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Rheology and friction loss of raw and digested sewage sludge with high TSS concentrations: a case study

K. Füreder, K. Svardal, J. Krampe and H. Kroiss

ABSTRACT

High total suspended solids (TSS) digestion of municipal sewage sludge reduces the required space and volume for digestion plants. However, an important consequence of high TSS is the major influence on sludge rheology. The present case study investigates the rheology of sludge from a 130 m^3 high solids digestion pilot plant at Vienna's main wastewater treatment plant (4 M PE_{120}). Raw sludge ranged from 6 to 8% TSS and digested sludge from 3.2 to 4.6%. TSS show an exponential impact on rheological parameters. Increasing raw sludge TSS from 6 to 8% at least doubles the shear stress and increases friction loss by a factor of three. However, under real operating conditions simulated at the pilot plant, there are additional impact factors. The mixing ratio between waste activated and primary sludge influences raw sludge rheology, while solids retention time and loss on ignition affects digested sludge rheology. Nevertheless, friction loss calculations based on a simple power law relationship between shear rate and shear stress proved to be applicable and sufficiently accurate for both raw and digested sludge with high TSS. Altogether, this case study underlines the relevance of comprehensive rheological considerations, measurements and calculations when designing high TSS sludge digestion.

Key words | head loss in sludge pipes, high TSS digestion plant, high TSS sludge rheology, high-solid digestion, laminar and turbulent flow, non-Newtonian fluid dynamics, rheological variability of sewage sludge

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ABBREVIATIONS

DS	digested sludge
LOI	loss on ignition (%)
MID	electromagnetic flow meter
PE_{120}	population equivalent; assuming 120 g COD PE^{-1} d^{-1}
PS	primary sludge
RawS	raw sludge (=WAS + PS + thickening-polymer)
SRT	solids retention time (in digestion plant) (d)
TSS	total suspended solids (concentration) (%)
WAS	waste activated sludge
WWTP	wastewater treatment plant

NOMENCLATURE

D	pipe inside diameter (m)
f	fanning friction factor (–)
k	pipe wall roughness (–)
K	fluid consistency index ($Pa.s^n$)
n	flow behavior index (–)
R	pipe inside radius (m)
Re_{MR}	Metzner and Reed Reynolds number (–)
$Re_{MR,krit}$	critical Metzner and Reed Reynolds number (–)
v	average velocity (m s^{-1})
$\dot{\gamma}$	shear rate (s^{-1})
ρ	fluid density (kg m^{-3})
τ	shear stress (Pa)
τ_y	yield stress (Pa)
τ_w	wall shear stress (Pa)

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INTRODUCTION

Anaerobic digestion is a standard method for stabilizing sewage sludge at digested sludge total suspended solids

(TSS) concentrations of approximately 2%. However, the global urbanization process is putting pressure on existing digester volumes resulting from increasing sludge loads (Eshtiaghi *et al.* 2013). To avoid the extension of existing digester volumes or to reduce the digester volume and physical footprint of new plants, digesters can be operated at TSS concentrations higher than 2% (Kapp 1984; Duan *et al.* 2012; Reichel 2015). However, there are specific limiting factors: high solid concentrations in the feed lead to high NH_4-N- and, depending on pH, also to high NH_3-N-concentrations in the digested sludge, which can have an inhibiting effect on archaea methanogens. Reichel (2015) and Jahn *et al.* (2016) show that for a stable anaerobic degradation of organic compounds, NH_4-N concentrations must not exceed 2,000 $mg\,L^{-1}$, corresponding to approximately 60 $mg\,L^{-1}$ NH_3-N at pH 7.4 and 37 °C, which is in line with investigations by Kroiss (1985). Another important consequence is the impact of high TSS on the rheological properties of sludge, affecting pumping, mixing, heat exchangers, pipe dimensioning, friction loss and subsequently energy requirements (Eshtiaghi *et al.* 2012; Ratkovich *et al.* 2013).

Vienna's main wastewater treatment plant (WWTP) is a two-stage activated sludge plant with a capacity of 4 M PE_{120}. Space requirements, minimization of digester volume, and as a consequence costs, are the driving forces for the construction of a high-TSS digestion plant, which is planned to be operational in 2020. In order to have a sound basis for design and operation, a 130 m^3 pilot scale digester with approximately 4% TSS was operated for two years (Reichel 2015). Four percent TSS in digested sludge (DS) can be achieved by feeding the raw sludge (RawS) with 7–8% TSS. Regarding rheology, a major challenge in increasing the TSS is the exponential increase in shear stress and friction loss. Hence, the present case study investigates the impact of TSS on the rheological properties and friction loss of raw sludge with 6 to 8% TSS, and digested sludge with 3.2 to 4.6% TSS. Both raw and digested sludge, sampled between April 2013 and June 2014, represent the rheological variability of sludge from Vienna's main WWTP when operated over a period of approximately one year. In contrast to waste activated sludge (WAS), hardly any data on the rheology of mixed raw sludge was found in the literature. In order to allow the comparison with literature data, the present case study also examined WAS from 2 to 6% TSS. Furthermore, the case study investigated the practical applicability of non-Newtonian friction loss calculations based on a simple power law relationship between shear rate and shear stress. In addition, the flow regime (laminar/turbulent) of raw and digested sludge samples with high TSS was studied at different velocities and diameters with regard to the practical implementation of sludge pipelines.

In this paper, raw sludge is defined as a mixture of WAS and primary sludge (PS), with polymers added for thickening.

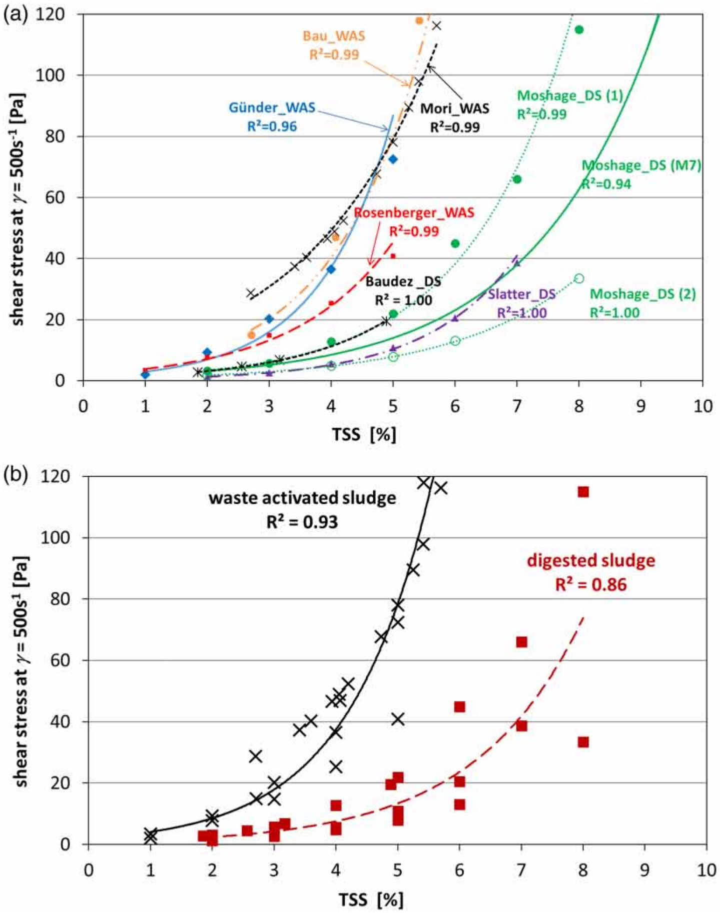
Impact of TSS on the rheological behavior of WAS and digested sludge

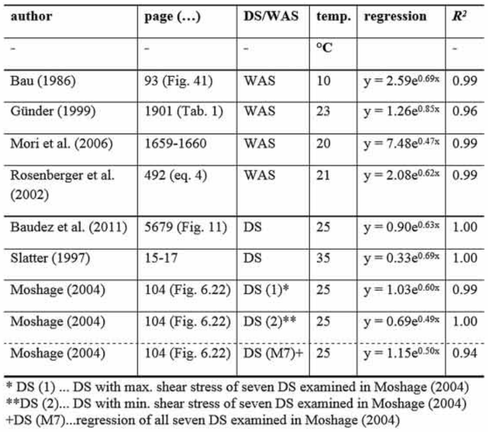
Sludge rheology has been subject to a wide variety of different analyses, compare Ratkovich *et al.* (2013) and Klinksieg (2010) for compact overviews. Numerous authors focused especially on the impact of TSS on the rheology of WAS and digested sludge. According to Ratkovich *et al.* (2013) only investigations with sufficient similarity to the experimental set up in this paper, regarding TSS, temperature and measurement process, were taken into account. In addition, only shear stresses determined at a shear rate of 500 s^{-1} were considered, being the maximum shear rate of the rheological measurements carried out in the present study.

The TSS/shear stress relationship in all qualified papers (Bau 1986; Slatter 1997; Günder 1999; Rosenberger *et al.* 2002; Moshage 2004; Mori *et al.* 2006; Baudez *et al.* 2011) can be either modeled as exponential law ($\tau = a \cdot e^{b \cdot TSS}$; $R^2 > 0.96$) or as power function ($\tau = a \cdot TSS^b$; $R^2 > 0.96$). Exponential models tend to over-estimate, while power functions tend to underestimate shear stress at high TSS concentrations. Overall, exponential modeling gave the best results (Figure 1(a)). The TSS-shear stress relationship of all data points taken together for WAS and digested sludge can be approximated with an exponential law as well (Figure 1(b)). In accordance with Hellmann & Riegler (2003) it shows that the shear stress of WAS rises much faster than the shear stress of digested sludge.

Friction loss calculations

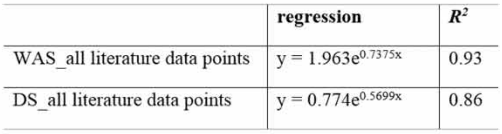
Friction loss calculations of non-Newtonian liquids such as sludge are based on the relationship between shear rate $\dot{\gamma}$ and shear stress τ, which is obtained by means of rheological measurements. Sludge with high TSS is a pseudoplastic fluid exhibiting a yield stress (τ_y). Slatter (2004, 2008), Swamee & Aggarwal (2011), Founargiotakis *et al.* (2008) and Haldenwang *et al.* (2012) showed complex implicit or explicit solutions based on the Herschel-Bulkley model ($\tau = \tau_y + K \cdot \dot{\gamma}^n$). Nevertheless – as to be shown in this





author	page (...)	DS/WAS	temp.	regression	R^2
-	-	-	°C		-
Bau (1986)	93 (Fig. 41)	WAS	10	$y = 2.59e^{0.69x}$	0.99
Günder (1999)	1901 (Tab. 1)	WAS	23	$y = 1.26e^{0.85x}$	0.96
Mori et al. (2006)	1659-1660	WAS	20	$y = 7.48e^{0.47x}$	0.99
Rosenberger et al. (2002)	492 (eq. 4)	WAS	21	$y = 2.08e^{0.62x}$	0.99
Baudez et al. (2011)	5679 (Fig. 11)	DS	25	$y = 0.90e^{0.63x}$	1.00
Slatter (1997)	15-17	DS	35	$y = 0.33e^{0.69x}$	1.00
Moshage (2004)	104 (Fig. 6.22)	DS (1)*	25	$y = 1.03e^{0.60x}$	0.99
Moshage (2004)	104 (Fig. 6.22)	DS (2)**	25	$y = 0.69e^{0.49x}$	1.00
Moshage (2004)	104 (Fig. 6.22)	DS (M7)+	25	$y = 1.15e^{0.50x}$	0.94

* DS (1) ... DS with max. shear stress of seven DS examined in Moshage (2004)
**DS (2)... DS with min. shear stress of seven DS examined in Moshage (2004)
+DS (M7)...regression of all seven DS examined in Moshage (2004)



	regression	R^2
WAS_all literature data points	$y = 1.963e^{0.7375x}$	0.93
DS_all literature data points	$y = 0.774e^{0.5699x}$	0.86

Figure 1 | Literature review on the correlation of TSS and shear stress at $\dot{\gamma} = 500\ \mathrm{s}^{-1}$ – exponential modeling: (a) evaluation of individual literature, (b) evaluation of all literature data points together.

paper – for practical applications also a simple power law model can be used:

$$\tau = K \cdot \dot{\gamma}^n \tag{1}$$

where K is the fluid consistency index and n is the flow behavior index. For laminar flow, the fanning friction factor f is obtained by Equation (2):

$$f = \frac{2 \cdot \tau_w}{\rho \cdot v^2} \tag{2}$$

where the wall shear stress τ_w can by calculated according to Böhme (2000) and Chhabra & Richardson (2008):

$$\tau_w = K \cdot \left[\frac{Q}{\pi R^3}\left(\frac{3n+1}{n}\right)\right]^n \tag{3}$$

In contrast to Herschel-Bulkley based equations applied in Slatter (2004, 2008), friction loss equations based on a simple power law relationship between shear rate and shear stress are independent of pipe wall roughness k, both for laminar and turbulent flow (Annen 1961; Chhabra & Richardson 2008). For turbulent flow, the fanning friction factor f is obtained according to Dodge & Metzner (1959):

$$\frac{1}{\sqrt{f}} = \left(\frac{4}{n^{0.75}}\right) \cdot \log\left(Re_{MR} \cdot f^{1-(n/2)}\right) - \frac{0,4}{n^{1.2}} \tag{4}$$

where the Metzner and Reed Reynolds Number Re_{MR} is calculated according to Metzner & Reed (1955):

$$Re_{MR} = \frac{v^{2-n} \cdot D^n \cdot \rho}{8^{n-1} \cdot K \cdot ((3n+1)/4n)^n} \tag{5}$$

Re_{MR} depends on the average velocity v, pipe diameter D and the rheological properties of the sludge. It shows a positive correlation with v and D; and a negative correlation with TSS. As sludge becomes progressively more fluid with increasing temperature (Baudez *et al.* 2013), Re_{MR} also shows a positive correlation with temperature. In analogy to Newtonian liquids, the flow regime of sludge depends on the magnitude of Re_{MR}. For Chhabra & Richardson (2008) an acceptable approximation of $Re_{MR,krit}$ is 2,000–2,500.

MATERIALS AND METHODS

Sludge samples

The samples of WAS were obtained from the first stage of Vienna's main WWTP, where the sludge age is 1.5–2 d. To remove larger particles, the samples were sieved (1.5 × 20 mm). The removed fraction was <0.25 wt%. For reasons of homogenization, samples were briefly shaken (by hand; for 3 seconds) directly prior to filling the measuring system. WAS samples with different TSS were derived from one single sludge sample in order to exclude other impact factors than TSS. The initial TSS of 1.8% was concentrated to higher TSS by using a centrifuge (Sigma 3–16 L; 4,200 rpm; 3–5 min). A total of 10 WAS samples with TSS ranging from 1.8–6.2% was measured. The experiments were conducted at temperatures of both 8 °C and 20 °C, representing the minimum and maximum water temperatures in the activated sludge tank. TSS concentrations of the measurement series at 8 °C (1.8/2.7/3.6/5.4/6.0%) deviate slightly from TSS concentrations at 20 °C (1.9/2.9/3.9/4.8/6.2%).

In contrast to WAS samples, which only vary in TSS, the properties of raw and digested sludge samples represent the rheological variability of sludge from Vienna's main WWTP treatment plant when operated over a period of approximately one year. Raw sludge, a mixture of WAS and PS plus polymer addition for thickening, was sampled in the outlet of a pilot scale excess sludge thickener between April 2013 and June 2014. In front of the mechanical excess sludge thickening, WAS and PS were settled together in the existing static thickener of Vienna's main WWTP. The mixing ratio WAS/PS of raw sludge was estimated based on the incoming TSS loads of WAS and PS to the static thickener. On a yearly average, the mixing ratio WAS/PS of the raw sludge was 50/50. However, due to different weather conditions and operational reasons, the percentage of PS ranged from 40 to 60%. The polymer used (ACAT: FlocStar 214 L) is a cationic flocculant with a very high charge and a high molecular weight (active substance: ethoxylated isotridecanol). The dosage of polymer added at the excess sludge thickener was varied between 1 and 4 kg active substance/t TSS. To remove larger impurities, raw sludge samples were sieved (1.5 × 20 mm) and the removed fraction was <0.5 wt%. For reasons of homogenization, samples were briefly shaken directly prior to filling the measuring system. Furthermore, the time delay between sampling and measurement had to be carefully controlled since exceeding a delay of 6 hours led to relevant changes in the structure of the polymer and thus to an underestimation of the actual viscosity and the shear stress of raw sludge. Therefore, the delay due to transport, sample preparation and measuring procedure was kept between 3 and 6 hours. The experiments were conducted at temperatures between 8 °C and 40 °C in order to get information about the impact of temperature on shear stress and friction loss of raw sludge. A total of 21 raw sludge samples with TSS ranging from 6.0–8.1% was measured. However, as the pilot scale plant was fed with a raw sludge TSS of about 7 to 8% most of the time, most of the raw sludge samples show a TSS between 7 and 8% ($n = 15$) and fewer samples show a TSS between 6 and 7% ($n = 6$).

Digested sludge was sampled at the outlet of a 130 m^3 high TSS pilot plant digester located in the treatment plant. The treatment before filling the measuring system (sieving, shaking) was similar to the treatment of WAS samples. For digested sludge, all experiments were conducted at 38 °C, representing the typical temperature for anaerobic digestion. A total of nine digested sludge samples with TSS ranging from 3.2–4.6% was measured between April 2013 and June 2014. The first five digested sludge samples were investigated at a solids retention time (SRT) of 25 d, while the remaining four samples were investigated at an SRT of 20 d.

Rheological measurements

The friction loss calculation of sludge is based on flow curves (=the relationship between shear rate $\dot{\gamma}$ and shear stress τ) which are obtained by means of rheological measurements. The measurements were carried out with an Anton Paar Physica MCR 301 rheometer equipped with concentric cylinder geometry CC39 (measuring gap 1.638 mm, Searle system). For temperature control, the tempering cylinder C-LTD180/XL was used. Based on the experiments of Moshage (2004), the procedure was conducted as follows: within a period of 180 s, the shear rate was increased to a maximum of 500 s^{-1}, held constant for 300 s, and finally was decreased to 0 s^{-1} within a period of 180 s. The upward ramp of the flow curve represents unstressed sludge and is used for further calculations. Each upward ramp consist of 180 shear rate/shear stress data points. At a number of three replicates and under repeatability conditions as defined in DIN ISO 5725-1 (1994), the mean value of the relative standard deviation of all 180 data points was <2% for WAS and digested sludge and <5% for raw sludge. The maximum values of the relative standard deviation, which in most cases occur at low shear rates, came to <5% for WAS and digested sludge and to <10% for raw sludge. The number of replicates per measurement was set to two for WAS and digested sludge and to three for raw sludge. Power-law modeling was carried out with the mean values of the replicates.

Differential pressure measurements

For the validation of the friction loss calculations based on rheological measurements, differential pressure measurements at a rheological test track were carried out (Figure 2).

The test track was a circular pressure hose (TORONTO HED; $L = 40$ m; $D = 50$ mm; material: styrene-butadiene rubber (SBR) with fabric inserts and steel wire helix, smooth wall; http://www.bebeflex.at/toronto.htm). The friction loss was determined with pressure sensors at the beginning and end of the test track. For pumping, an eccentric pump with a maximum flow rate of 16 $m^3 h^{-1}$ was used. The volume of the storage tank for the sludge was 5 m^3. Each flow rate (resp. velocity) was set for 2 to 5 minutes, carrying out pressure and flow rate measurements each 6 seconds. Hence, the number of measurement replicates was between 12 and 30 for each velocity. The relative standard deviation ranged between 1 and 3% for the flow rate and between 1 and 5% for the differential pressure. The mean values of the measurement data were used for the validation of friction loss calculations. The validation process was fraught with the following uncertainties:

i. 0.5 L sample out of a 5 m^3 storage tank
ii. time delay sampling/measuring → structural change of polymer (only for raw sludge)
iii. sample is sieved, and then shaken directly before measurement
iv. deviations due to using a simple power law shear stress/shear rate model
v. deviations due to shear stress peak of the flow curves (only for raw sludge, see Figure 3(a))
vi. circuit test track instead of straight test track
vii. deviations in diameter of test track: ± 1 mm

Due to these uncertainties, it is an important additional aspect whether the rheological measurements are validated on a rheological test track.

RESULTS AND DISCUSSION

Power law modeling

The relevant parameters (K, n) for friction loss calculations are to be gained from the shear stress/shear rate relationship of the upward ramp of flow curves. In Figure 3, power law

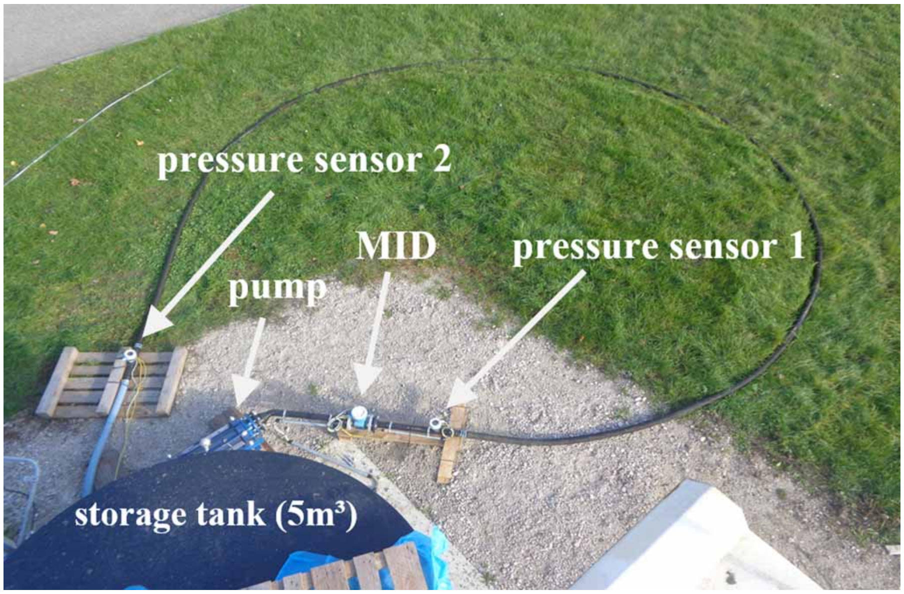


Figure 2 | Rheological test track – pressure hose $D = 50$ mm, 2 pressure sensors, electromagnetic flow meter (MID), eccentric pump, storage tank 5 m^3.

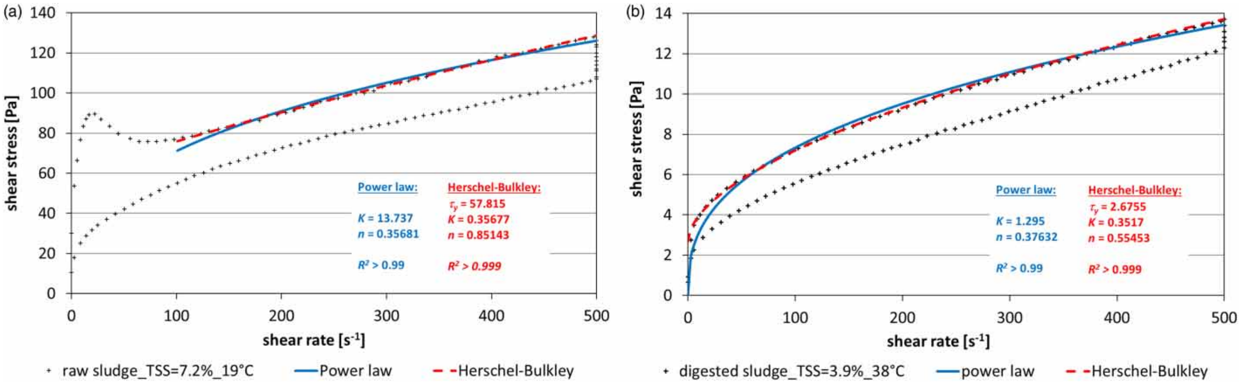


Figure 3 | Power law modeling compared to Herschel-Bulkley modeling – (a) raw sludge (TSS = 7.2%; T = 19 °C) and (b) digested sludge (TSS = 3.9%; T = 38 °C).

modeling of the upward ramp of a raw sludge sample with 7.2% TSS (a) and a digested sludge sample with 3.9% TSS (b) is compared to Herschel-Bulkley modeling. Since the upward ramps of raw sludge show a characteristic peak shear stress at low shear rates, the models were not evaluated below a shear rate of 100 s^{-1} (Figure 3(a)), whereas for digested sludge they could be evaluated over the entire range of 0–500 s^{-1} (Figure 3(b)). Both Herschel-Bulkley and power law modeling show good results. However, Herschel-Bulkley modeling ($R^2 > 0.999$) shows a slightly better correlation than power law modeling ($R^2 > 0.99$) for both raw and digested sludge. This can be explained by the yield stress behavior ($\rightarrow \tau_y$) of sewage sludge.

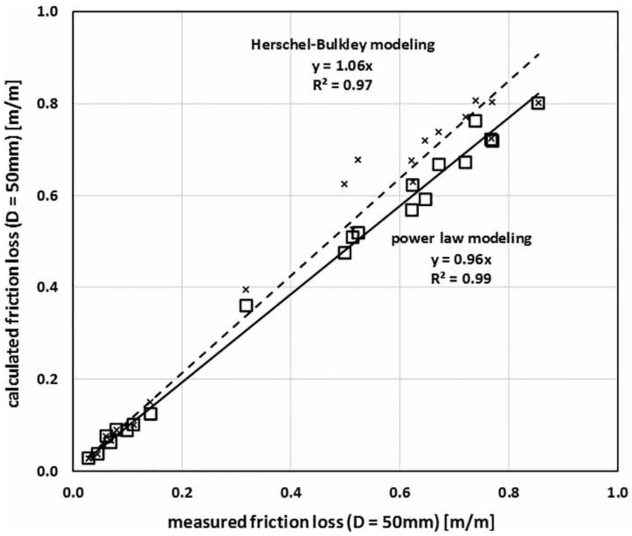
Compared to sludge with 1–2% TSS, the rheological properties of sludge with high TSS significantly differ from water. Depending on the shear rate (500 s^{-1} to 0 s^{-1}), the shear stress – as well as the dynamic viscosity – of raw sludge with 7.2% TSS is approximately 200 to 10,000 times higher than water. The shear stress and the dynamic viscosity of digested sludge with 3.9% TSS is approximately 40 to 1,500 times higher than water, which has a major impact on friction loss, pipe dimensioning and pumping.

Friction loss calculation: validation of power-law modeling

Friction loss calculation based on a power law relationship between shear rate and shear stress according to Equations (1)–(5) was validated by differential pressure measurements at the rheological test track. For comparison, friction loss calculations based on the more complex Herschel-Bulkley model were also accomplished. For the validation, the same modeling-approach was applied to 21 different 'physical states' of sewage sludge, differing in sludge type, TSS, temperature and velocity (Figure 4). Both power law modeling ($R^2 = 0.99$) and Herschel-Bulkley modeling ($R^2 = 0.97$) show high coefficients of determination. However, power law modeling (k = 0.96) tends to underestimate, while Herschel-Bulkley modeling (k = 1.06) tends to overestimate the friction loss measured at the rheological test track (Figure 4). Nevertheless, considering the inherent uncertainties of the validation process (see above), the results proved the applicability of power law modeling for friction loss calculations regarding design purposes of high TSS sludge digestion.

Shear stress and friction loss of WAS and raw sludge with high TSS

According to literature (data in Figure 1) the relationship between TSS and shear stress could be approximated with an exponential law for both WAS and raw sludge. WAS samples at 8 ° and 20 °C were derived from one single sludge sample, where only TSS was varied. The data of this investigation show a high correlation coefficient ($R^2 > 0.99$) as reported in literature. In contrast to that, raw sludge measurements were conducted with different sludge samples taken over a period of approximately one year, representing the variability of real operating conditions encountered in the full-scale plant. This resulted in a markedly lower correlation ($R^2 \geq 0.80$), and also a high shear stress variability was determined for samples with similar TSS (Figure 5(a)). This can mainly be attributed to the variable mixing ratio WAS/PS of raw sludge. The following relationship could be identified: the higher the share of PS, the lower the shear stress. This is exemplified in Figure 5(a) for two raw sludge samples with 8% TSS and a temperature of 30–40 °C that only differ in the percentage



	sludge	TSS	T	v
	[-]	[%]	[°C]	[m s^{-1}]
1	RawS	8.0	17	0.21
2	RawS	8.0	17	0.31
3	RawS	8.0	17	0.44
4	RawS	8.0	17	0.54
5	RawS	7.5	18	0.37
6	RawS	7.5	18	0.78
7	RawS	7.5	18	1.19
8	RawS	7.5	18	1.64
9	RawS	7.5	18	2.05
10	RawS	7.2	19	0.25
11	RawS	7.2	19	0.42
12	RawS	7.2	19	0.66
13	RawS	7.2	19	0.96
14	DS	3.9	38	0.85
15	DS	3.9	38	1.31
16	DS	3.9	38	1.77
17	DS	3.9	38	2.21
18	DS	3.2	38	0.53
19	DS	3.2	38	1.04
20	DS	3.2	38	1.56
21	DS	3.2	38	1.99

Figure 4 | Validation of power law modeling (□) and Herschel-Bulkley modeling (☒) by differential pressure measurements at the rheologic test track – 21 data points differing in sludge type (RawS/DS), TSS (8.0%/7.5%/7.2%/3.9%/3.2%), temperature (17 °C/18 °C/19 °C/38 °C) and velocity (0.21–2.21 m s^{-1}); Herschel-Bulkley modeling according to Slatter (2008).

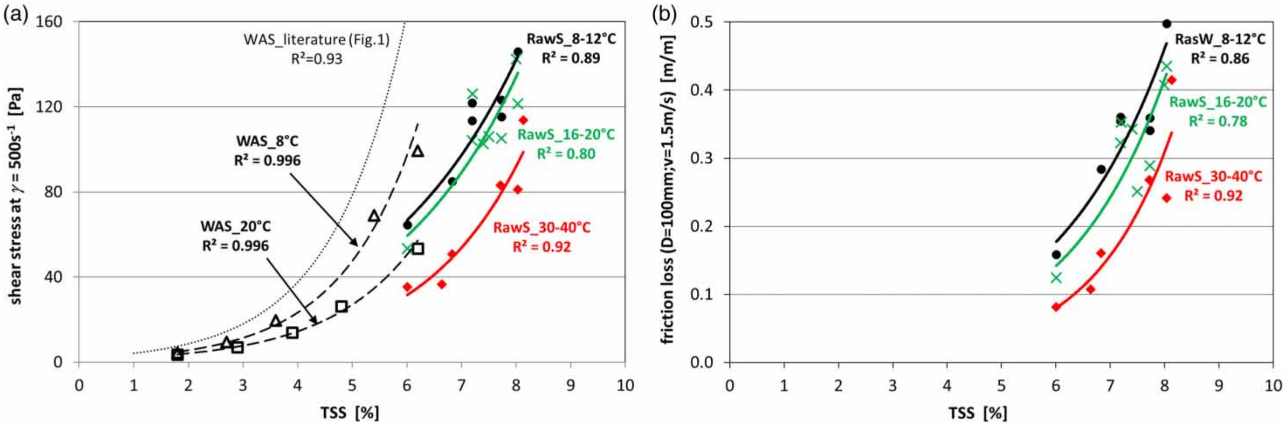


Figure 5 | (a) TSS vs. shear stress of WAS and RawS at $\dot{\gamma} = 500$ s^{-1} (exponential modeling) and (b) TSS vs. friction loss of RawS (exponential modeling).

share of PS. At a PS share of approximately 60% the shear stress is 80 Pa, at a PS share of approximately 40% the shear stress is 115 Pa. This is in accordance with Markis *et al.* (2013), who showed that the viscosity and consequently, the shear stress of raw sludge decreases by a factor of 5 when increasing the share of PS from 20 to 80%. Furthermore, PS has a very heterogeneous nature (Bhattacharya 1981). This is likely to be an additional impact factor regarding the rheological variability of different raw sludge samples with similar TSS. Nevertheless, TSS shows a major influence on the shear stress of raw sludge. On average, the shear stress of raw sludge with 8% TSS is about twice as high compared to 6% TSS (Figure 5(a)).

The influence of temperature on the shear stress of WAS and raw sludge is demonstrated, showing an inverse correlation (Figure 5(a)). The significantly lower shear stress of WAS compared to the assessed literature can be attributed to the low sludge age (1.5–2 d) of the measured WAS (Füreder 2013). In the investigated WWTP, the sludge age of 1.5–2 days corresponds to a very low development of filamentous bacteria and a low sludge volume index <100 mL g^{-1}, respectively. As reported by Klinksieg (2010), a low sludge volume index corresponds to low shear stress.

In analogy to shear stress, TSS has a major influence on the friction loss of raw sludge. The friction loss of raw sludge with 8% TSS appears to be approximately two to three times higher than with 6% TSS (Figure 5(b)). This is shown exemplarily for a pipe with $D = 100$ mm, $v = 1.5$ m/s and a raw sludge temperature of 16–20 °C. Increasing the TSS from 6 to 8%, results in an increase of friction loss from 0.15 to 0.45 (Figure 5(b)). The TSS/friction loss correlation can be approximated by an exponential equation for all three temperature classes ($R^2 \geq 0.78$). The influence of temperature on friction loss is similar to its influence on shear stress. The variability of friction loss for samples with about the same TSS is also similar to the situation with shear stress (Figure 5(b)).

Shear stress and friction loss of digested sludge with high TSS

Digested sludge samples were taken at the pilot plant over a period of approximately one year, representing real operating conditions. For the evaluation, the sludge samples were split into two data sets: samples with SRT = 25 d and samples with SRT = 20 d. The shear stress of the samples is in the same order of magnitude as in the literature. The relationship between TSS and shear stress could be approximated with an exponential law for both digested sludge data sets (Figure 6(a)). However, digested sludge samples with 20 d SRT show a higher shear stress and friction loss than samples with 25 d SRT (Figure 6(a) and 6(b)). This is consistent with Dai *et al.* (2014) and Monteiro (1997), who found that the shear stress of digested sludge stands in inverse correlation to SRT.

Furthermore, the impact of SRT overlaps with the impact of loss on ignition (LOI). Samples with approximately 62 to 66% LOI mostly show higher shear stress and friction loss than samples with approximately 58 and 62% LOI (Figure 6(c) and 6(d)), which is consistent with the research of Skinner *et al.* (2015), Moshage (2004) and Klinksieg (2010). Skinner *et al.* (2015) reported a strong negative correlation between LOI and dewaterability of digested sludge. So the higher the LOI, the lower the dewaterability. In turn, Moshage (2004) and Klinksieg (2010) found that low dewaterability of digested sludge strongly correlates with high shear stress. Based on these publications and the results shown in

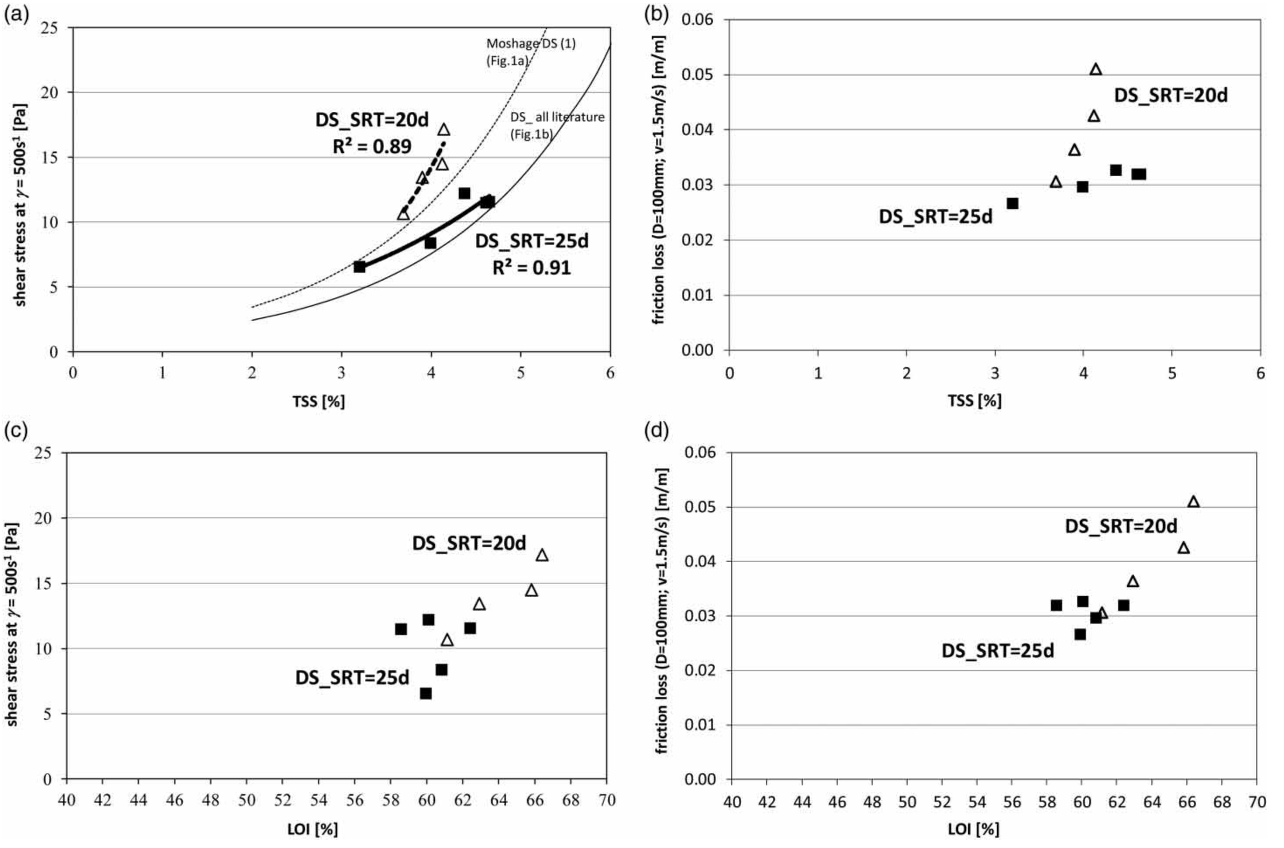


Figure 6 | Digested sludge (T = 38 °C) with TSS ranging from 3.2–4.6% – (a) TSS vs. shear stress at $\dot{\gamma} = 500\ \mathrm{s}^{-1}$, (b) TSS vs. friction loss, (c) LOI vs. shear stress at $\dot{\gamma} = 500\ \mathrm{s}^{-1}$, (d) LOI vs. friction loss.

Figure 6(c), it can be concluded that increased LOI of digested sludge correlates with an increase in shear stress.

Flow regime of raw and digested sludge with high TSS

The flow regime of sewage sludge depends on Re_{MR}. Re_{MR} depends on pipe diameter D, average velocity v and the rheological properties of the sludge (K, n) (see Equation (5)). The higher v and D, the more likely is turbulent flow. Calculations for 13 different samples show that the flow regime of raw sludge with 7–8% remains laminar ($Re_{MR} < Re_{MR,krit}$) even at high average velocity of $v = 3\ \mathrm{m\ s^{-1}}$ and a large pipe diameter of $D = 0.50\ \mathrm{m}$ (Figure 7(a)).

Raw sludge with 7–8% TSS results in a digested sludge TSS of approximately 4%. For digested sludge with 4% TSS, the flow regime can be either laminar ($Re_{MR} < Re_{MR,krit}$) or turbulent ($Re_{MR} > Re_{MR,krit}$). Depending on pipe diameter and sludge properties, a stable turbulent flow regime can only be reached at high velocities of 2–3 m/s (Figure 7(b)).

CONCLUSIONS

The current case study on the rheological behavior of raw and digested sewage sludge with high TSS concentrations was an indispensable part within the design of the 4 M PE_{120} high TSS digestion plant under construction at Vienna's main WWTP, to be operational in 2020. It emphasizes the importance of comprehensive rheological considerations, measurements and calculations when designing a sludge digestion with high TSS. In accordance with literature, TSS proved to have an exponential influence on the rheological behavior of raw sludge. Hence, increasing TSS from 6 to 8% at least doubles the shear stress of raw sludge, having major effects on pipe dimensioning and pumping. The correlation between TSS and friction loss could be approximated with an exponential function as well. However, under the real operating conditions simulated at the pilot plant, the impact of TSS on raw sludge rheology is overlapped by the impact of the mixing ratio WAS/PS. The higher the share of PS, the lower the shear stress. For digested sludge, the exponential correlation between TSS and shear stress is overlapped by the influence of SRT and LOI. Digested sludge with 20 d SRT and approximately 64% LOI mostly showed higher shear stress and friction loss than digested sludge with 25 d SRT and approximately 60% LOI.

Within the case study, friction loss calculations based on a simple power law relationship between TSS and shear stress could be validated for raw and digested sludge with high TSS. For friction loss calculations, the flow regime is of high importance. Raw sludge with 7–8% TSS has a strictly laminar behavior, even for a high average velocity of $3\ \mathrm{m\ s^{-1}}$ and a large pipe diameter of 0.5 m. Digested sludge with approximately 4% TSS showed either laminar or turbulent behavior depending on flow velocity and pipe diameter.

Flow regime and head loss predictions of digested sludge is a complex matter depending on many parameters changing over time, such as TSS, SRT, LOI and temperature. In this regard, the influence of SRT and LOI needs to be further elucidated. Regarding raw sludge rheology, the influence of the mixing ratio WAS/PS needs further investigations. Moreover, the impact of sludge age,

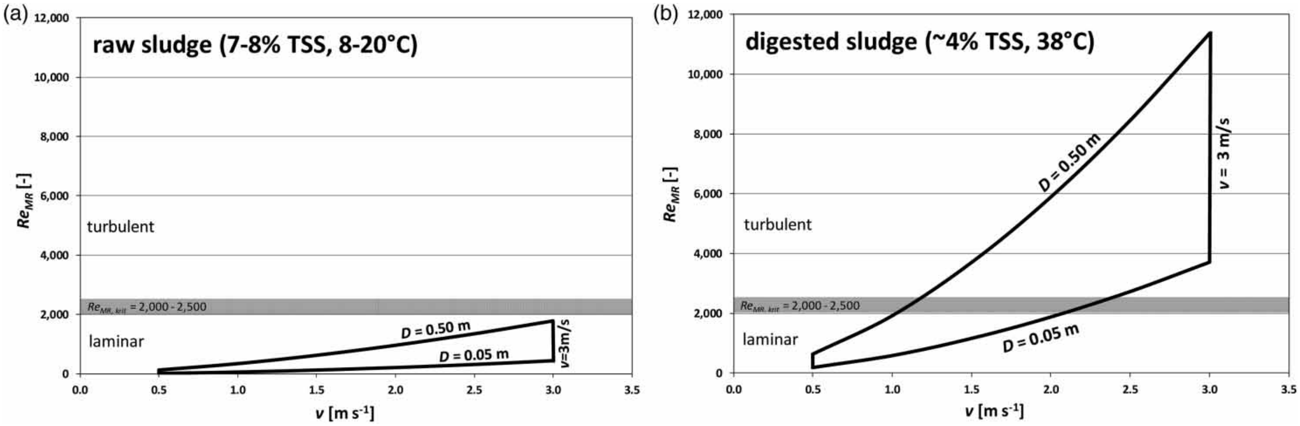


Figure 7 | RE_{MR} as a function of v ($0.5–3.0\ \mathrm{m\ s^{-1}}$) and D (0.05–0.50 m) – (a) raw sludge: calculated with 13 different samples (TSS = 7–8%; T = 8–20 °C) and (b) digested sludge: calculated with six different samples (TSS = 3.8–4.6%; T = 38 °C).

extracellular polymeric substances and sludge thickening properties on the rheology of raw sludge needs to be investigated.

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