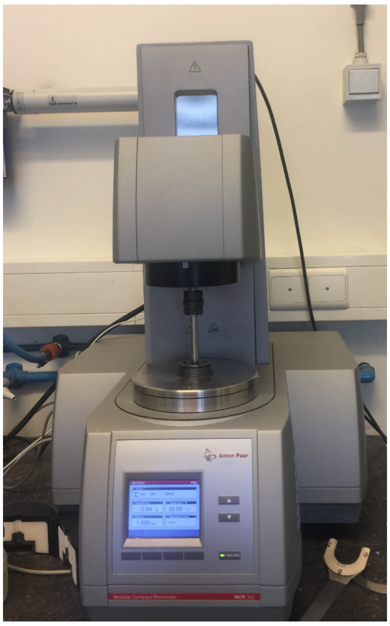
**Rheological characterization of secondary sludge: impact of solid concentration and temperature**

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## Abstract

Rheological characterization of sludge is essential, since it is related to access sludge transportation and mixing performance, which is included in many processes in waste water treatment and sludge disposal. This study was carried out for characterizing the secondary sewage sludge after gravitational thickening from a Dutch wastewater treatment plant (WWTP), which was also concentrated by vacuum filtration. The measurements of flow curves and yield stress were carried out under conditions of different solid concentrations (TS) and temperatures. Both the Ostwald and Herschel-Bulkley (HB) models were used for fitting the measured data; and a hybrid model was recommended for describing the flow behavior in a wide range of shear rates. HB model was better for fitting the flow curve of the raw sludge within the whole range of shear rates and only at lower shear rates of the concentrated sludge. Moreover, Ostwald was better for the flow curves at higher shear rates of the concentrated sludge. Regarding the parameters in the model fitting, K and n values were in certain relationship with the temperature of each sample. A power law or exponential relationship was used for describing the correlation between the yield stress and the TS.

# 1 Introduction

## 1.1 Importance of sludge rheology

An efficient and economic transport and mixing of sludge during the processes of waste water treatment and sewage sludge disposal is very important for waste water treatment plants (WWTPs) (Baroutian, 2013a). Because the flow behavior of sludge is crucial for the design of operating parameters in treatment and different systems, such as mixing system of digester or pumping design ((Baudez, 2013a)). Therefore, a sufficient understanding of its rheology characteristics is required for optimization the operation of WWTPs and energy saving (Eshtiaghi, 2013).

Sewage sludge, a water-based suspension, is well-known as a non-Newtonian fluid (Baroutian, 2013b), in which the shear rate is not linearly related to the shear stress. This means the apparent viscosity of sludge changes with applied shear stress or shear rates (Seyssiecq, 2003).From the previous studies, the wasted activated sludge (WAS) , was found to be viscoelastic at low shear rates and behaved as shear-thinning at higher shear rates ((Markis, 2014) (Baudez,2013b)). Many factors can influence the rheology the sludge, in which, TS and temperature were found to obviously influence the rheological behavior of secondary sludge ((Khalili, 2011),(Cao, 2016)).

## 1.2 Rheological models

Various mathematical models have been applied to describe rheological behavior of non-Newtonian fluid. The most commonly used models in literature are Ostwald(equation 1) and Herschel-Bulkley models(HB)(equation 2)((Baroutian, 2013a). The former one is based on a power-law equation and the later on contains the yield stress($\tau_0$). The Ostwald model can be purely used within a shear-thinning range, like an intermediate range of shear rates(Mori, 2006). While the HB model can be used for describing the flow behavior from rest, and indicates the flow started when the applied stress exceeded the $\tau_0$ (Markis et al., 2014).

$$\tau = K\gamma^n \qquad (1)$$

$$\tau = \tau_0 + K\gamma^n \qquad (2)$$

Due to different flow behaviors of sludge within different processes in treatment plant, such as mixing or recirculation, the rheological study in a wide range of shear rates should be conducted and could offer efficient basis for processes design and management (Baudez et al., 2013a).

## 1.3 Research objectives

This study characterized the rheological prosperities of raw WAS from a WWTP and concentrated WAS by vacuum filtration. Flow curves and yield stress were measured to study its characterizations at different TS concentrations and temperatures. The impacts of the TS and the temperature on the rheological properties were studied, and correlated using the rheological models.

## 2 Material and methods

### 2.1 Material preparation

Sludge samples were taken from the WWTP De Groote Lucht (Vlaardingen, the Netherlands). The secondary sludge was collected after a gravitational thickening and before a belt thickener. The raw sludge was further concentrated to higher TS concentrations by vacuum filtration in the lab, which has been reported not to influence the floc structure (Markis et al., 2014).Different samples with varied TS concentration were obtained by controlling the vacuum filtration time. The TS of the raw and concentrated sludge are shown in Table 1. All the samples were stored at 4°C and measured within maximum 4 days.

*Table 1 TS of the sludge samples*

| Type | TS(%) |
|---|---|
| Raw | 1.2 |
| Concentrated 1 | 4.2 |
| Concentrated 2 | 6 |

### 2.2 Rheological measurement

An Anton Paar physica MCR 302 rheometer(Anton Paar GmbH, Austria) equipped with a rotational Couette geometry was used, with a CC27 system for measurement (the diameter of bob is 13.332mm; the diameter of cup is 14.466mm). The temperature was controlled within a tolerance of  0.05°C. After stabilizing of the temperature, the measurement started.

1.Flow curve

The measurement of flow cure was carried out following procedures:

1. A pre-shear step(normally 1000min $^{-1}$) was applied for 90s , followed by 60s of rest.
2. The measurement was carried out by increasing the shear rate ranging from 0.01 $s^{-1}$ to 1000 $s^{-1}$ with decreasing time intervals using the logarithmic ramp mode.

The adoption of pre-shear was to obtain homogeneous material and avoid flow obstruction(Piani, 2014). The step of rest was set for rebuilding structure(Markis et al., 2014).

2 Yield stress identification

For the yield stress identification of each sample, the steps were shown as follows:

1. The similar pre-shear followed by the rest producer as in flow curve measurement was conducted firstly.
2. A torque ramp mode was carried out to sample with gradually increasing to exceed the yield stress, with in total 60 intervals' measurement. The deflection angle was measured and the corresponding shear stress with suddenly increase of angle was regarded as the yield stress.

All measurements were conducted with sample at 10°C,20°C,35°C,45°C and 55°C respectively.

### 2.3 Data process

The measured data were regressed by the Ostwald and HB models, respectively. SSE(The sum of squared errors) was used for assessments. The relationships between the TS and the temperature with the fluid consistency ''K'', the flow index ''n'' and yield stress "$\tau_0$" were investigated. For yield stress, the extrapolation of flow curve at 0 shear rate was not conducted in this study, as steady state was not achieved(Baudez et al., 2013a).

# 3 Results and discussion

## 3.1 Model fitting of flow curves

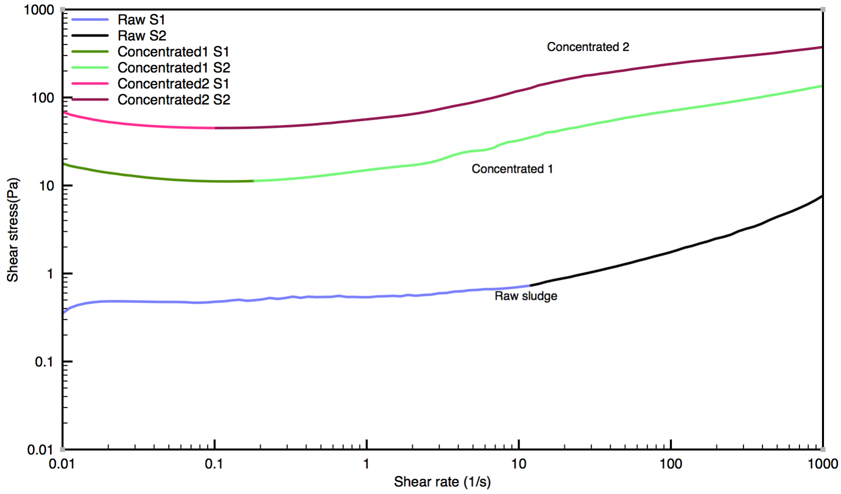



*Figure 1 Rheograms of these 3 types of sludge; raw sludge(TS 1.2%), Concentrated 1(TS 4.2%),Concentrated 2 (TS 6.0%)*

Flow curves of these 3 types of sludge at 20°C are illustrated in Figure 1. All sludge samples showed a yielding trend, and no steady state was achieved. For the raw sludge(TS 1.2%), the shear stress increased from low to high shear rates. For the concentrated sludge, the tendency was different: the shear stress declined at lower shear rates and then kept increasing with the increase of shear rate. The results of curve fitting with whole range of shear rates of each sludge are shown in Table 2.According to the result of curve fitting with the two equations motioned before, the fitting quality for the raw sludge with 2 model was much better than that of the concentrated sludge, presented by lower SSE values. It was due to the obviously different trends with lower and higher shear rates range of concentrated sludge . However, the regression with flow curve in the whole range of the shear rates was actually not reliable, with SSE higher than 0.5 and even reach $10^4$.Based on this finding, a method that divided the whole curve of each sludge into 2 segments based on tendency was adopt for model fitting in this study and the transition point varied with TS and temperature, which would be discussed in section 3.3 and 3.4. The range of shear rates with tend increasing stress was regarded as the upper segment, presented by higher range of shear rates in this study. The rest part was named as the lower part. The data for the model fitting is presented in Table 3.

*Table 2 Summarized results of model fitting with 3 types of sludge, 20℃*

| TS(%) | | K | n | $\tau_0$ | SSE |
|---|---|---|---|---|---|
| 1.2 | Ostwald | 0.16 | 0.54 | - | 1.21E+01 |
| | HB | 0.04 | 0.76 | 0.5 | 4.70E-01 |
| 4.2 | Ostwald | 17.75 | 0.29 | - | 1.58E+03 |
| | HB | 13.01 | 0.34 | 5.63 | 1.15E+03 |
| 6 | Ostwald | 73.05 | 0.24 | - | 2.53E+04 |
| | HB | 60.56 | 0.27 | 13.24 | 2.39E+04 |

In comparison with the results shown in Table 2, it was obvious that fitting with two segments separately of each sludge even with the same rheological model was more suitable, with lower SSE values. It corresponded with the different trends of lower and upper segment shown in flow curve. It indicated that the method dividing whole range into 2 parts and fitted with model separately was adaptable for analyzing.

Besides, for each type of the sludge, suitable model of fitting for different segment may also be different. For the raw sludge, the HB model was the better model for describing the flow behavior. For the concentrated sludge, for the lower part, HB model was also the better option; while, in higher range of shear rates, although yield stress was included in the equation of HB model, the obtained value from fitting was very small and could be estimated as 0. In this situation, there was no differences between Ostwald and HB model, indicating Ostwald was more suitable for presenting the flow behavior of the concentrated sludge at higher shear rates. In total, for rheological model fitting, the method that hybrid models with different range of shear rates was more suitable than single model fitting for whole range. The term yield stress was more important for the raw sludge and lower part of concentrated sludge. At higher shear rates of concentrated sludge, this term may could be negligible.

*Table 3 Parameters for rheological modeling fitting*

| TS(%) | | | K | n | To | SSE |
|---|---|---|---|---|---|---|
| 1.2 | Ostwald | Lower | 0.57 | 0.06 | | 3.48E-02 |
| | | Upper | 0.11 | 0.61 | | 1.75E+00 |
| | HB | **Lower** | **0.13** | **0.31** | **0.42** | **2.41E-02** |
| | | **Upper** | **0.02** | **0.83** | **0.68** | **2.71E-01** |
| 4.2 | Ostwald | Lower | 7.53 | -0.17 | | 1.21E+01 |
| | | **Upper** | **16.63** | **0.3** | | **3.55E+02** |
| | HB | **Lower** | **0.03** | **-1.16** | **10.74** | **2.91E-01** |
| | | Upper | 16.63 | 0.3 | 0 | 3.55E+02 |
| 6 | Ostwald | Lower | 33.37 | -0.13 | | 2.59E+02 |
| | | **Upper** | **68.69** | **0.25** | | **1.36E+04** |
| | HB | **Lower** | **0.02** | **-1.6** | **44.69** | **2.96E+00** |
| | | Upper | 68.69 | 0.25 | ~0 | 1.36E+04 |

Although better fitting performance was obtained by this method, the abnormal value(negative values of n) of parameter could be deviated at lower shear rates, since it was simply predicted by mathematical method. The physical meaning of these parameter was not determined in the calculation. It indicated more studies about model fitting should be conducted at low shear rates of flow curve.

## 3.2 Yield stress identification

Yield stress is regarded as the flow ability of sludge(Spinosa & Lotito, 2003).From the observation of rheogram, all the sludge exhibited the yield stress and it varied with different TS concentrations and temperatures. However the method of yield stress determination was not clear. Three different methods were adopted in this study for characterizing that. The initial flow point presented in flow curve could be regarded as the yield stress, since yield stress must be reached once flow starts. HB model also took yield stress into account and it could be detected by the model fitting. Besides this, in yield stress measurement of this study(Figure 2), the reflection angle was monitored for capturing the specific moment that exceeding yield stress(abrupt angle increase). The data with each method at 20℃ is shown in Table 4. For the raw sludge, there was no difference in the value obtained from 3 methods. However, for the concentrated sludge, the value detected based on reflection angle was always the highest and the value predicted by HB model fitting was the lowest one.

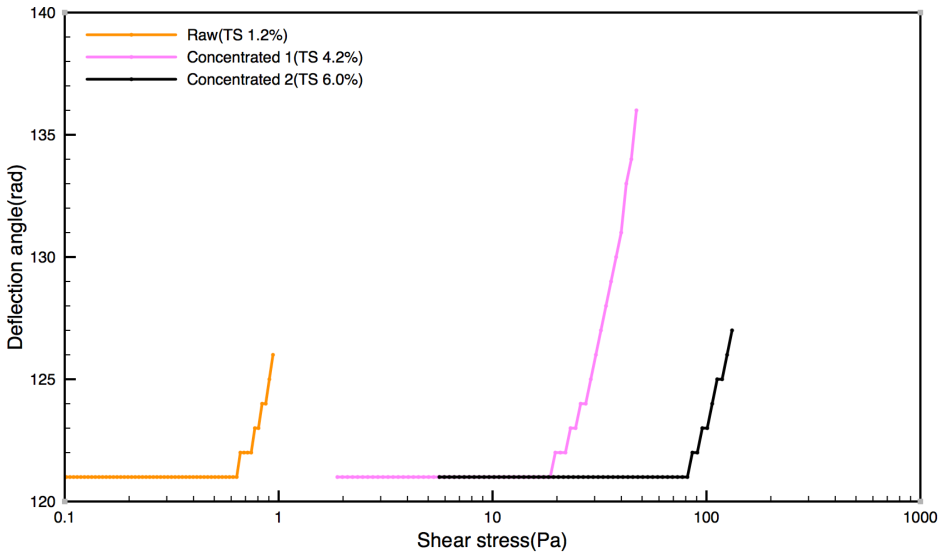


*Figure 2 Deflection angle measurement for identifying yield stress*

For regarding the initial point in flow curve as the yield stress, the overestimation could be achieved for concentrated sludge due to the decreasing yield stress trend at lower shear rates. So the accurate yield stress could be higher than the value of initial flow point. For the predicted value from HB model fitting, as introduced before, the abnormal value of parameter in equation obtained and caused the value of yield stress less reliable. The reflection angle measured in the yield stress experiment presented the deformation status of sludge samples. The abrupt increase of reflection angle was regarded as overcoming the resistance oppose deformation. From the result obtained in this study, the method of deflection angle measurement was recommended for yield stress identification.

*Table 4 Summarized data of yield stress(Pa) determined by different methods*

| S3-1 | | | S3-2 | | | S4-2 | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Initial point | HB | Angle | Initial point | HB | Angle | Initial point | HB | Angle |
| 0.4 | 0.4 | 0.4 | 17.8 | 10.7 | **19.7** | 68.6 | 44.7 | **77.3** |

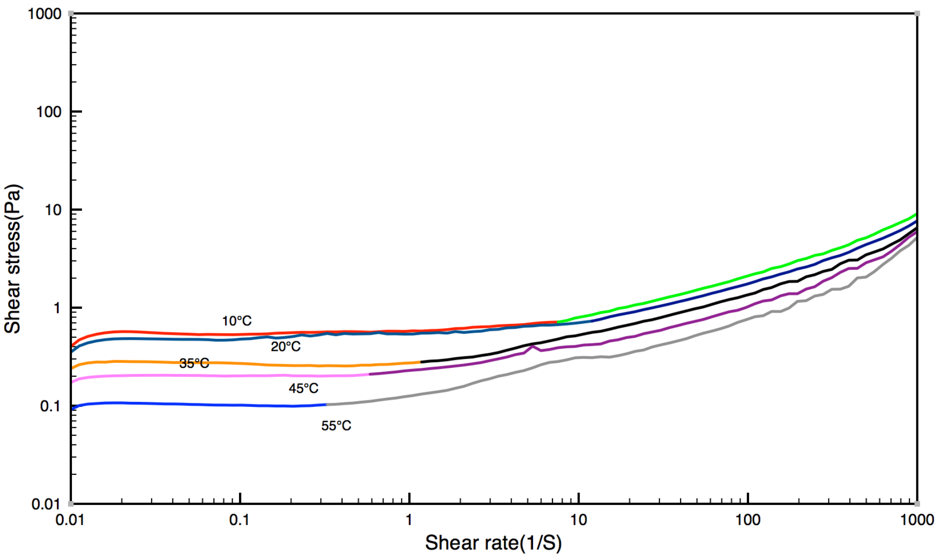
## 3.3 Effect of TS and temperature on flow curve

### 3.3.1 Impact of TS

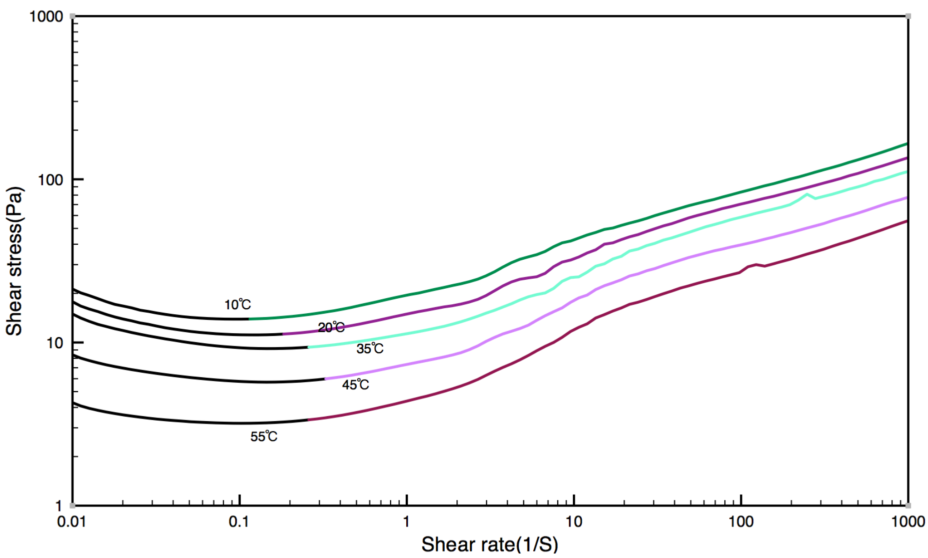
Flow curves were conducted at 10°C,20°C,35°C,45°C and 55°C of each type of sludge respectively. The flow curves of each type of sludge are presented in Figure 3. Similarly, the flow curves of all the raw sludge showed an increasing trend of shear rates from low to high shear rates, while for the concentrated sludge, the trend at the beginning part was oppose of that. The summarized data(shown in Appendix) for the model fitting also showed that the HB model was more suitable for describing the raw sludge's flow behavior. For concentrated sludge, hybrid model(HB for lower shear rate and Ostwald for higher range) was recommended at each temperature, which means the model propriety for flow curve fitting was not affected by the temperature but only influenced by the TS. For the relationship between parameter of K, n and TS was not addressed over here, since only 3 types of sludge with different TS were included in this study.

### 3.3.2 Impact of temperature

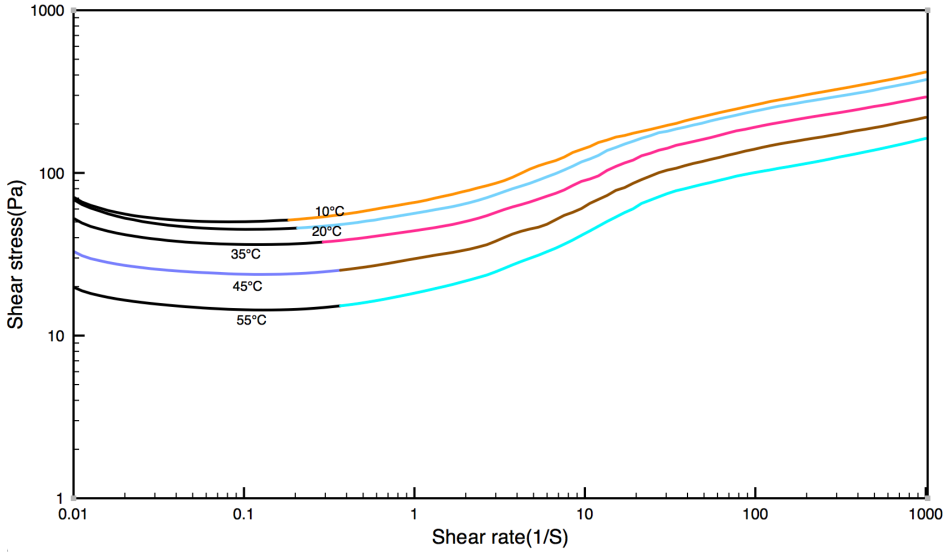
The impact of temperature on the sludge rheology was also investigated in this study. Figure 3 illustrates the flow curves of each type of sludge at different temperature and each flow curve was divided into 2 parts based on its tendency. For sludge samples with the same TS but at different temperature, the initial flow point and transition point of 2 segments were different. The shear stress value of the initial flow point decreased with the increasing of temperature. It was possibly due to the cohesive force reduced by thermal motion after sludge was heated(Baroutian, 2013a).As for the transition point, the corresponding shear rate value declined with increasing temperature for the raw sludge; while for the concentrated sludge, in total, the value showed increasing trend as the rising of temperature from 10°C to 45°C. Although different flow curves could be obtained at different temperature, the flow curve at 10°C and 20°C of each type of sludge was very similar and even coincided within certain range of shear rates. Which may introduce that the prosperities of sludge did not change a lot between 10°C to 20°C.The model fitting of each segment with Ostwald and HB model was also conducted, and as mentioned before, the parameters of model fitting for each segment also varied with temperature. The correlation between these parameters and temperature is discussed as follows.




*(a)Raw sludge*




*(b)Concentrated 1*




*(c)Concentrated 2*

*Figure 3 Flow curves of all the sludge samples at different T*

For the parameter K, the variation with temperature was also related to the different segment within one flow curve .A linear relationship was found with K and temperature of each type of sludge at higher shear rates, as presented in Figure 4($R^2$ 0.8~0.99). However, for the range of lower shear rates of each type of sludge, the K value fluctuated with the increasing of temperature, and it was very small(<0.15). The finding of linear relationship corresponded with the conclusion in former study(Baroutian, 2013a).

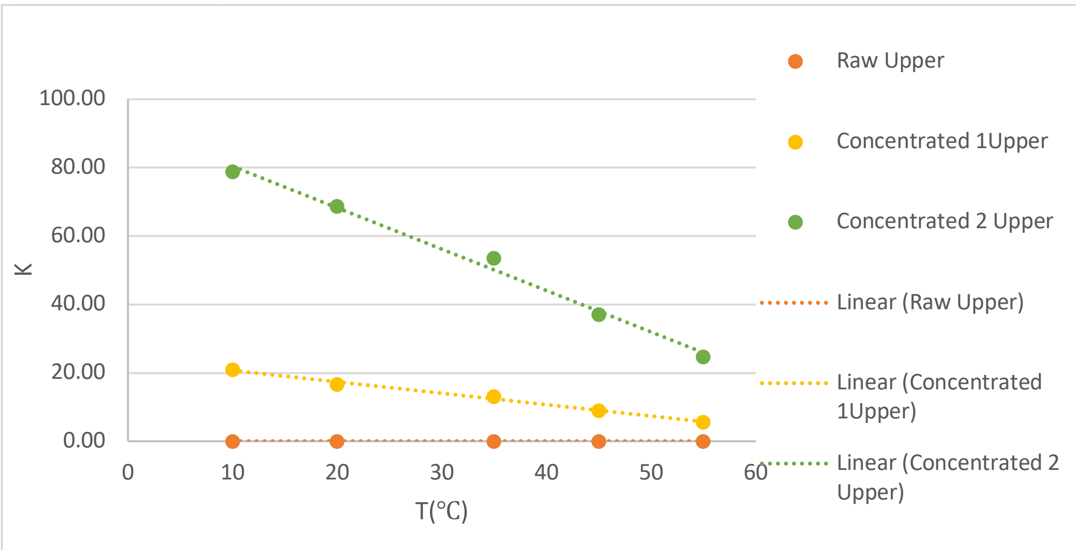



*Figure 4 Variation of Parameter K with temperature*

For index n, some negative values were obtained by the mathematical regression. For the raw sludge at low shear rates, apparent decrease was found from 35°C to 55°C. For other segments, the value of n showed a linear relationship and even constant within the range of temperature. Which also corresponded to the Baroutian's research, that the n value kept constant in the range of temperature from 25°C to 55°C with HB model fitting(Baroutian, 2013a).

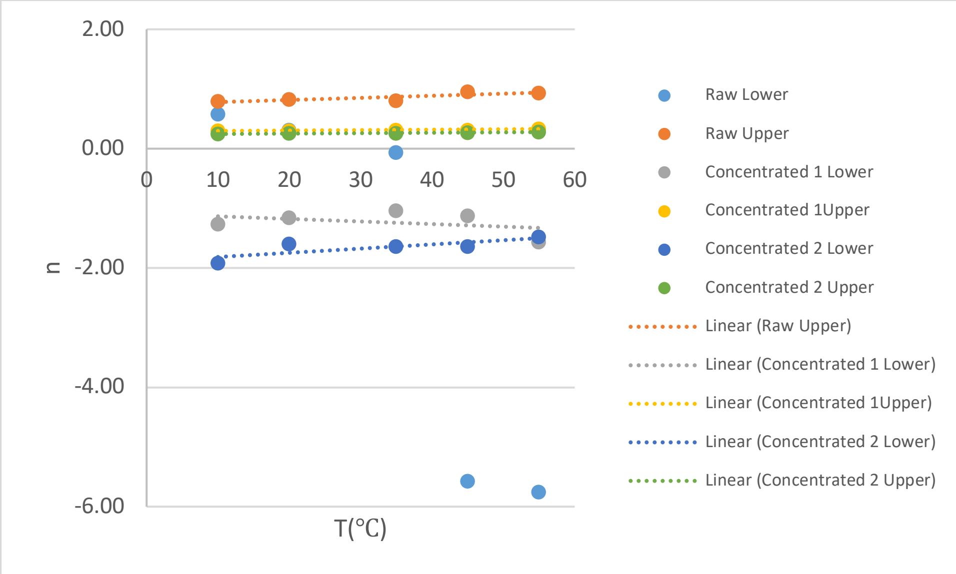



*Figure 5 Variation of n with temperature*

## 3.4 Effects of TS and temperature on yield stress

### 3.4.1 Impact of TS

Appendix 1 illustrates the summarized data of yield stress of each type of sludge at each temperature by 3 methods. Yield stress increased with the increased TS and more abruptly from TS of 4.2% to TS of 6.0%. The relationship between TS and yield stress identified by reflection angle measurement at each temperature could be described by Power law or exponential model, with almost same $R^2$(0.98~0.99) and slight higher $R^2$ with power law fitting, shown in Figure 6.This was consistent with the results of Markis et al. (2016), and Lotito and Lotito (2014),, that the power law model suggested for presenting correlation between yield stress and TS. It also indicated that this property was temperature-independent.

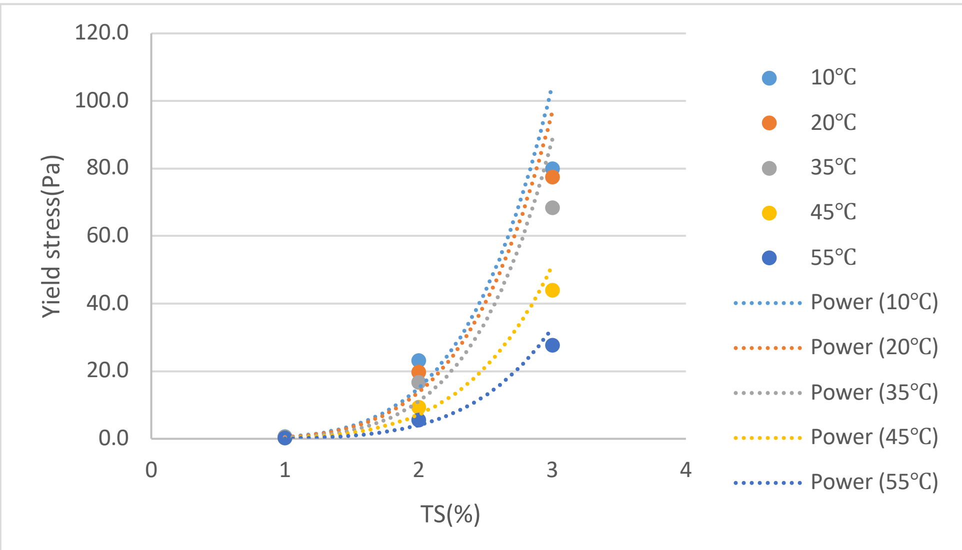



*Figure 6 Yield stress of each type of sludge at specific temperature*

### 3.4.2 Impact of temperature

The temperature also influenced the yield stress of each type of sludge. The characterizing method of yield stress discussed over here was the measurement of reflection angle. Summarized data can be found in *Figure 7Figure 7*. In total, the yield stress declined with the increasing of temperature.

However the magnitude of change was different, slightly decrease was found from 10°C to 35 °C and the acute decline was found within range from 35°C to 55°C. Which indicated the temperature could result in the change of resistance and structure of sludge and the influence on that depended on the specific temperature. Besides, with the increase of temperature, the difference between the yield stress of sludge from low to high TS became smaller. The exponential decay model($R^2$ 0.87~0.92) can be used for presenting the correlation between yield stress and temperature. Which also was in agreement with the finding of Lotito and Lotito (2014).

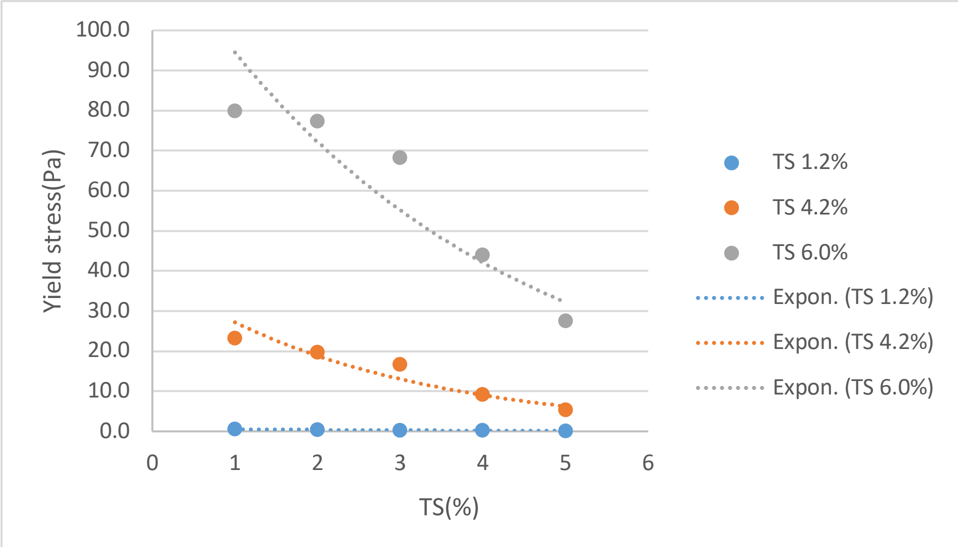



*Figure 7 Variation of yield stress with temperature*

## 4 Conclusions

From the observed flow curves, the yield stress increased along the range of shear rates of the raw sludge at each temperature, and for the concentrated sludge, the tendency was different at lower and higher shear rates at each temperature. Based on this finding, the flow curve could be divided into 2 parts based on the tendency and hybrid model fitting was recommended for describing the flow behavior of each sludge. HB model was better for presenting flow behavior of raw sludge; while for the concentrated sludge, HB was a better option at lower shear rates and Ostwald model was more suitable for higher shear rates range's description. For the parameters in equation of model fitting, K value was linear related to the temperature of each type of sludge at higher shear rates and n value was almost constant within the whole range of temperature except for at lower shear rates of raw sludge. As for yield stress identification, three methods were adopted in this study and the measurement with reflection angle is recommended. Yield stress was in power law or exponential relationship with TS and followed an exponential decay with temperature.

However, additional work still needs to be done with rheological behavior at lower shear rates, since abnormal value of model fitting was obtained and the physical meaning of these parameters need to be determined for better understanding of flow behavior(Dieudé-Fauvel, 2009).

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Appendix

*Appendix 1 Summarized date for yield stress predicted by 3 methods*

| | S3-1 | | | S3-2 | | | S4-2 | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| T(℃) | Initial point | HB | Angle | Initial point | HB | Angle | Initial point | HB | Angle |
| 10 | 0.4 | 0.5 | 0.5 | 21.3 | 13.4 | 23.1 | 71 | 50.1 | 79.8 |
| 20 | 0.4 | 0.4 | 0.4 | 17.8 | 10.7 | 19.7 | 68.6 | 44.7 | 77.3 |
| 35 | 0.2 | 0.2 | 0.3 | 15 | 8.9 | 16.7 | 52.6 | 36.4 | 68.3 |
| 45 | 0.2 | 0.2 | 0.2 | 8.4 | 5.7 | 9.2 | 32.9 | 24.1 | 43.9 |
| 55 | 0.1 | 0.2 | 0.1 | 4.3 | 3.2 | 5.4 | 19.9 | 14.5 | 27.6 |

*Appendix 2 The summarized date of model fitting*

| | | | 10℃ | | | | 20℃ | | | | 35℃ | | | | 45℃ | | | | 55℃ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TS(%) | model | | K | N | To | SSE | K | N | To | SSE | K | N | To | SSE | K | N | To | SSE | K | N | To | SSE |
| 1.2 | Ostwald | whole | 0.18 | 0.55 | | 1.43E+01 | 0.16 | 0.54 | | 1.21E+01 | 0.09 | 0.60 | | 5.00E+00 | 0.04 | 0.71 | | 4.59E+00 | 0.01 | 0.85 | | 2.97E+00 |
| | | lower | 0.61 | 0.04 | | 5.25E-02 | 0.57 | 0.06 | | 3.48E-02 | 0.26 | -0.01 | | 3.72E-03 | 0.21 | 0.01 | | 9.64E-04 | 0.21 | 0.01 | | 9.25E-04 |
| | | upper | 0.13 | 0.60 | | 2.34E+00 | 0.11 | 0.61 | | 1.75E+00 | 0.08 | 0.62 | | 2.60E+00 | 0.04 | 0.72 | | 3.24E+00 | 0.04 | 0.71 | | 3.41E+00 |
| | **hb** | **whole** | **0.05** | **0.75** | **0.55** | **5.80E-01** | **0.04** | **0.76** | **0.50** | **4.70E-01** | **0.03** | **0.76** | **0.290** | **1.02E+00** | **0.11** | **0.90** | **0.252** | **1.16E+00** | **0.00** | **1.02** | **0.168** | **1.31E+00** |
| | | **lower** | **0.06** | **0.58** | **0.53** | **2.90E-02** | **0.13** | **0.31** | **0.42** | **2.41E-02** | **0.04** | **-0.07** | **0.230** | **3.72E-03** | **0.00** | **-5.57** | **0.203** | **9.38E-05** | **0.00** | **-5.76** | **0.203** | **3.94E-05** |
| | | **upper** | **0.03** | **0.79** | **0.69** | **4.18E-01** | **0.02** | **0.83** | **0.68** | **2.71E-01** | **0.02** | **0.80** | **0.372** | **8.65E-01** | **0.01** | **0.95** | **0.326** | **9.20E-01** | **0.01** | **0.94** | **0.306** | **9.86E-01** |
| 4.2 | Ostwald | whole | 22.27 | 0.29 | | 1.83E+03 | 17.75 | 0.29 | | 1.58E+03 | 14.06 | 0.30 | | 1.45E+03 | 14.06 | 0.31 | | 4.95E+02 | 5.79 | 0.33 | | 1.72E+02 |
| | | lower | 8.53 | -0.18 | | 1.16E+01 | 7.53 | -0.17 | | 1.21E+01 | 6.69 | -0.15 | | 9.68E+00 | 4.72 | -0.10 | | 3.26E+00 | 2.76 | -0.07 | | 7.46E-01 |
| | | upper | 20.98 | 0.30 | | 2.20E+02 | 16.63 | 0.30 | | 3.55E+02 | 13.05 | 0.31 | | 4.43E+02 | 8.89 | 0.32 | | 2.00E+02 | 5.60 | 0.33 | | 1.05E+02 |
| | **hb** | **whole** | **15.63** | **0.34** | **7.74** | **1.06E+03** | **13.01** | **0.34** | **5.63** | **1.15E+03** | **10.26** | **0.34** | **4.644** | **1.13E+03** | **7.59** | **0.34** | **2.196** | **4.25E+02** | **5.31** | **0.34** | **0.613** | **1.66E+02** |
| | | **lower** | **0.02** | **-1.27** | **13.36** | **1.80E-01** | **0.03** | **-1.16** | **10.74** | **2.91E-01** | **0.05** | **-1.04** | **8.880** | **3.07E-01** | **0.02** | **-1.12** | **5.671** | **2.08E-01** | **0.00** | **-1.57** | **3.217** | **5.17E-02** |
| | | **upper** | **20.98** | **0.30** | | **2.20E+02** | **16.63** | **0.30** | **0.00** | **3.55E+02** | **13.05** | **0.31** | **~0** | **4.43E+02** | **8.89** | **0.32** | **~0** | **2.00E+02** | **5.60** | **0.33** | **~0** | **1.05E+02** |
| 6.0 | | whole | 82.94 | 0.24 | | 2.10E+04 | 73.05 | 0.24 | | 2.53E+04 | 57.12 | 0.24 | | 1.73E+04 | 38.92 | 0.26 | | 9.23E+03 | 25.52 | 0.28 | | 4.84E+03 |
| | | lower | 39.35 | -0.10 | | 2.43E+02 | 33.37 | -0.13 | | 2.59E+02 | 30.15 | -0.09 | | 1.58E+02 | 21.17 | -0.07 | | 6.01E+01 | 12.71 | -0.07 | | 2.05E+01 |
| | Ostwald | upper | 78.74 | 0.25 | | 1.04E+04 | 68.69 | 0.25 | | 1.36E+04 | 53.51 | 0.26 | | 9.78E+03 | 36.98 | 0.27 | | 6.20E+03 | 24.69 | 0.28 | | 3.74E+03 |
| | | **whole** | **70.40** | **0.26** | **13.12** | **1.98E+04** | **60.56** | **0.27** | **13.24** | **2.39E+04** | **46.76** | **0.27** | **11.030** | **1.64E+04** | **34.71** | **0.27** | **4.588** | **9.04E+03** | **25.25** | **0.28** | **0.305** | **4.84E+03** |
| | | **lower** | **0.00** | **-1.92** | **50.1** | **4.67E+00** | **0.02** | **-1.60** | **44.69** | **2.96E+00** | **0.01** | **-1.64** | **36.380** | **4.14E+00** | **0.00** | **-1.65** | **24.060** | **3.98E+00** | **0.01** | **-1.48** | **14.500** | **1.53E+00** |
| | **hb** | **upper** | **78.74** | **0.25** | **~0** | **1.04E+04** | **68.69** | **0.25** | **~0** | **1.36E+04** | **53.51** | **0.26** | **~0** | **9.78E+03** | **36.98** | **0.27** | **~0** | **6.20E+03** | **24.69** | **0.28** | **~0** | **3.74E+03** |