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WASTEWATER SLUDGE PIPELINE PREDICTIONS USING CONVENTIONAL VISCOMETRY AND ULTRASOUND BASED RHEOMETRY

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To optimise the design and operational management of wastewater treatment plants (WWTP's) there needs to be an understanding of the viscous properties of wastewater sludges, which at higher concentrations become non-Newtonian. Worldwide, there is more and more pressure to attain higher sludge concentrations which complicates mixing and pumping. Pipeline design at higher concentrations also requires prior knowledge of sludge rheology. The comparison of the rheological parameters of wastewater sludge world-wide has been hampered due to different rheological measurement techniques and interpretation of results used. For the past seven years wastewater sludges have been rheologically characterised in Sweden and in South Africa, using the same tube viscometer. Seventy-six sludges were tested in tube and rotary viscometers at 16 WWTPs in Sweden and South Africa with solids concentrations ranging from 2 to 8%. A correlation could be obtained of the rheological parameters as a function of sludge concentration. In addition to this, a real-time in-line fluid visualisation and characterisation system, was also used to determine the rheology of the sludge. Three wastewater sludge concentrations were rheologically characterised using the Flow-Viz system and a conventional tube viscometer. It is demonstrated that a significant effect on pressure drop predictions occurs when using results from the Flow-Viz system compared to tube viscometry, which is mainly due to more accurate determination of the yield stress. This work provides confidence for the pursuit of the development of a universal correlation for sludge rheological parameters using in-line real time rheological parameters for improved pipeline design.

KEY WORDS: rheology, waste water sludge, non-Newtonian, pressure drop prediction.

1. INTRODUCTION AND BACKGROUND

With increase in solids concentration wastewater sludges become viscous and exhibit complex non-Newtonian behavior which effects designing plants which contain mixing, pumping and pipeline elements. Large variations in sludge properties also exist depending on the type of process used.

Heywood et al. (2010) conducted an extensive study on primary digested and thermally-hydrolyzed digested sludge in the UK to evaluate pump suction and discharge pressures as a function of sludge concentration and rheological parameters. For rheological characterization, they used a rotary viscometer utilizing the infinite-sea approximation with various bob sizes to suit different concentration sludges to obtain the associated shear rates in the actual existing pipelines. Solids concentrations (w/w%) ranged from 3.3% to 7.6%, exhibiting shear thinning behavior. The shear rate in the 387 mm internal diameter pipe was estimated at 50 s^{-1}. For discharge pressure predictions the actual pipeline of 13.1 km where sludges were sampled was used. Sludge concentration > 5% resulted in significantly higher predicted pressures than what the pumping system could handle. Mixtures of different sludges resulted in lower predicted pressure drops, probably due to rheological behavior of the mixed sludge.

Eckstädt et al. (2013) in Poland rheologically characterized wastewater sludges ranging from 1.22% to 5.30%. A coaxial cylinder rheometer was used. The sludge displayed viscoplastic behavior, was characterized by the Herschel-Bulkley model with yield stress values ranging from 0.13 to 3.9 Pa. Although Heywood et al. (2011) used the power-law model to describe their sludge behavior, visual inspection of the flow-curves clearly shows the existence of a yield stress at the range of the shear rates obtained while 75% of the yield stresses obtained by Eckstadt et al. (2013) were less than 1 Pa and as low as 0.1 Pa. The effect of the existence and importance of the yield stress has been debated and argued (Barnes and Walters, 1985; Barnes, 2007). Due to the variations in rheological measurement procedures and the pipeline pressure prediction approaches, data could not be compared.

Currently no universal correlation of the rheological properties as a function of solids concentration of wastewater sludges exists, making it difficult to predict pipeline pressure drop as, the viscous properties changes significantly with concentration.

For the past seven years this group has been studying the rheology of wastewater sludges both in Sweden and in South Africa using the same tube viscometer to compile a database for engineers for efficient pipeline and pump system design. Using the initial database, Haldenwang et al., 2012 attempted to provide a pipe flow pressure drop prediction model relating friction factor to non-Newtonian Reynolds number using a composite power law relationship.

This database was recently extended with additional results obtained with a rotary viscometer.

The objectives of this work were to: (a) Evaluate if a single relationship between Bingham rheological properties (yield stress and viscosity) and solids concentration could be obtained for sludge samples from different countries. (b) Evaluate how the degree of variation in rheological properties can affect the pressure drop prediction in pipelines based on rheological properties of 76 sludges tested both locally and in Sweden. (c) Evaluate the effect of real-time in-line rheological measurement in comparison to the off-line measurements on the pressure drop predictions.

2. EXPERIMENTAL

Three methods were used to rheologically characterise the wastewater sludges

A **rotary viscometer** (Anton Paar MC-1) with a 50 mm diameter cup and measuring cylinder attachment with a 2 mm gap which can measure both torque and speed was used.

A portable **tube viscometer** used consisted of 1100 L mixing tank, ITT Flygt 4.2 kW 4/3 submersible centrifugal pump fitted with an ABB variable speed drive. Three tubes of

63.6, 52.6 and 26.8 mm ID were linked to the pump and each pipe was fitted with high and low range differential pressure transducers and flow rates were measured with a 25 and 50 mm electromagnetic flow meter. The laminar flow pressure drop and flow rate measurements in laminar flow were used to construct flow curves and establish rheological parameters. (Haldenwang et al., 2010).

A non-invasive industrial rheometric system, called Flow-Viz was developed by SP – Technical Research Institute of Sweden and CPUT – South Africa. The system is based on a Pulsed Ultrasound Velocimetry and combine Pressure Difference (UVP+PD) measurement technique (Kotze et al., 2014, 2015; Wiklund et al., 2014). The pipe rig used was slightly modified from the one described in the previous section. The rig consisted of two (PVC) pipes with ID of 63.2 and 22.5 mm. A stainless steel pipe (316L) with an inner diameter of 48.4 mm was used for the non-invasive UVP+PD tests. Only the larger pipes (63.2 and 48.4 mm) were used for tube viscometry tests. A non-invasive ultrasound sensor unit was installed onto the 48.4 mm stainless steel pipe for in-line measurements. A pressure difference measurement is used in combination with the velocity profile to determine shear viscosities and rheological parameters such as yield stress. More information regarding the UVP+PD methodology can be found in Wiklund et al. (2007). The system is shown in Fig. 1.

Fig.1a Operator's panel and User Interface

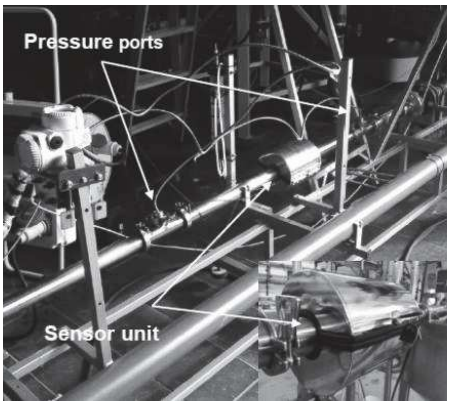

Fig.1b experimental flow loop with UVP+PD sensor unit installed

<u>Materials tested</u>

The sludges reported in this work are from the following wastewater treatment plants (WWTP) and the year of study showing concentrations as w/w:

- 8 from a WWTP in Stockholm ranging in solids concentration from 3.4-7.1% (2007)
- 21 from 6 WWTP's in the Cape Town area ranging in solids concentration from 2-7.8%, (2013)
- 4 from 3 WWTP's in the Boland area ranging in solids concentration from 3-4.7% (2013)
- 43 from 4 WWTP's in the Cape Town area ranging in solids concentration from 3-7.8% (2015)
- Secondary sludge filter cake from a filter belt press at Potsdam wastewater treatment plant (WWTP) was diluted to 3 concentrations (6.8%, 5.1% and 4.3%.) and were tested in the tube viscometer fitted with the UVP+PD system.

Sludges included both primary and secondary types. Sludges were tested in the portable tube viscometer or in some cases in a rotary viscometer.

3. RESULTS AND DISCUSSION

3.1. SLUDGE RHEOLOGY AND PRESSURE DROP PREDICTIONS

To describe the rheology of the sludges, the Bingham model was used as shown in Equation 1.

$$\tau = \tau_y + K\dot{\gamma}\,, \tag{1}$$

where τ is the shear stress, τ_y the yield stress, K the fluid consistency index or Bingham viscosity and $\dot{\gamma}$ the shear rate. Both yield stress and viscosity vary with solids concentration for wastewater sludges (Chhabra and Richardson, 1998).

For laminar flow of non-Newtonian fluids in pipes Govier and Aziz (1972) developed a model which can be adapted for Bingham fluids. For turbulent flow the Reynolds number developed by Slatter (1994) was used based on the Clapp Reynolds number. The rheological parameters τ_y and K of all 76 sludges are plotted against solids concentration in Figs 2 and 3.

The rheological properties vary considerably over the range of concentrations. If this would be used for predicting the pressure drop in a 250 mm pipeline of 10 km for 40 and 70 l/s flow rate the variation in head loss and power would differ significantly. For a 4% solids concentration sludge, the variation in yield stress and viscosity extracted from Fig 2a and Fig 2b respectively are presented in Table 1.

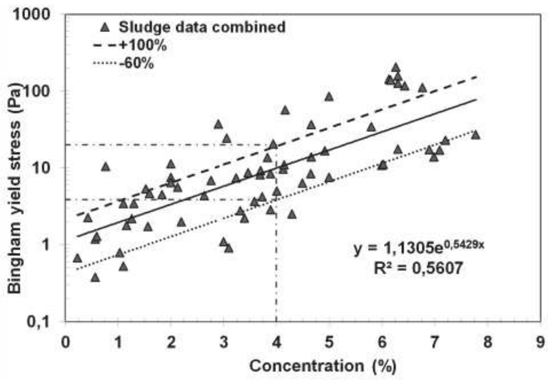

Fig.2a Bingham yield stress of all sludges

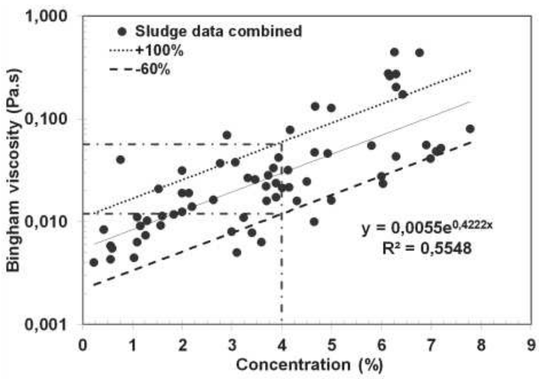

Fig.2b Bingham viscosity of all sludges

Table 1

Variation in rheological properties for a 4% sludge.

Description	Solids Concentration (%)	Yield stress τ_y(Pa)	Bingham viscosity K (Pa)
WWTP sludge (Max rheology)	4%	20	0.0568
WWTP sludge (Minrheology)	4%	3.85	0.012

When these properties are used to predict head-loss and power required as shown on the system curve (Fig. 4), the variation is quite dramatic. The results are shown in Table 2. If pump curves and head-loss calculations for water were used the results would be completely wrong. It can also be seen that for 4% sludge at these flow rates there is a good chance that the flow will be laminar due to the viscous character of the sludge. A similar calculation was presented in (Haldenwang et al., 2015).

Table 2

Head loss variation for case study of a 4% sludge.

Description	Point	Lam/Turb	Head loss (m)	Power kW)
Water 40 l/s	A	Turbulent	22	8.7
Water 70 l/s	D	Turbulent	75	52
4% Sludge (min rheology 40 l/s)	B	Laminar	88	35
4% Sludge (max rheology 40 l/s)	C	Laminar	450	178
4% Sludge (min rheology 70 l/s)	E	Turbulent	120	83
4% Sludge (max rheology 70 l/s)	F	Laminar	485	336

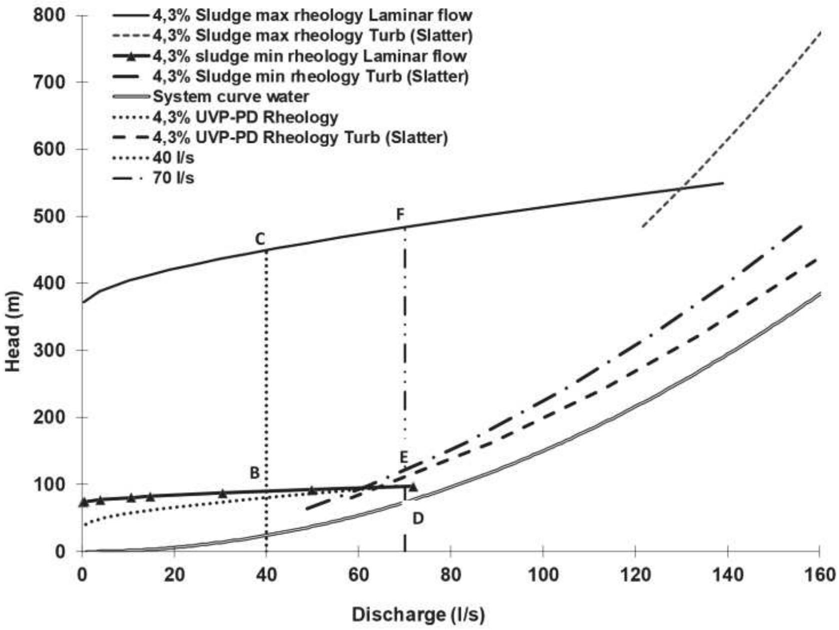

Fig.3 System curve of case study with 4% sludge

3.2. UVP+PD RHEOLOGY OF WASTEWATER SLUDGES

Figure 4 shows the Doppler spectra and velocity profile measured in 6.8% sludge. All measurements were conducted in laminar flow. From Fig. 4 it can be seen that a plug is present due to a yield stress. The plug radius was directly measured and together with the pressure drop the yield stress was determined, (Berta et al., 2016). Similar velocity profiles were measured in the other sludge concentrations.

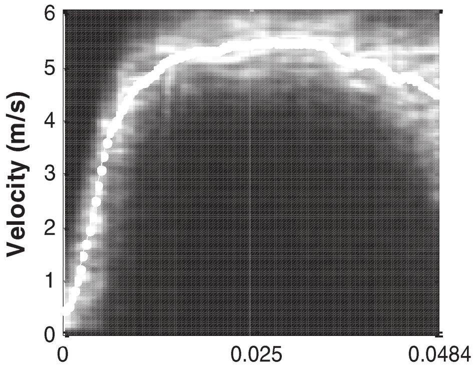

Fig.4 Velocity profile measurement in 6.8% sludge, flow rate 5 l/s; (Kotzé et al., 2015).

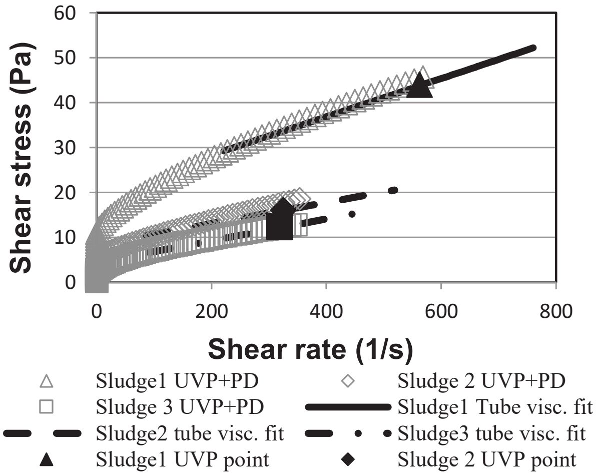

Fig.5 Velocity profile measurement and sludge rheology comparison using UVP+PD; comparison between tube viscometry model fit and UVP+PD (Kotzé et al., 2015).

Figure 5 illustrates that the UVP+PD method is able to detect variations in viscosity and shear thinning behavior due to changes in solids concentrations. There is good agreement between the two methods over the same shear rates. The complete flow curve is measured at one flow rate using the UVP+PD method which is a major advantage. If the tube viscometer were used as an in-line instrument only the single points on each graph would be obtained which are shown by the three black markers. Table 3 shows the summary of rheological parameters obtained using conventional tube viscometry and UVP+PD. The major difference between the two methods used is evident in the yield stress values determined by linear fitting (tube viscometry) and direct measurement (see Section 2). There was no tube viscometer data available in the low shear rate region (< 200 s^{-1}) due to pumping limitations and therefore a Bingham plastic behaviour was assumed (n = 1).

It can be seen from the flow curves in Fig. 5 that the Herschel-Bulkley model better describes the rheology due to the fact that lower shear rates can be obtained. When the Herschel-Bulkley rheology values are used for head loss predictions and this is compared to that obtained by the tube viscometer, the differences are significant. The results in Fig. 6 show that in laminar flow the predictions using the UVP+PD method are significantly lower due to the lower, in our opinion more accurate and direct measurement of the yield stress.

Table 3

Summary of rheology results of Potsdam WWTP secondary sludge: comparison between UVP+PD and tube viscometer (Kotzé et al., 2015).

Sludge solids concentration	UVP+PD			Tube viscometry			
	K	n	τ_y	K	n	τ_y	τ_y difference
(%)	(Pa.s)	(-)	(Pa)	(Pa.s)	(-)	(Pa)	(%)
6.8	0.420	0.70	10.89	0.0426	1	19.80	82
5.1	0.126	0.78	4.77	0.0230	1	8.43	77
4.3	0.340	0.59	2.00	0.0242	1	4.40	120

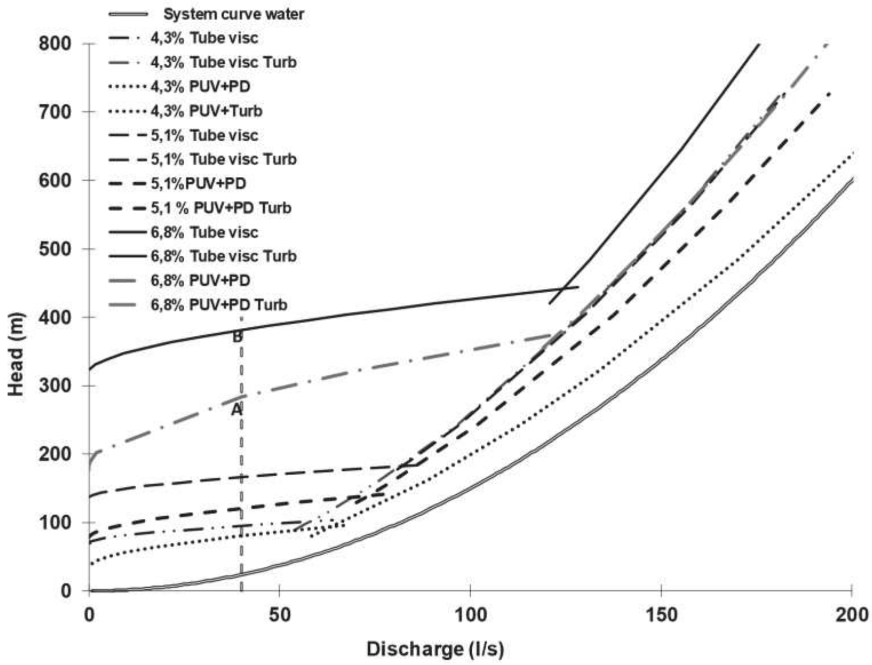

Fig.6 Comparison of head-loss predictions using Tube viscometer and UVP+PD rheology

For the 6.8% sludge, at 40 l/s discharge from A-B this resulted in a difference of 34% in head loss and power. In turbulence, the Bingham viscosities are not very different when measured in the tube viscometer and therefore the turbulence predictions are closed banded. The UVP+PD predictions show a steadier increase in head in the turbulent region as the viscosity increases.

4. CONCLUSIONS

Seventy-six sludges were rheologically characterised using the Bingham plastic model with a solids concentration ranging between 2 to 8%. The scatter in data is in line with findings by other researchers. A relationship between Bingham yield stress and viscosity and solids concentration for intercontinental sludge samples was obtained.

It was shown that the Flow-Viz technology can measure the rheological properties of complex fluids such as wastewater sludges.

The yield stress measurements obtained by the Flow-Viz system is more accurate as this is not a fitting parameter but is directly determined from the plug radius. For tube viscometry the value of the yield stress depends very much on the shear rate range that can be measured which depends on the tube diameters available. Rotary viscometry on the other hand is an off-line method and samples are not always representative of the actual fluid rheology due to different shearing and solids settling in the attachment such as cup and bob or parallel plate. The head loss results obtained from the two methods varies significantly and it is our opinion that those obtained using the UVP+PD method is more accurate as it is a direct measurement from which the rheological measurements are obtained. This work shows that there is merit in pursuing a universal correlation for sludge rheology as a function of solids concentration based on real-time in-line rheological measurements under plant conditions.

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