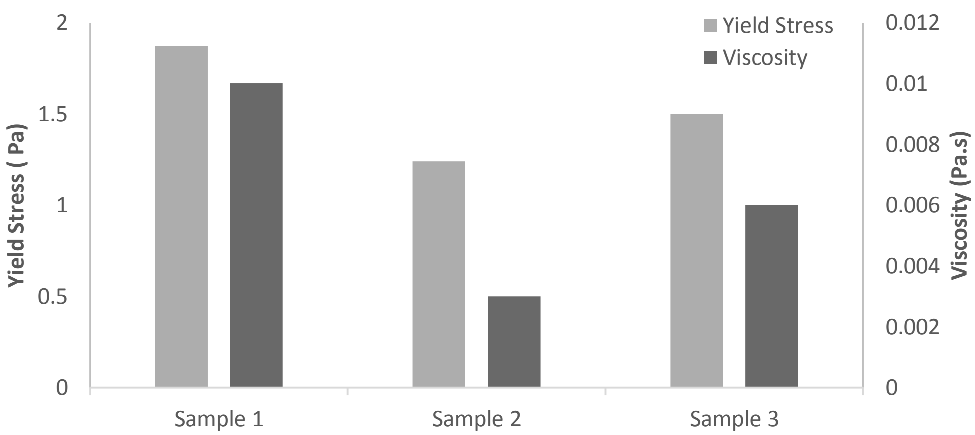


Fig. 18 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different digested sludge at different storage time

(a)



(b)

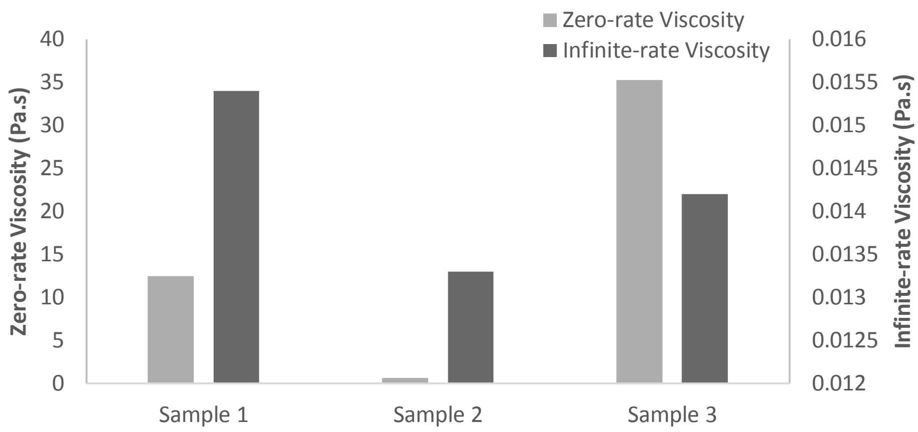


Fig. 19 Rheological model based parameters for different digested sludge at different storage time (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

4. Conclusion

In can be concluded that temperature, total solid concentration and polymer dose significantly affect the dewaterability and rheological behaviour of digested sludge. In this study, shear stress-shear rate and viscosity shear rate profiles were developed and the dewaterability and yield stress were determined for varying total solid concentration, temperature and polymer dose. Maintaining the temperature of the digested sludge at the digester operating condition of 35-36˚C was found to be beneficial to the dewatering process. The total solid content particularly the organic fraction of the solid which is composed of polymeric substances (protein, polysaccharides etc.) is responsible for the significant variation in the rheological property of digested sludge. The biodegradation of organics enhances the shear thinning 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. Digested sludge conditioning and flocculation process is also significantly affected by temperature and solid concentration; hence, polymer consumption can be reduced by operating the dewatering process at optimum temperature condition and varying the polymer dose as a function of total solid concentration of the digested sludge. The hysteresis test shows that digested sludge exhibits shear-thinning thixotropic behaviour in the hysteresis loop.

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