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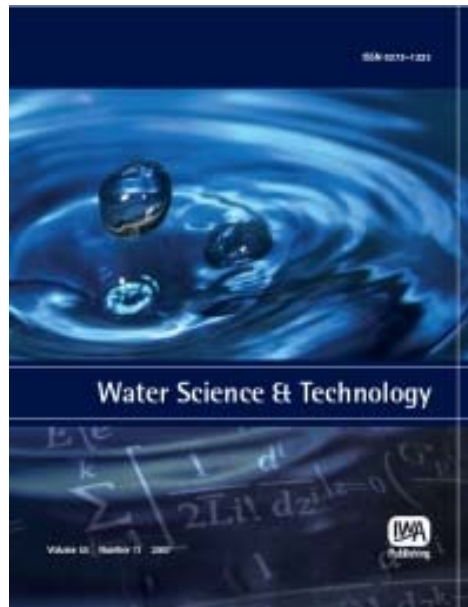


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Rheological behavior of sewage sludge with high solid content

Yingchao Cheng and Huan Li

ABSTRACT

Sludge rheological properties play a fundamental role in determining its performance in pipes, tanks or reactors. However, the relative information on high-solids sludge is very rare. In this study, the rheological properties of high-solids sludge were investigated systematically and a new rheological model was built. The results showed that the low-solids sludge with total solids content (TS) 2–15% was pseudoplastic fluid, and the high-solids sludge with TS 7–15% exhibited thixotropic property. Sludge viscosity increased exponentially with the increasing TS, and decreased in function of power along with the increasing shear rate. The new complex model combining the exponential model and the power model can perfectly describe the relation between TS, shear rate and viscosity of the high-solids sludge. Both sludge organic content and temperature have influence on sludge viscosity, but the influence was not significant for the low-solids sludge. For the high-solids sludge with TS 6%, 8%, 10% and 12%, their viscosities increased by 5.0, 9.1, 25.7 and 24.9 times, respectively, when sludge organic content increased from 28% to 53%, and decreased by 36.5%, 49.5%, 54.0% and 65.4%, respectively, when sludge temperature rose from 9 to 55 °C.

Key words | rheology, sewage sludge, solids concentration, viscosity

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INTRODUCTION

Primary sludge and excess sludge are the residues discharged from wastewater treatment process. Since sludge contains various pollutants, proper treatment and disposal are necessary (Farno *et al.* 2014). In wastewater treatment plants (WWTPs) they are commonly mixed, concentrated, digested and dewatered in sequence. The dewatered sludge can be further composted, dried and then incinerated, or finally disposed of in landfill sites. During these different steps, total solids content (TS) and volatile solids content (VS, percentage in TS) of sludge change step by step due to the removal or conversion of water and organic matter in sludge. For example, TS of excess sludge generally range from 0.2 to 2%, TS of thickened sludge are about 2–4%, TS of digested sludge are 2–6% and TS of dewatered sludge are around 20% and more. Along with the change of sludge TS and VS, sludge rheological properties also change. Sludge rheological properties play a fundamental role in determining sludge performance in pipes, tanks or reactors during sludge treatment and disposal (Baroutian *et al.* 2013). Due to the complex compositions of sludge, its rheological properties are influenced by various factors

including wastewater sources, treatment processes, chemical additives and mechanical operations like thickening (Baroutian *et al.* 2013; Gupta *et al.* 2013).

Activated sludge is generally recognized as a kind of non-Newtonian fluid, i.e. apparent viscosities measured under different shear rates are different (Ron 2001). Rose-Innes & Nossel (1983) reported that the thickened sludge with TS 1.5–9% was a kind of pseudoplastic fluid. For the concentrated activated sludge with TS 1.6–3.1% from nine different membrane bioreactors (MBRs), the viscosity decreased by one or two orders of magnitude along with increasing shear rate (Rosenberger *et al.* 2002). Some models have been developed to describe the relationship between sludge apparent viscosity and shear rate. The Ostwald model (power) was used to describe the relation between shear rate and viscosity of the sludge with TS 0.3–3% derived from a MBR (Pollice *et al.* 2006). The Bingham model (linear with yield) was used to describe the rheological behavior of the digested sludge with TS 4 and 6%, which was recognized as plastic fluid, i.e. initial stress was necessary for the sludge to begin flowing

(Eftekharzadeh *et al.* 2007). Sludge with TS 9% exhibited shear-thinning properties (apparent viscosity decreased with increasing shear rates), and the Herschel–Bulkley model (power with yield) was suitable (Eftekharzadeh *et al.* 2007). The result was in accordance with that conducted from the mixture of primary and secondary sludge with TS 4.3–9.8% (Baroutian *et al.* 2013).

Solids concentration was the most important factor governing the fluid resistance of sludge (Rose-Innes & Nossel 1983). Some models have been developed to describe the relation between sludge viscosity and its solids concentration (Table 1). Besides shear rate and solids concentration, sludge composition and temperature are also relevant factors influencing sludge rheological behavior. It was found that the activated sludge with higher extracellular polymeric substances (EPS) content had slightly higher viscosity (Rosenberger *et al.* 2002). Some pretreatments can disintegrate sludge aggregates and cells, break the microbial slurry where sludge particles interact with each other, and thus cause a decrease in apparent viscosity of sludge (Mohapatra *et al.* 2012). Temperature is another factor influencing sludge viscosity, and sludge becomes more fluid when the temperature increases. Thermal treatment was consequently used to decrease sludge viscosity, and longer treatment duration commonly led to lower viscosity. Furthermore, the influence of heating history on sludge viscosity was found to be irreversible because the conversion of sludge solids to dissolved constituents was partially irreversible (Manoliadis & Bishop 1984; Baudez *et al.* 2013a; Farno *et al.* 2014).

During the previous studies on sludge rheological properties, the object was mostly activated sludge with low solid content ranging from 0.2 to 6% (Ratkovich *et al.* 2013).

Table 1 | Different form of correlation relationships between combinations of shear rate ($\dot{\gamma}$, s^{-1}), solids concentration (MLSS, mixed liquor suspended solids, g/L) and temperature (T , K) with apparent viscosity (μ , Pa·s)

Model	Sludge TS (%)	References
$\mu = e^{(aMLSS^b)\dot{\gamma}^{(cMLSS^d)}}$	1.6–3.1	Rosenberger <i>et al.</i> (2002)
	0.37–2.29	Laera <i>et al.</i> (2007)
$\mu = aMLSS^b\dot{\gamma}^c$	0.27–1.02	Yang <i>et al.</i> (2009)
$\mu = a\frac{MLSS^b}{\dot{\gamma}}$	0.27–3.10	Garakani <i>et al.</i> (2011)
$\mu = a\frac{MLSS}{\dot{\gamma}} + bMLSS + c$	0.37–2.29	Laera <i>et al.</i> (2007)
	0.27–1.02	Yang <i>et al.</i> (2009)
$\mu = aMLSS^bT^c$	0.27–1.02	Yang <i>et al.</i> (2009)
$\mu = aMLSS^b e^{\frac{E_a}{R_{gas}T}}$	0.27–3.10	Garakani <i>et al.</i> (2011)
$\mu = a\frac{MLSS^b}{\dot{\gamma}} e^{\frac{E_a}{R_{gas}T}}$	0.27–3.10	Garakani <i>et al.</i> (2011)

Note: In the equations, a , b , c and d are parameters to calibrate, E_a is the activation energy ($kJ\ mol^{-1}$), and R_{gas} is the universal gas constant ($8.3145\ J\ K^{-1}\ mol^{-1}$).

However, high-solids sludge is also applied during different treatment processes, e.g. high-solids anaerobic digestion (Duan *et al.* 2012), transport (Eftekharzadeh *et al.* 2007) and mixture (Bollon *et al.* 2013). For example, high-solids anaerobic digestion of the sludge with TS 6–15% has gained increasing attention due to its advantages of smaller reactors, higher volumetric methane yield and less heating energy consumption. Nevertheless, the information on rheology properties of high-solids sludge is very rare (Slatter 1997; Sozanski *et al.* 1997; Kirby 1998). Thus, this work focused on the rheology properties of the sludge with TS 2–15%. At first, sludge rheological properties were investigated at different shear rates, and then the relation between sludge viscosity and sludge solids concentration was quantitatively measured. The influence of temperature was then explored at the temperatures of 35 and 55 °C, which are also the temperatures usually used in sludge anaerobic digesters. Based on the above data, a model was built for high-solids sludge to describe the relationship between solids concentration, shearing rate and sludge viscosity. Finally, the influence of sludge organic content was also analyzed, which may provide some insight into the variation of sludge viscosity.

MATERIALS AND METHODS

Sludge samples

Dewatered sludge used in this study was collected at seven WWTPs in Kunming City. Samples were sealed in ziplock bags and stored at 4 °C in a fridge. All the experiments were conducted within a week after sludge samples were collected. Other information on sludge samples is shown in Table 2.

Measurement of sludge viscosity

Rheological measurements were carried out with a rate-controlled viscometer (SNB-2, Nirun, Shanghai, China) with Searle system consisting of a rotational spindle and a beaker (Figure 1). The viscometer is equipped with five different spindles (No. 1–5), which have different measuring ranges of 6–6,000 mPa, 60–60,000 mPa, 300.3–300,000 mPa, 1,201.2–1,200,000 mPa and 6,006–6,000,000 mPa·s, respectively. Conversion factors between shear rate and measuring speed are 1.224, 0.220, 0.220, 0.214 and 0.209, respectively for the spindles No. 1–5 (shear rates were obtained by multiplying measuring speeds with conversion factors). To get

Table 2 | Characteristics of dewatered sludge from seven WWTPs

No.	Wastewater treatment process	Dewatering process ^d	TS (%)	VS (%)
1	Oxidation ditch	Belt filter press	28–32	36–37
2	A ² O ^a	Belt filter press	19–21	38–43
3	ICEAS ^b	Belt filter press	18–21	44–49
4	3AMBR ^c	Horizontal spiral centrifuge	24–25	23–25
5	A ² O ^a	Belt filter press	18–19	39–43
6	A ² O ^a	Belt filter press	15–16	52–60
7	A ² O ^a	Horizontal spiral centrifuge	19–20	36–38

^aA²O, anaerobic-anoxic-oxic.^bICEAS, intermittent cycle extended aeration system.^c3AMBR, anoxic anaerobic aerobic - membrane bioreactor.^dFlocculants were all polyacrylamide (PAM).

accurate results, sludge viscosities were measured with different spindles so that the measuring value would fall into 10–90% of the measuring range. Therefore, spindles No. 1–4 were used to measure sludge with TS 2–4%, 6–7%, 8–9% and 10–15%, respectively. Before measurement, sludge samples were stirred gently at 5 rpm for a short time in order to ensure the samples were homogeneous and avoid irreversible influence on the samples.

Four hundred milliliters of prepared sample was first put into a 400-mL beaker (with the body diameter of 82 mm), and the spindle of the viscometer immersed into sludge samples until the scratch line was just immersed by liquid level. The measuring speed (the spindle speed) was set as 5–90 rpm. The measuring time was set as 30 s during the test in order to avoid the inaccurate results derived from the sedimentation of some particles in sludge suspension.

Measurement of sludge rheological behavior

To measure the viscosities of the sludge with different solids concentrations, the collected dewatered sludge was first diluted with deionized water to different samples with TS 2–15%. For a certain sample, the measuring speeds increased gradually from 5 to 90 rpm and then decreased gradually to 5 rpm. Thus, two series of viscosity values were obtained, which were used to produce an upward curve and a downward curve, respectively. If the viscosity values under different speeds were constant, the sample was a Newtonian fluid; if the values were related to the shear rates and the downward curve covered the upward curve exactly, the sample was a pseudoplastic fluid; if the downward curve was under the upward curve and formed

**Figure 1** | The rheometer (SNB-2, Nirun, Shanghai, China) with geometrical dimensions of 370 × 325 × 280 mm.

a hysteresis zone, the fluid was time-dependent and defined as a thixotropic fluid; if the downward curve was above the upward curve, the sample was a rheopectic fluid (Schramm & Zhu 2009). After these measurements, TS and VS of sludge samples were confirmed by gravimetric method.

When measuring sludge viscosity at high temperature, a thin oil layer with known viscosity is usually used to cover sludge samples in order to avoid evaporation (Baudez *et al.* 2013b; Farno *et al.* 2014). In this study, the maximum temperature in the experiments was 55 °C and the evaporation effect was negligible during testing time (within 10 min). Hence, an oil cover was not applied. The beakers containing sludge samples were put into a water bath, and sludge temperatures were controlled at 9 °C, 21 °C, 35 °C

and 55 °C for 1 h, respectively. These temperatures are representative values for local ambient temperature in winter, in summer, mesophilic and thermophilic anaerobic digestion, respectively.

Analytical procedures

TS and VS were determined according to standard methods (MEP 2002).

RESULTS AND DISCUSSION

Effects of solid content on sludge rheological behavior

Based on the Ostwald (power law) model (Equation (1)) and the definition of dynamic viscosity (Equation (2)), the relationship between apparent viscosity and shear rate can be expressed as Equation (3).

$$\tau = k \cdot \gamma^n \quad (1)$$

$$\mu = \tau / \gamma \quad (2)$$

Thus,

$$\mu = k \cdot \gamma^{n-1} \quad (3)$$

where, τ is the shear stress, Pa; k is the flow consistency index (Pa·sⁿ); μ is the apparent viscosity, Pa·s; n is the flow behavior index.

According to Equation (3), the variation of sludge viscosities along with shear rates is described in Figure 2 and the parameters of the upward curve are shown in Table 3. It can be found that the results can be well described by the Ostwald model, indicating that the sludge with TS 2–15% behaved as a pseudoplastic fluid.

It was noted that sludge with TS 2% behaved as a non-Newtonian fluid, just like the previous reports (Rose-Innes & Nosse 1983; Eftekharzadeh *et al.* 2007). However, in other experiments using the sludge from other WWTPs, the sludge with TS 2% was sometimes quite fluid and its viscosity was relatively stable despite the increase of shear rate. This performance was similar to a Newtonian fluid whose viscosity is constant with regard to shear rate, or fluctuant in a small range according to the measurement condition. This may be ascribed to the difference in sludge particle density and organic content.

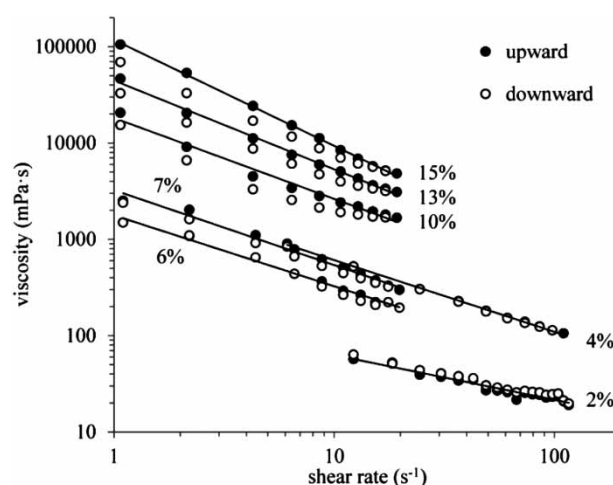


Figure 2 | Relationship between shear rates and viscosities of the sludge with TS 2–15% (only results for 'sludge 7' are shown).

Table 3 | Parameters of the Ostwald model at different sludge TS

TS (%)	K (mPa·s)	n	R^2
2	182.56	0.536	0.9435
4	3,367.6	0.256	0.9988
6	1,773.2	0.264	0.9926
7	3,235.8	0.222	0.9859
10	18,185	0.160	0.9828
13	44,511	0.078	0.9959
15	117,648	−0.100	0.9989

When sludge solids concentration increased to 4 or 6%, sludge viscosities declined with shear rates, and the upward and downward curves of sludge viscosity almost overlapped. This performance was in accordance with the properties of a pseudoplastic fluid, which was demonstrated by Rose-Innes & Nosse (1983). As shear rates increased, the dramatic drop of sludge viscosity may be explained by sludge composition. Sludge with TS 4–6% was still a suspension of irregular particles. EPS in sludge particles are usually made of organic polymers with winding or circular molecular chains. These substances interwove irregularly in an initial state, leading to a relatively high internal resistance against flow motion, i.e. a higher viscosity. As the spindle speed increased, the shear rate accordingly rose and sludge particles in the suspension oriented along the flow direction. Those chain molecules combined, stretched and rearranged, which enabled sludge particles and molecular groups to slide across each other more smoothly. Meanwhile, the shear stress crushed the irregular groups and then resulted in quicker flow of sludge.

When the shear rate slowed down to zero, chain molecules were restored to their non-oriented natural position and became spherical, and sludge aggregations were regained by Brownian movement. This process was very rapid, so that sludge exerted a pseudoplastic property.

When solids concentration reached 7–15%, sludge flow ability declined significantly with an evident increase in viscosity. Sludge viscosities also declined with increased shear rates, indicating the shear-thinning property. The feature was in accordance with pseudoplastic fluid. The downward curve of sludge viscosity turned out beneath the upward, and there were two different viscosity values at the same shear rate. This meant that sludge viscosity was time-related, i.e., the sludge was a thixotropic fluid. The initial sludge was in gel state or flocculated with a relatively higher viscosity. With the extension of stirring time, sludge viscosity declined gradually to a possible minimum value due to the destruction of sludge gels or flocs and the regular rearrangement of EPS, and then the sludge evolved into a colloidal state with lower viscosity. Simultaneously, sludge particle structure was still tending to re-form into the initial state. When the two rates were equal, a dynamic equilibrium formed, and sludge viscosity reached its minimum value. Thus, sludge with high solid content exhibited thixotropic characteristics. With regard to pseudoplastic fluid, the reconversion of destructed structure after shear stopped was as rapid as the shear-thinning effect caused by shear stress. Therefore, the time interval was too short to be detected by common equipment. Contrary to a thixotropic fluid, the time for particles' rearrangement cannot be neglected.

Based on the above analyses, sludge rheological property evolved from Newtonian fluid to pseudoplastic fluid when sludge solids concentration increased from lower than 2–15%. Moreover, the sludge with solids concentration ranged from 7 to 15% exhibited thixotropic property. When sludge solids concentration was more than 15%, sludge behaved like a viscoelastic body, which showed almost no deformation in a short time. The results in Figure 2 were deduced using the sludge from No. 7 WWTP, but the sludge obtained from the other six WWTPs showed similar performance (the results were not shown). No matter what kind of fluid, sludge viscosity dropped drastically as shear rate rose, but began to stabilize at the shear rate of 12–15 s⁻¹. At this shear rate, the curve stepped into the second Newtonian region, and sludge viscosity was relatively stable and almost independent of shear rate. Therefore, sludge viscosities at this shear rate were compared in order to analyze the effects of other variable factors in the following experiments.

Effects of solid content on sludge viscosity

Considering the variation of n along with sludge TS (Table 3), the relation between them cannot be described by any equation in Table 1. It seems that there is a linear relation between n and sludge TS, and also between $\ln(k)$ and sludge TS (Figure 3). Thus, a new equation was developed from Equation (3).

$$\mu = e^{(a \cdot TS + b)} \cdot \gamma^{(c \cdot TS + d)} \quad (4)$$

where, a , b , c and d are parameters to calibrate.

According to Equation (4), the relation between $\ln(\mu)$ and sludge TS at an given shear rate should be linear as in Equation (5). The sludge samples obtained from the other six WWTPs were also measured, and their viscosity data at the shear rate 15 s⁻¹ are shown in Figure 4. The results show that the sludge with higher solid content had higher viscosity. A similar trend was also found at the other shear rates ranging from 5 to 20 s⁻¹ (the results were not shown). The performance verified an exponential relationship between sludge solids concentration and its viscosity.

$$\ln \mu = (a + c \ln \gamma)TS + (b + d \ln \gamma) \quad (5)$$

Using the data obtained from the seven WWTPs, the coefficients in Equation (5) can be calculated by linear regression. The results and other parameters are shown in Table 4. For the seven WWTPs, the relationship between sludge viscosity, solids concentration and shear rate can be described by Equation (4). There is no significant difference between the calculated results and the measured data. Thus, the model was satisfactory for the sludge with TS 2–15%.

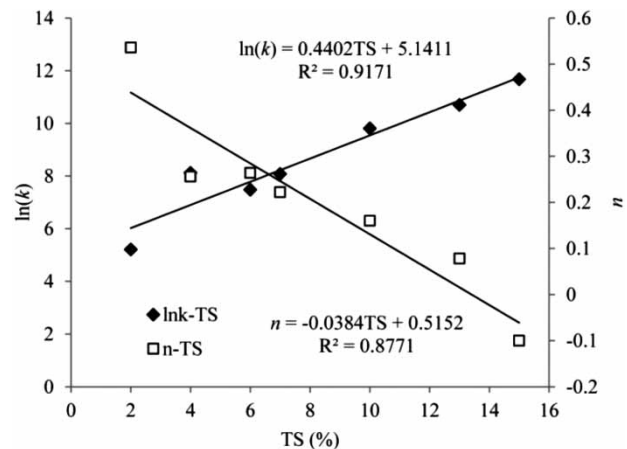


Figure 3 | The relation between sludge TS and the coefficients in the Ostwald model.

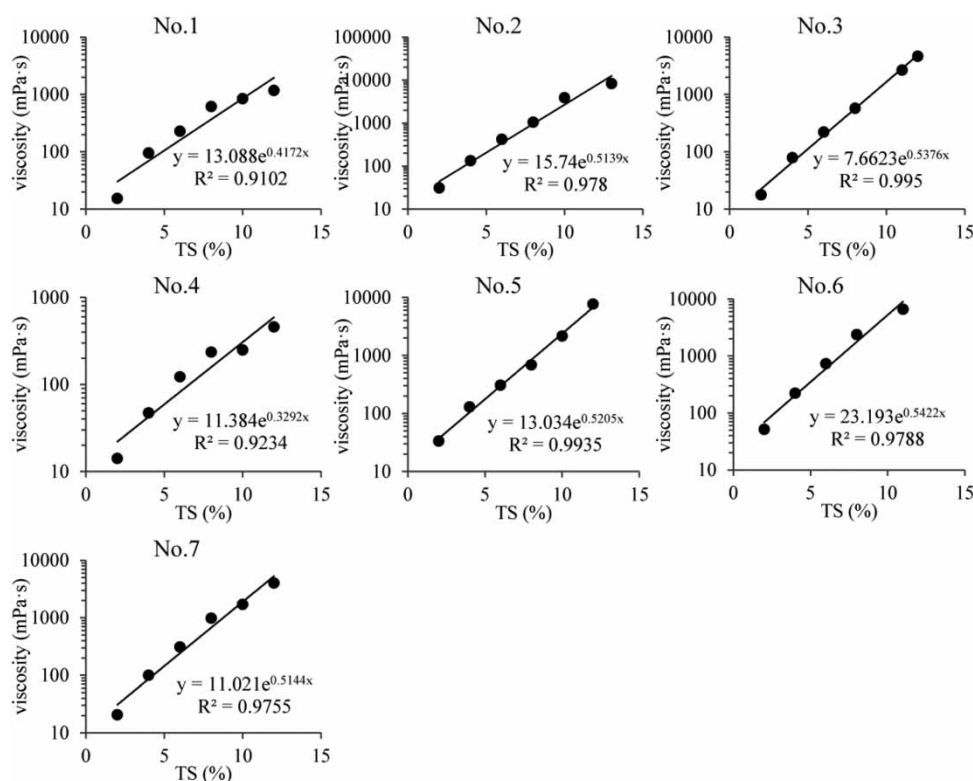


Figure 4 | Effect of sludge TS on viscosities at shear rate 15 s⁻¹ (sludge samples were derived from seven WWTPs).

Table 4 | Parameters for the model describing the relation between sludge viscosity and solid concentration, shear rate (data refer to Equation (5))

WWTP	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>F</i> ($\alpha = 0.05$)	<i>R</i> ²	<i>p</i> *
No. 1	0.24	5.20	0.05	-0.80	187	0.910	< 0.01
No. 2	0.56	4.38	-0.03	-0.42	3,909	0.995	< 0.001
No. 3	0.70	2.98	-0.07	-0.24	1,366	0.987	< 0.001
No. 4	0.21	5.44	-0.02	-0.50	420	0.965	< 0.05
No. 5	0.57	4.30	-0.04	-0.36	5,222	0.996	< 0.001
No. 6	0.55	5.36	-0.04	-0.46	341	0.952	< 0.01
No. 7	0.53	4.41	-0.03	-0.51	2,045	0.991	< 0.001

**p*-values of the four parameters are all less than the given values.

From knowledge of a previous study (Chai & Zhang 2000), power for stirring is proportional to viscosity when there is no turbulence. This means that the energy consumption also increased exponentially with sludge TS. According to the curve, there was a drastic increase of sludge viscosity when sludge TS increased higher than 8%. Therefore, the sludge with TS higher than 8% is not recommended in wet anaerobic digestion processes due to exponentially increasing energy consumption.

Effects of temperature on sludge viscosity

The relationship between sludge viscosity and temperature is shown in Figure 5. On the whole, the viscosity decreased with the increasing temperature. The result was in

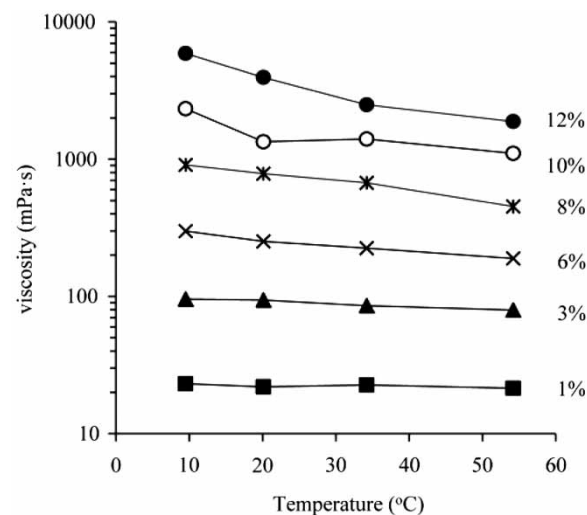


Figure 5 | Effect of temperature on the viscosities of the sludge with TS 1–12% at shear rate 15 s⁻¹.

accordance with the conclusion obtained by Farno *et al.* (2014). In this study, sludge temperature did not exert an obvious influence on viscosities of the sludge with TS 1%–3%; viscosities only decreased by 7.36% and 16.75% when the temperature rose from 9 °C to 55 °C, respectively; while for the sludge with TS 6%, 8%, 10% and 12%, viscosities decreased by 36.54%, 49.55%, 53.97% and 65.44%, respectively, when the temperature rose from 9 to 55 °C. This meant the sludge with high solid content was more easily influenced by temperature. This can also be explained by the variation of EPS content in the suspension (Rosenberger *et al.* 2002). When sludge solids concentration was low, EPS in the surface layer of different sludge particles had a very low binding degree, and the connected structures were very loose even if these polymers bound. Therefore, sludge temperature had almost no influence on its viscosity, though the shape or form of organic macromolecules evolved with the changed temperature. While sludge solids concentration was high, there was more tendency to lining or binding of those organic macromolecules in sludge suspension, leading to a bigger friction resistance; thus sludge viscosity dropped. Hence, anaerobic digestion of high-solids sludge should be operated under mesophilic or thermophilic conditions, and thermal pretreatment is also beneficial from the view of sludge viscosity.

Effects of sludge composition on sludge viscosity

The sludge samples collected from the seven different WWTPs had different organic contents (VS/TS), which possibly impacted sludge viscosity. It was found that sludge viscosities increased exponentially along with increased VS contents (Figure 6), and a similar relation was also found at the other shear rates ranging from 5 to 20 s⁻¹ (the results were not shown). In general, sludge with higher VS had more EPS, which can enhance the connection of sludge particles. Therefore, higher organic content led to higher viscosity in the suspension with high solid concentration.

For the sludges with TS 2%, 4%, 6%, 8%, 10% and 12%, their viscosities increased 2.7, 3.7, 5.0, 9.1, 25.7 and 24.9 times, respectively, when sludge VS content increased from 28 to 56%. The influence of VS content on sludge viscosity was minor at sludge TS of 2%. This was partially caused by scattered particles in the thin fluid. The distance between the particles was far enough that the resistance that the viscometer suffered was mainly derived from the intercept of the particles. The shape or form of the particles did not exert great influence. Therefore, sludge VS content was not the main factor impacting sludge viscosity.

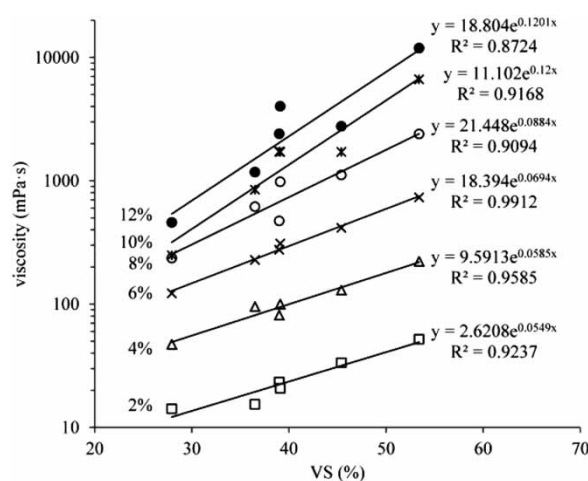


Figure 6 | Effect of VS contents on the viscosities of the sludge with TS 2–12% at shear rate 15 s⁻¹.

However, sludge organic content exerted a great influence on the viscosity of the sludge with high solid concentration. In high-solids sludge, the distance between particles narrowed drastically and the organic polymers in the surface layer of different particles formed a linear or network structure. This change enlarged the friction resistance, and thereby the influence of sludge organic content was more significant.

Certainly, sludge characteristics are not only judged by its organic content, and other factors, e.g. organic compositions, EPS contents and residual flocculants, also impact sludge viscosities. Since the sludge samples here were collected from seven different WWTPs, their characteristics were different and the measured viscosities were not only determined by their organic content. However, the results verified that sludge VS can be taken as a rough indicator of sludge viscosity. In general, sludge with higher organic content should be more viscous. This deduction is convenient when viscometers are unavailable or accurate viscosities are unnecessary. Accordingly, the high-solids sludge with high organic content needs a considerable increase in energy consumption for transport and stirring during further treatment processes. Thus, when sludge is concentrated, the sludge with high organic content gains more increase in viscosity than that with low organic content.

CONCLUSION

Sludge with solid content ranging from 2 to 15% was a pseudoplastic fluid, and it exhibited thixotropic property when solid content was higher than 7%. For the high-solids

sludge, the relation between viscosity and shear rate can be described by the power law model, while the relation between viscosity and solid content can be expressed as an exponential model. A complex model can describe their relation well. Sludge organic content exerted little influence on the sludge with TS 2%, but for high-solids sludge, high organic content resulted in high viscosity. Similarly, for high-solids sludge, the effect of temperature on sludge viscosity was more significant, and sludge viscosity dropped with an increased temperature.

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