Rheology characteristics of activated sludge and thermal treated sludge at different process temperature
GuoHong Feng, He Ma, Tiantian Bai and Yabing Guo

ABSTRACT
In this paper, flow behavior for activated sludge and thermal treated sludge at different process temperature and various solids content were analyzed. Results show viscosity of activated sludge and thermal treated sludge both decreased with increasing temperature, while temperature dependence of viscosity for both types of sludge were not same at the whole study range. The relationship between viscosity and temperature could be expressed by Arrhenius equation for activated sludge, and it was interesting that this law was only suitable when certain solid content (80 g/L) for thermal treated sludge. Moreover, the logistic model was certified to be accurate in describing the functionality for thermal treated sludge. As solid content was at range of 80–100 g/L, active energy of viscosity for both kinds of sludge were similar, indicating that physiochemical properties’ change of sludge after thermal hydrolysis had little effect on viscosity sensibility. Arrhenius law was also suitable for describing the relationship between storage modulus and process temperature for activated sludge. However, for thermal treated sludge, Arrhenius law was invalid. Yield stress for activated sludge was prominent, while it could be ignored for thermal treated sludge.

Key words | activated sludge, liquid characteristics, process temperature, solid characteristics, thermal pre-treatment

INTRODUCTION
A large number of sewage sludge was produced from biological wastewater treatment process. In China, approximately 6.25 and 5.25 million dry tons of sewage sludge was produced in 2013 and 2011, respectively (Hai et al. 2012; Yang et al. 2015). In the USA, the annual amount of biosolids is greater than 8 million dry tons (Peccia & Westerhoff 2015). Sewage sludge reduction is an important objective in sludge treatment. However, the special characteristics of sewage sludge (a large number of water, low degradation and complex components) determine that sludge reduction is a most difficult process. Sludge treatment is facing serious challenges with increasing management costs and stringent environmental legislation.

Anaerobic digestion (AD) or methanisation is one of the most widely used methods of treating sludge by converting a part of organic matter into biogas to achieve high-energy recovery and limit environmental impact. Compared with traditional AD of low solid sludge, high solid AD (total solid content of feed especially about 15% (w/w)) is more interesting due to its merits such as higher loading, smaller reactor volume, and lower energy consumption (Xu & Lancaster 2009; Dai et al. 2014; Barber 2016). During the AD process, hydrolysis of organic is the main rate-limiting step. Therefore, various methods such as thermal pre-treatment, ultrasonic pre-treatment and microwave, have been introduced to improve organic matter biodegradation, and it has been proven that thermal pre-treatment was a successful approach to make sewage sludge more amenable to AD (Li & Noike 1992; Erdincler et al. 2000; Müller 2001; Neyens & Baeyens 2005; Bougrier et al. 2008; Pham et al. 2010). Moreover, researchers have reported that optimum operation of thermal pre-treatment involved application temperature between 160 and 180 °C, for a time period of between 20 and 60 min, although the studied temperature ranges from 60 °C to 275 °C, under the pre-treatment time of 10–180 min. Usually, pre-treatment temperature under 100 °C was considered as low temperature pre-treatment, and temperature higher than 200 °C was defined as high temperature pre-treatment. Characteristics of increasing thermal pre-treatment temperature beyond the optimum
temperature are as follows: (1) decreased anaerobic digestibility of downstream sludge; (2) significantly increased production of refractory material and color; (3) required high energy; (4) improved dewaterability and slightly decreased viscosity for sludge. At lower temperature, disintegration of organic matter in sludge could not significantly advance, but could improve the biogas production in AD, and hygienization of sludge (Neyens & Baeyens 2003; Climent et al. 2007; Barber 2016; Farno et al. 2016).

The coupled technology of thermal pre-treatment and AD has been available at HIAS wastewater treatment plant in Norway since 1995 (Odeby et al. 1996). At present, there are 39 facilities operating, and 36 facilities are in various stages of design (Kleiven, personal communication). For the coupled technology of thermal pre-treatment and AD, AD process is usually sited downstream of thermal pre-treatment. And after thermal pre-treatment, sludge temperature generally reached to 80–90 °C, which should be cooled in order to suitable for the following mesophilic (35–38 °C) or thermophilic (55–58 °C) AD.

Sludge rheology has significant impact on sludge management and treatment, especially in the design of aerobic and anaerobic digesters, transportation for the calculation of pressure losses in pipes and pump selection, heat exchangers, sludge dewatering and biogas production units (Baudez et al. 2011; Feng et al. 2014a, 2014b, 2015). For Newtonian liquids, pressure drop of pipe flow could be obtained from pipe diameter, velocity and friction factor depending on flow regime (laminar or turbulent). While for non-Newtonian liquids with elasticity, the transition velocity from laminar to turbulent was higher than those of Newtonian liquids, and pipe friction factors in turbulent flow were significantly lower than those of Newtonian fluids with the same Reynolds number (Seysseiecq et al. 2005). Proff presented two validity equations for the calculation of pipe friction coefficients based on numerous sewage sludge experiments (Proff & Lohmann 1997). Hedstrom number and Reynolds number were also introduced to study the impact on friction factor and how it affect the pressure drop for activated sludge with Bingham properties (Ratkovich et al. 2013). In the digestion process, to increase biogas production, it was necessary to recycle and recirculate digested sludge in order to mix it with incoming sludge. Efficient mixing could provide an optimum environment for digestion. In contrast, it could lead to the formation of dead zones within the digester and poor microbial environment for biogas production (Karim et al. 2004). Viscosity and yield stress of sludge were essential to achieve efficient mixing due to the fact that these two parameters have an important effect on the choice of mixing equipment, propellers and energy consumption of the digesters (Markis et al. 2016).

In view of the importance of sludge rheology, previous papers have done some works and indicated that activated sludge is a kind of material with shear thinning, temperature dependent and viscoelasticity (Baroutian et al. 2013; Farno et al. 2014; Cheng & Li 2015; Wang et al. 2016). After thermal pre-treatment (temperature: 170 °C; time: 60 min), non-Newtonian fluid characteristics of activated sludge, including liquid and solid characteristics, were significantly weakened. Consistency index decreased, while the flow index increased, suggesting that thermal treated sludge was much closer to Newtonian fluids compared to untreated sludge (Verma et al. 2007; Hammadi et al. 2012; Baudez et al. 2013; Feng et al. 2014a, 2014b). Farno et al. studied the effect of temperature and thermal history on the digested sludge rheology characteristics, including viscoelasticity, yield stress, viscosity, and the irreversible effect of temperature was more significant at higher solid content, higher temperature and longer treatment time. Reductions of yield stress and apparent viscosity followed a logarithmic correlation with duration of thermal treatment. Sludge with thermal history showed a smoother transition from solid-like behavior to liquid-like behavior compared to untreated sludge, due to compositional change in sludge. While their study concentrated on the sludge with solid content of 3–7.2% and thermal pre-treatment temperature of 50–80 °C (Farno et al. 2014, 2016).

Although sludge rheological characteristics have been studied widely, these papers only investigated the rheological behavior of treated sludge at room temperature or the thermal pre-treatment temperature is lower than that of optimum. The information about the flow behavior of treated sludge at different process temperatures is scarce. Therefore, in the present paper, rheological behavior (including liquid and solid characteristics) of raw sludge (activated sludge without thermal pre-treatment) and treated sludge (activated sludge with thermal pre-treatment) at different process temperatures (10–60 °C) was studied in detail, which covered the temperature of mesophilic and thermophilic AD. We proposed that thermal motion has a more important impact than sludge structure for liquid characteristics as the process temperature between 10–60 °C, while at the solid regime, sludge structure also has more significant effect. Moreover, it was found that yield stress of raw sludge was prominent, while it was insignificant for treated sludge.
MATERIAL AND METHODS

Sludge sample

Activated sludge was sampled from the outlet of a dewatering device in a municipal wastewater treatment plant (in Zibo, China), and known as raw sludge. The collected activated sludge was treated by thermal pre-treatment at 170 °C for 60 min in a high-pressure reactor, which was called treated sludge. Then the treated sludge was cooled to room temperature for the following rheological test. Each measurement for physical characteristics (including total suspended solids (TSS), volatile suspended solids (VSS), particle size and calorific value) for the two kinds of sludge was carried out twice, and the average value was introduced. The measured value and relative errors are listed in Table 1. Raw sludge and treated sludge test samples with different solid content were prepared by diluting dewatered sludge and treated sludge with deionized water. In this study, raw sludge samples were at a wide range of concentration from 20 g/L to 120 g/L, and that of treated sludge was from 20 g/L to 150 g/L.

Rheological test

A rotational rheometer (DHR-2, TA Instruments, USA) equipped with concentric cylinder geometry (cup diameter: 30.39 mm; bob diameter: 27.98 mm; length: 41.90 mm) was used for measuring rheological properties of the raw and treated sludge. A rheology advantage software program, specially designed for DHR-2, was used for system control, data collection and analysis. To avoid water evaporation in sludge during each measurement, thin layer Newtonian oil was employed covering on the sludge surface, and a supplementary plastic ring was fitted around the measuring geometry.

In rheology, there are two main types of measurements (steady test and dynamic test) to observe complementary information about internal structure of suspension. Steady tests also called flow tests are carried out to analyze liquid characteristics (main, including viscous), while dynamic tests give access to viscoelastic behavior of the two kinds of sludge. In order to observe the liquid characteristics for two kinds of sludge at different operation temperatures, flow temperature ramp test was introduced. In the flow temperature ramp test, shear rate was kept at a constant (100 s⁻¹), and the measurement temperature increased gradually from 10 °C to 60 °C. Therefore, viscosity at specific temperature was obtained. Dynamic rheological test (also called ‘dynamic mechanical test’ or ‘oscillatory test’), has been proven to be a successful method for prediction of sludge viscoelastic (Ayol et al. 2006). In this dynamic mechanical test, temperature ramp was introduced which means that the measurement temperature went from 10 °C to 60 °C at the rate of 5 °C/min to investigate the sludge viscoelasticity at different operation temperatures. In addition, the applied stress maintains a low constant to ensure the test in a linear viscoelastic region.

In order to diminish errors caused by large particles, the sludge was screened by a sieve with a pore diameter of 0.6 mm before each test. After loading, sludge was left at rest for 1 min to eliminate the effect of loading shear. Each rheological test was carried out twice, and the average value was introduced.

RESULTS AND DISCUSSION

For dense aggregated suspensions like waste sludge, process temperature is the main factor influencing their rheological properties, such as viscosity, viscoelasticity and yield stress. The temperature of sludge after thermal pre-treatment could reach up to 90 °C, therefore, the treated sludge should be cooled to a certain temperature by heat exchange to satisfy the following AD process.

Liquid characteristics of two kinds of sludge at different process temperatures

Sludge liquid characteristic mainly refers to viscosity, often determined by the ratio of shear stress to shear rate, and it is a measure of resistance generated by movement between two adjacent layers of a fluid (Ratkovich et al. 2013).

Figure 1 shows the change of viscosity for both the raw and treated sludge, respectively. It was remarkable that the viscosity decreased sharply after thermal pre-treatment. Raw

<table>
<thead>
<tr>
<th>Sludge types</th>
<th>TSS (%)</th>
<th>VSS/TSS (%)</th>
<th>COD (g/L)</th>
<th>BW (g/g)</th>
<th>D (μm)</th>
<th>S (m²/g)</th>
<th>pH</th>
<th>Calorific value (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw sludge</td>
<td>21.3 ± 0.11</td>
<td>47.9 ± 0.3</td>
<td>1.9 ± 0.08</td>
<td>1.45 ± 0.10</td>
<td>52.1 ± 0.9</td>
<td>0.50 ± 0.01</td>
<td>7.50 ± 0.04</td>
<td>10.8 ± 0.4</td>
</tr>
</tbody>
</table>

BW, bound water content; D, particle size of sludge floc; S, specific surface area of sludge floc; TSS, total suspended solids content; VSS, volatile suspended solids content.
sludge is a feature of three-dimensional gel-like biofilm matrix, and extra polymeric substances like the main composition of sludge interact with water in a manner similar to gels (Keiding et al. 2001; Anderson et al. 2002), which could enhance connection among sludge particles, and strengthen binding of those organic macro molecules, leading to bigger friction resistance (Feng et al. 2014a). Therefore, viscosity of raw sludge was much higher than that of treated sludge.

As can be seen from Figure 1, viscosities for two kinds of sludge both decreased sharply with increase of process temperature. Higher process temperature accelerated the movement among molecules, and intensified particles’ thermal motion. Therefore, more ‘free volume’ inside sludge was formed, and distance between molecules became larger. As a result, twine and binding strength among chain segment in sludge became weaker, leading to lower viscosity for both types of sludge.

To investigate the functionality between viscosity and process temperature, fitting model (Arrhenius type equation) was calculated. It was interesting that the determination coefficient of the fitting model were all larger than 0.98 (Table 2), indicating that Arrhenius type equation could exactly express the relationship between process temperature and viscosity for raw sludge, which was in accordance with the conclusion of Mu (Mu et al. 2007). While for the fitting of treated sludge, Arrhenius type equation was adequate only at a solid content of 80–100 g/L (determination coefficient about 0.98). When the solid content was lower than 80 g/L, the determination coefficient was about 0.9, indicating Arrhenius equation could not accurately express the functionality between viscosity and process temperature for treated sludge with low solid content, and a logistic model was more appropriate (determination coefficient about 0.999) at the study range of 20–100 g/L (Table 3).

The model equations for raw sludge and treated sludge were developed as the following Equations (1) and (2), and the model parameters are presented in Table 1.

\[
\mu = Ae^{E_a/RT} \tag{1}
\]

\[
\lg (\mu - c) = a + p \times \lg (1 + T/b) \tag{2}
\]

where \(A\) is pre-exponential factor (mPa·s); \(T\) is absolute temperature (K); \(R\) is universal gas constant \((R = 8.3145 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1})\); \(E_a\) is activation energy for viscosity (J·mol\(^{-1}\)). \(E_a\) expresses the sensitivity between viscosity and process temperature, and higher \(E_a\) corresponds to more sensitive viscosity.

As can be seen in Table 1, though two types of sludge could not be accurately described by same model at whole range of solid content, while at the solid content of 80–100 g/L, Arrhenius type equation could adequately express the relationship between viscosity and process temperature. It was interesting that there was a no significant difference in the activation energy for viscosity for two types of sludge, and the value was 5.39 and 6.62 J·mol\(^{-1}\) for raw and treated sludge.

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**Table 2** | Regression model parameters (Arrhenius equation) for both types of sludge at various solid content

<table>
<thead>
<tr>
<th>Sludge types</th>
<th>Raw sludge</th>
<th>Treated sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid content (g/L)</td>
<td>(R^2)</td>
<td>(A) (mPa·s)</td>
</tr>
<tr>
<td>20</td>
<td>0.981</td>
<td>0.04</td>
</tr>
<tr>
<td>54</td>
<td>0.978</td>
<td>1.70</td>
</tr>
<tr>
<td>80</td>
<td>0.992</td>
<td>11.11</td>
</tr>
<tr>
<td>100</td>
<td>0.997</td>
<td>13.65</td>
</tr>
<tr>
<td>120</td>
<td>0.985</td>
<td>21.68</td>
</tr>
</tbody>
</table>
Table 3 | Regression model parameters (logistic model) for both types of sludge at various solid content

<table>
<thead>
<tr>
<th>Sludge types</th>
<th>Solid concentration (g/L)</th>
<th>R²</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal treated sludge</td>
<td>20</td>
<td>0.997</td>
<td>0.036</td>
<td>289.3</td>
<td>0.8</td>
<td>-20.67</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>0.998</td>
<td>-0.187</td>
<td>297.8</td>
<td>1.13</td>
<td>-52.86</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>0.997</td>
<td>0.086</td>
<td>306.6</td>
<td>1.57</td>
<td>-19.65</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.999</td>
<td>0.324</td>
<td>284.9</td>
<td>2.60</td>
<td>-17.85</td>
</tr>
<tr>
<td>Raw sludge</td>
<td>20</td>
<td>0.996</td>
<td>0.539</td>
<td>306.6</td>
<td>1.60</td>
<td>-24.10</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>0.994</td>
<td>1.142</td>
<td>316.6</td>
<td>10.87</td>
<td>-14.89</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>120</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

sludge, respectively. Activation energy is essential for movement of a molecule. Thermal pre-treatment resulted in the hydrolysis of organic macromolecule into small organic molecule, such as polysaccharides and protein hydrolysis into monosaccharide and amino acid, respectively, which all contributed to small particle size, smooth particle size distribution, and perfect sedimentation characteristic. Although there was so much variation in physical and chemical properties after thermal hydrolysis, which maybe made little contribution to the value of Ea, and leading to similar sensitive viscosity at various process temperature at the study range of 10–60 °C for both types of sludge.

Viscoelasticity of two kinds of sludge at different process temperatures

Feng et al. pointed out that sludge may be called viscoelastic material, meaning that sludge could flow characterized by viscous characteristic as applied stress is sufficiently high (Feng et al. 2014a). Meanwhile, as the applied stress reduces to zero, a partial elastic recovery is observed, maybe relating to storage of elastic energy in inter-particle bounds (elastic characteristic) (Seyssiecq et al. 2005). In rheology, three parameters are introduced to characterize material viscoelasticity, such as complex modulus (G″), storage modulus (real part of complex modulus, G′), and loss modulus (imaginary part of complex modulus, G′′). Storage modulus G′ could be expressed by ratio of elastic stress over strain, and G′′ represented the ratio of viscous stress over strain, which could be studied by a shear stress sweep test (Fielding et al. 2000; Ayol et al. 2006).

A previous study indicated storage modulus and loss modulus are both independent of strain in the linear viscoelastic region (Feng et al. 2014a). In order to obtain the dependence of G′ and G′′ on process temperature, a dynamic temperature ramp test at a low stress was employed which could ensure the study in linear viscoelastic region. Figure 2 shows the relationship between storage modulus (G′), loss modulus (G″) and process temperature for the two types of sludge in linear viscoelastic region. As can be seen, G′ decreased with increasing process temperature (10–60 °C) and G″ slightly increased. In linear viscoelastic region, sludge was mainly controlled by solid behavior (elastic) instead of hydrodynamic interactions. Therefore, the value of G′ was larger than that of G″. In addition, for the raw sludge with different solid content of 54–120 g/L, functionality between G′ and process temperature satisfy Arrhenius law accurately due to the high determination coefficient (R² > 0.96). There is a no perfect equation to describe the relationship between G″ and process temperature. Meanwhile, a non-Arrhenius relationship between viscoelastic parameters (G′ and G″) and temperature was observed at the thermal pre-treatment temperature of 50–80 °C (duration of thermal pre-treatment: 1 h) for waste activated sludge with solid content of 6.1%, which may be due to the released soluble COD (Farno et al. 2016). In addition, at higher process temperature, value of G′ was lower, which indicated that the solid-like behavior of sludge was weaker meaning that the ability to resist deformation was weaken, corresponding to stronger viscous property. The regression model parameters (viscoelastic parameters) were listed in Table 4.

For treated sludge with various solid concentration (in linear viscoelastic region), the change tendency of storage and loss modulus at different process temperatures was shown in Figure 3. It was noted that there was a narrow linear viscoelastic region as the solid content was lower than 100 g/L, which became widely with increasing solid content. Otherwise, the values of viscoelastic parameters (storage and loss modulus) for treated sludge were both far below those of raw sludge. The narrow linear viscoelastic region and low storage modulus both indicated that treated
sludge did not present similarities with the raw sludge, meaning that it was not a feature of emulsions or gels, but they behave more like Newtonian fluid as the solid content was lower than 100 g/L.

Figure 3 also shows that $G'$ and $G''$ was higher at lower process temperature. As the process temperature was higher than 19°C, $G'$ was below $G''$ for the treated sludge of solid content 100 g/L, while the transformation temperature increased to 44°C at solid content of 120 g/L. Further increasing solid content to 150 g/L, the liquid-like regime disappeared at the study range of (10–60°C). With increasing solid content, non-hydrodynamic interactions became the dominant interaction gradually. Although treated sludge with solid content of 150 g/L mainly behave like viscoelastic materials, the $G'$ (about 2.3 Pa at room temperature) was close to one-three hundredth of that of raw sludge at solid content of 120 g/L (about 700 Pa at room temperature). Arrhenius type equation was used to fit functionality between viscoelastic parameters and process temperature, and fitting values of viscoelastic parameters were listed in Table 5. Extremely low value of determination coefficient ($R^2$) suggested that the functionality between viscoelastic parameters and process temperature could not be expressed accurately by Arrhenius type equation for all treated sludge in this study, which was similar with that of Farno, but not identical. Farno et al. stated that at lower thermal pre-treatment temperature (50–80°C, duration of thermal pre-treatment: 1 h), linear model was obtained between $G'$, $G''$ and temperature (Farno et al. 2016). The differentiation may be attributed to the incomplete hydrolysis of the organic substance in sludge at lower temperature thermal pre-treatment.
Yield stress of two kinds of sludge at different solid concentration

Yield stress defined as the stress required to initiate flow can be confirmed as an indicator of sludge flowability, which can be divided into two kinds: static yield stress and dynamic yield stress. Static yield stress was measured in an undisturbed sample, while dynamic yield stress was determined from the extrapolation of steady flow curve. Note, in this paper, dynamic yield stress was employed below in which no steady state flow occur.

Figure 4 shows the change of yield stress for treated sludge and raw sludge at different solid content. For raw sludge, the yield stress was obvious as the solid content was higher than 100 g/L (18.7 Pa at the solid content of 120 g/L). While for treated sludge with solid content of 187 g/L, the yield stress was only 0.2 Pa, which indicated that after thermal pre-treatment, activated sludge could be treated as liquid fluid. Moreover, for raw sludge, the yield stress increased exponentially with solid content, which was in agreement with those previous reported (Forster 2002; Markis et al. 2014). At higher solid content, the resistance of solid particles opposed deformation, resulting to larger yield stress. While for yield stress of treated sludge and raw sludge with same concentration, there was significant difference maybe due to the intricate hyphae of microorganisms in activated sludge. During thermal pre-treatment, proteins, polysaccharides and lipids were hydrolyzed, leading to destruction of the colloidal properties of macromolecules, losing their natural shapes and sometimes precipitating irreversibly out of solution in an inactive form. Bound water originally trapped in a cell and bound to the particles was released into free water. All the above mentioned

Table 5 | Regression model parameters (viscoelastic) for treated sludge at various solid content

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$G'$</th>
<th>$G''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_0$ (Pa)</td>
<td>$G_0^0$ (Pa)</td>
<td>$R^2$</td>
</tr>
<tr>
<td>solid content (g/L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>no convergence</td>
<td>0.7</td>
</tr>
<tr>
<td>120</td>
<td>0.89</td>
<td>243.7</td>
</tr>
<tr>
<td>150</td>
<td>0.82</td>
<td>17.415</td>
</tr>
</tbody>
</table>
demonstrated thermal hydrolysis that decreased the flow resistance for the waste activated sludge. As a result, the yield stress nearly disappeared.

CONCLUSIONS

Liquid and viscoelastic characteristics of activated sludge (raw sludge) and thermal pre-treatment sludge (treated sludge) were investigated particularly by steady and dynamic rheological test at a series of process temperature (10–60 °C) which includes mesophilic and thermophilic digestion temperature. It was shown that sludge structure was weakened after thermal pre-treatment. Temperature dependence of viscosity for raw sludge satisfied Arrhenius equation, while that of treated sludge was only expressed by this law at certain solid content (solid content was larger than 80 g/L). And at the whole range of solid content, relationship between temperature and viscosity could be expressed by a logistic model accurately. As solid content at the range of 80–100 g/L, there is no an obvious difference in activation energy for viscosity for the two types of sludge, which indicated that change of sludge physicochemical properties after thermal pre-treatment had little effect on viscosity sensibility.

Meanwhile, viscoelastic analysis shows that impact of process temperature on storage and loss modulus was different for the two types of sludge. Raw sludge is the feature of prominent solid characteristics than that of treated sludge. Functionality of storage modulus and temperature follows Arrhenius law, while there is not an appropriate model for describing temperature dependence of loss modulus. In addition, for treated sludge, the viscoelastic characteristic and yield stress was not obvious. As a result, for the coupled technology of thermal treatment and AD, engineers need not consider viscoelasticity excessively as the solid content was lower than 100 g/L for treated sludge during the design of digestion process.

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