PRESSURE DROP PREDICTION FOR EFFICIENT SLUDGE PIPELINE DESIGN

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

BACKGROUND AND MOTIVATION

Head loss data for wastewater treatment sludge is not available in standard design tables and is therefore mostly estimated. The more highly concentrated the sludges becomes, the more non-Newtonian the flow behaviour is and the higher the pressure drop or energy required to transport the sludge. There is still no widely accepted design correlation of sludge viscous properties as a function of solids content, causing frustration to design engineers who, in the absence of obtaining costly rheological data, have to make estimates which could compromise efficient design of pump and pipe systems.

RATIONALE

The measurement of the flow behaviour of non-Newtonian fluids such as sludge, also called rheology, is not a simple matter. Wastewater treatment sludges due to their non-Newtonian behaviour do not have a simple constant viscosity and therefore require more complex modelling.

This has been researched world-wide but because the properties of sludges vary so much from plant to plant, there has not been much success in presenting pressure loss predictions. A number of researchers have tried to relate the rheological parameters to sludge solids concentration. When combined, a wide scatter of results is obtained.

The complication is that unless the measurements are done with similar equipment, either tube viscometers or rotary viscometers with the same geometries, it is difficult to compare results. This group prefers tube viscometry as it resembles a pipeline and actual head losses are measured. A test rig with reasonable sized pipe diameters (maximum pipe diameter of 63 mm ID) was designed and constructed to determine the pressure drop versus flow rate relationships. The test rig was shipped to Sweden where a range of sludges were prepared from different processes for testing pump performance and rheology by Haldenwang and co-authors. Tests were also conducted in South Africa (Cape Flats WWTP) which resulted in a correlation relating sludge viscous properties to solids concentration based on results obtained from two continents. This model needs further validation. The existing dataset from which the model was derived needs to be populated with sludge data from more treatment facilities using the same equipment as used by Haldenwang and his team.

Measurement of the sludge rheology in-line and real-time has been attempted by many with varied success. The Flow Process and Rheology Centre at CPUT in collaboration with their Swedish partners at the Swedish Institute of Food and Biotechnology, SIK in Goteborg, have developed and patented a system using ultrasound velocity profiling and pressure drop measurements to achieve this.

The addition of real-time, in-line viscometry measurements will reconcile the difference that exist between rotational and tube viscometry which caused the delay in the development of a more widely accepted model.

The more the sludge is thickened to reduce water, the more non-Newtonian the sludges become and the more important it is to gain an understanding of the flow properties of these sludges.

PROJECT OBJECTIVES

The aims of the project were

- To expand the existing sludge database obtained from tube viscometer measurements to validate/improve, if necessary, the pressure drop-flow rate predictions developed and published previously.
- Rheology will not affect pumping operations
- Rheology will quantify variation of these properties which will affect pumping operations.
- To test the application of the in-house developed UVP viscometer over a range of sludge concentrations.

METHODOLOGY

The selection of suitable waste water treatment sites in and around CT where high concentration sludges are available was key to the successful completion of the project. A meeting was arranged with the City of Cape Town to obtain permission and the WWTP at Potsdam was suggested as an option. Two BTech students then investigated the suitability of several sites in terms of sludge concentrations available and space for the portable tube viscometer. Three sites were identified: Potsdam, Melkbosstrand and Wesfleur.

The portable tube viscometer consisting of a recirculating pipe loop with 50 mm and 63 mm ID tubes was used for all the flow tests. A 4 x 3 inch centrifugal pump with a variable speed drive was used to control the flow rare? Flow rates were measured with a magnetic flow meter and pressure drop with differential pressure transducers. Calibration tests were done with water and the measured data in both pipes was compared with Colebrook-White equation for determining head losses in straight pipes in turbulent flow.

A test consisted of recirculating the sludge in the pipe loop and taking pressure drop and flow rate measurements in the three pipes with different diameters. From this a flow curve for each sludge concentration was constructed.

The flow curves, or rheograms, were obtained using the Rabinowitch-Mooney method. The rheograms were then used to determine the rheological parameters namely yield stress and Bingham viscosity.

Three waste water treatment plants, Potsdam, Melkbosstrand and Wesfleur in the Western Cape were identified where thickened sludges could be obtained. Sludge and process water were collected from Melkbosstrand and Wesfleur and all tests were conducted at Potsdam since there was enough space for the experimental setup.

Additional sludges from Wellington, Paarl and Stellenbosch WWTPs were tested in a smaller tube viscometer rig for consultants, who required the data for the design of a pipeline. Permission was obtained from Drakenstein Municipality (the client) to use the data in this report.

For the final objective an in-house developed Ultrasound Velocity Profile system combined with pressure drop (UVP-PD) system was used to determine the rheology of three sludges from Potsdam in-line and in real time. These results were compared with those obtained from the tube viscometer.

RESULTS AND DISCUSSION

The envisaged scope of experimental work was achieved and overall 21 sludges from six WWTPs were tested.

Rheological characterisation of viscous WWTP sludges

The original scope was to rheologically characterise sludges from three WWTPs. Sludges were obtained from Potsdam, Wesfleur and Melkbosstrand WWTPs with solids concentration varying between 2% and 7.8%. The tube viscometer data of wall shear stress versus shear rate was produced for each sludge and the Bingham yield stress and viscosity were derived.

In addition, four sludges from Wellington, Paarl and Stellenbosch WWTPs were tested. The concentration of these sludges was lower, ranging from 3% to 4.7%.

Testing of the UVP-PD system

During May 2014 the portable tube viscometer was taken to Potsdam and the UVP-PD system with a new non-invasive sensor unit was used to test three secondary sludges from the filter belt press. The rheology obtained from the UVP-PD system was compared with that obtained from the tube viscometer and for all three sludges the results were excellent.

CONCLUSIONS

The rheological properties of 21 sludges from six WWTPs in the Western Cape were tested ranging in solids concentration between 2% and 7.8%. Most tests were done in tube viscometers which are really small pipelines. The sludges tested comprised of primary and secondary as well as filter bed sludge.

The rheological properties of these sludges were over a wide range, with Bingham yield stresses varying between 1 Pa and 34 Pa and the Bingham viscosity from 0.005 to 0.079 Pa.s.

The effect on pressure drop predictions is significant as can be seen in Figure 43.The data was combined with that previously published by Haldenwang et al. (2010) and new predictions for both Bingham yield stress Figure 43 and Bingham viscosity Figure 44 were compiled. The data can only be predicted in a range of +/- 60% certainty.

It was envisaged that the results would be closer grouped because of the fact that all the tests were done in the same tube viscometer. This was however not the case and again shows how complex sewage sludges are. The rheological parameters such as Bingham yield stress and viscosity cannot only be linked to concentration. There are many other factors that influence the behaviour of these sludges, such as the process, flocculation pre-shear history, etc.

This again confirms the fact that when designing pipelines to transport viscous sludges, great care should be taken when estimating the rheology of such sludges. This will become more and more important as plants are trying to increase concentrations in the processes and the viscous properties increase. It will take further work before more accurate predictions will become available due to the complex nature of sewage sludge.

A new UVP-transducer which can measure non-invasively through a stainless steel pipe was tested with sludges for the first time. The UVP-PD system was successfully tested with three concentrations secondary sludge and the results were compared with the tube viscometer. The fact that one can now determine the rheology of sludges in-line and in real-time, has huge potential for process control in the waste water treatment industry.

RECOMMENDATIONS FOR FUTURE RESEARCH

The feasibility of using the UVP-PD system for measuring the rheology of sludges in-line has been proven. This has huge potential for optimisation of polymer dosing if one can link the rheological parameters of the sludge to the optimum polymer concentration.

The more sludge rheology data is made available, the more accurate pipeline pressure drop predictions will become. With the UVP-PD system this becomes now easier as the time taken for testing is much shorter and we have built a much smaller portable rig which could be used in future.

It is important to continue work towards identifying the critical physical and biological parameters in addition to concentration that will enable the development of a suitably simple model for prediction of sludge rheology.

ACKNOWLEDGEMENTS

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Mr Kevin Fawcett	Mott MacDonald PDNA

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We are grateful to Mr Ronald Brown at Drakenstein municipality for allowing us to use sludge rheological data which was measured for them.

Finally we wish to acknowledge the staff and students at CPUT under the leadership of Mr Richard du Toit who assisted with the experimental work.

CAPACITY BUILDING AND TECHNOLOGY TRANSFER

Three Civil Engineering BTech students were trained and the project provided funding for all their data acquisition which was required for their final year research projects. The students were Wonga Magqabi, Busisiwe Ncala in 2013 and Reatile Khuele in 2014.

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LIST OF ABBREVIATIONS

CPUT	Cape Peninsula University of Technology
DAQ	Digital Data Acquisition Module
FPRC	Flow Process and Rheology Centre
ID	Internal diameter
PD	Pressure drop
SIK	Swedish Institute for Food and Biotechnology
TS	Total solids
UVP	Ultrasound Velocity Profiling
UVP-PD	Ultrasound velocity profiling and pressure drop system
WWTP	Waste water treatment plant

NOMENCLATURE

A	Area (m^2)
B	Roughness function
d_x	Representative particle size (m)
D	Internal pipe diameter (m)
f	Fanning friction factor (-)
F	Force (N)
g	Gravitational acceleration (m/s^2)
He	Hedström number (-)
h_f	Frictional head (m)
K	Fluid consistency index ($Pa.s^n$)
K'	Apparent fluid consistency index (Pa.sn)
k	Hydraulic roughness (m)
L	Length of pipe or test section (m)
n	Flow behaviour index (-)
n'	Apparent flow behaviour index (-)
Δp	Differential pressure between 2 measuring points (Pa)
Q	Volumetric flow rate (m^3/s)
r	Localised distance along radius of pipe or concentric cylinder (m)
r_{plug}	Plug radius (m)
R	Internal pipe radius (m)
R_c	Radius cup (m)
R_b	Radius bob (m)
Re	Reynolds number (-)
Re_{MR}	Metzner and Reed Reynolds number (-)
Re_2	Slatter Reynolds number (-)
Re_r	Roughness Reynolds number (-)
u	Localised linear velocity at (r) value (m/s)
V^*	Shear velocity (m/s)
V	Velocity, mean velocity (m/s)
y	Distance from pipe wall = R-r (m); denotes dependent variable
$\dot{\gamma}$	Shear rate (1/s)
λ	Lambda friction factor (-)
μ	Dynamic viscosity (Pa.s)
δ	Ratio between cup and bob radius
ρ	Density (kg/m^3)
ω	Rotational speed (Rad/s)
τ_w	Wall shear stress (Pa)
τ_y	Yield stress (Pa)

1 INTRODUCTION AND OBJECTIVES

Head loss data for wastewater treatment sludge is not available in standard design tables and is therefore mostly estimated. The more highly concentrated the sludges becomes, the more non-Newtonian the flow behaviour is and the higher the pressure drop or energy required to transport the sludge. There is still no widely accepted design correlation of sludge viscous properties as a function of solids content, causing frustration to design engineers who in the absence of obtaining costly rheological data, have to make estimates which could compromise efficient design of pump and pipe systems.

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This has been researched world-wide but because the properties of sludges vary so much from plant to plant, there have not been much success in presenting pressure loss predictions. Some have tried to relate the rheological parameters to sludge solids concentration (Mori et al., 2006 and Seyssiecq et al., 2003). When combined, a wide scatter of results is obtained.

The complication is that unless the measurements are done with similar equipment either tube viscometers or rotary viscometers with the same geometries it is difficult to compare results. This group prefers tube viscometry as it resembles a pipeline and actual head losses are measured. A test rig with reasonable sized pipe diameters (maximum pipe diameter of 63 mm ID) was designed and constructed to determine the pressure drop versus flow rate relationships. The test rig was shipped to Sweden where a range of sludges were prepared from different processes for testing pump performance and rheology (Haldenwang et al., 2010). Tests were also conducted in South Africa (Cape Flats WWTP) which resulted in a correlation relating sludge viscous properties to solids concentration based on results obtained from at least 2 continents. This model needs further validation. The existing dataset from which the model was derived needs to be populated with sludge data from more treatment facilities using the same equipment (Haldenwang et al., 2012).

Measurement of the sludge rheology in-line and real-time has been attempted by many with varied success. The Flow Process and Rheology Centre at CPUT in collaboration with their Swedish partners at the Swedish Institute of Food and Biotechnology, SIK in Goteborg, have developed and patented a system using ultrasound velocity profiling and pressure drop measurements to achieve this. (Kotzé et al., 2008; 2012 and Kotzé and Haldenwang, 2008). The addition of real-time, in-line viscometry measurements will reconcile the difference that exist between rotational and tube viscometry which caused the delay in the development of a more widely accepted model.

The more the sludge is thickened to reduce sludge/solids handling cost, the more non-Newtonian the sludges become and the more important it is to gain an understanding of the flow properties of these sludges.

The aims of the project was

- To expand the existing sludge database obtained from tube viscometer measurements to validate/improve if necessary the pressure drop-flow rate predictions developed and published previously
- To measure the pressure drop versus flow rate on the waste water plants in existing pipes as well as the concentration of the sludges to independently test the design protocol developed.
- To test the application of the in-house developed UVP viscometer over a range of sludge concentrations.

2 LITERATURE

When one deals with the design of pipe and pump systems for the transport of water there are many handbooks dealing with this and every pump manufacturer will have pump performance curves available.

Designing pipe and pump system to transport viscous fluids is however a much more complex issue as one deals with viscous fluids with complex flow behaviour which also often varies considerably over time. The tool that is used to determine the flow behaviour of such complex fluids is rheology.

In this section some basics of pipe flow, a short introduction to rheology and models used will be given as well as appropriate Reynolds numbers used for pressure drop predictions.

2.1 Fundamentals of liquid pipe flow

Osborne Reynolds was the first to define flow regimes for liquids as laminar, transitional and turbulent. In laminar flow the viscous forces are dominant and in turbulent flow the inertial forces. The Reynolds number (Re) which is a ratio of inertial to viscous forces can be shown as follows:

$$\text{Re} = \frac{\rho V D}{\mu} \tag{1}$$

with ρ being the density, V the bulk velocity, D the pipe diameter and μ the dynamic viscosity. The laminar region is generally defined by a Reynolds number Re<2100 and the turbulent region Re>4000. In between these two regions is the unstable transition zone.
For laminar flow of a Newtonian fluids, in a circular tube using a force balance the shear stress at the wall is as follows.

$$\tau_w = \frac{D \Delta P}{4L} . \tag{2}$$

With ΔP being the pressure drop over a pipe length L
The Fanning friction factor f is defined as follows:

$$f = \frac{2\tau_w}{\rho V^2} = \frac{D(\Delta P / L)}{2\rho V^2} . \tag{3}$$

In the laminar flow region the relationship between the Fanning friction factor and Reynolds number is as follows.

$$f = \frac{16}{\text{Re}} \tag{4}$$

Often the Lambda (λ) friction factor is used and the relationship is:

$$\lambda = \frac{64}{\text{Re}} \tag{5}$$

The friction head loss/m for laminar flow can be expressed by the Darcy-Weisbach equation as follows.

$$\frac{h_f}{L} = \frac{4 f V^2}{2gD} . \tag{6}$$

For turbulent flow there are a number of friction factor Reynolds number equations available such as the Blasius, Chezy, Manning and Colebrook-White.
The Blasius equation is valid for smooth pipes from transition to a Reynolds number of 100 000, (Douglas et al., 1985)

$$f = \frac{0.079}{\mathrm{Re}^{0.25}} \tag{7}$$

Colebrook and White combined the laminar and turbulent flow equations of Prandtl and Nikuradze into the following form (Featherstone and Nalluri, 1995). The relationship between friction factor and a roughness ratio was defined as *k/D.*

$$\frac{1}{\sqrt{4f}} = -2 \ \log \left(\frac{k}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{4f}} \right) \tag{8}$$

Equation (8) can be transposed to yield an equation in terms of velocity:

$$V = -2\sqrt{2g\,D\,\frac{h_f}{L}}\ \log\left(\frac{k}{3{,}7D} + \frac{2{,}51\,\mu}{D\sqrt{2g\,D\,\frac{h_f}{L}}} \right) \tag{9}$$

The Moody diagram has been extensively used to determine friction factors for pipes of different roughness in both laminar and turbulent flow. An example is shown in Figure 1.

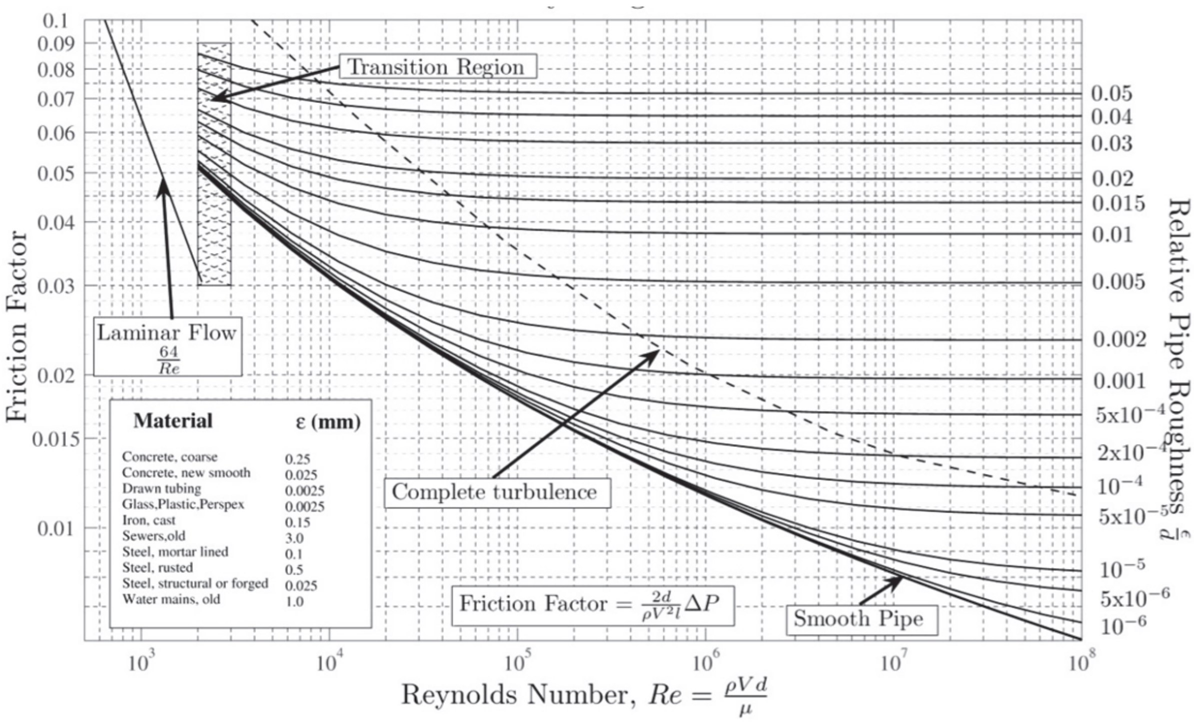

Figure 1 Moody diagram

(www.wikimedia.org/wikepedia/commons/8/80/Moody_diagram.jpg)

2.2 Fluid behaviour – Newtonian and non-Newtonian

When a thin layer or fluid is sheared between two parallel plates a distance *dy* apart and force *F* is applied this force will be balanced by the opposite internal friction. (Figure 2). For a Newtonian fluid in laminar flow the total shear stress is equal to the product of the viscosity and the shear rate of the fluid.

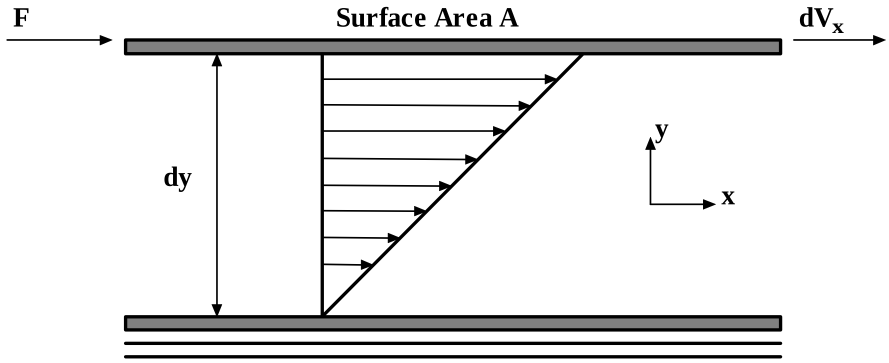

Figure 2 Schematic representation of one directional shearing flow

The mathematical relationship is given in Eqn. 10 with the first subscript in τ and $\dot{\gamma}$ indicating that the direction is normal to the shear force and the second refers to the fluid flow direction. (Chhabra and Richardson, 2008).

The constant of proportionality μ is the coefficient of dynamic viscosity. If a fluid is a Newtonian fluid it obeys this relationship which was first described by Sir Isaac Newton in 1687 (Barr, 1931).

$$\frac{F}{A} = \tau_{yx} = \mu\left(-\frac{dV_x}{dy}\right) = \mu\dot{\gamma}_{yx} \tag{10}$$

If this relationship is not linear then the material is called a non-Newtonian fluid. This also refers to relationships where the line does not go through the origin which makes the classification of non-Newtonian fluids very difficult.

Some of these relationships are depicted in Figure 3. Note that the flow behaviour depicted is only for time independent fluids.

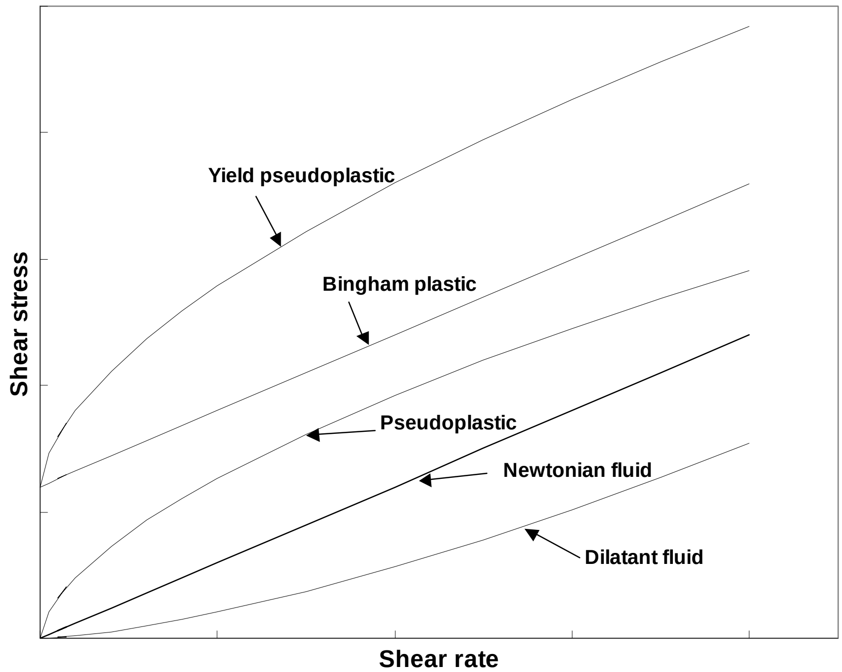

Figure 3 Rheological models

There are many models used to rheologically classify slurries and sludges. Only three will be given as these are the most popular to describe waste water sludges.

Pseudoplastic or shear-thinning model

The characteristic of these fluids is an apparent viscosity which decreases with increase of shear rate.

$$\tau_w = K\dot{\gamma}^n \qquad (11)$$

If $n < 1$, the fluid exhibits shear-thinning behaviour.
If $n > 1$, the fluid exhibits shear-thickening or dilatant behaviour.
If $n = 1$, the equation reverts back to the Newtonian equation with $K = \mu$
(Chhabra and Richardson, 2008).

Viscoplastic flow behaviour

When the fluid has a yield stress the fluid will not flow before the internal yield stress has been overcome by externally applied stresses. There has been much debate over whether the yield stress is real but for engineering design it is a reality which has to be dealt with and this includes viscous waste water sludges.

The following two models include a yield stress and they are the Bingham plastic model

$$\tau_w = \tau_y + K\dot{\gamma} \qquad (12)$$

and the Herschel-Bulkley or yield-pseudoplastic model

$$\tau_w = \tau_y + K\dot{\gamma}^n \qquad (13)$$

If $\tau_y = 0$, equation 12 reverts to the pseudoplastic equation.

If $n = 1$, equation 12 becomes the Bingham equation.

If $n = 1$, and $\tau_y = 0$, equation 12 describes the Newtonian flow equation.

2.3 Viscometry

To rheologically characterise non-Newtonian fluids traditionally either rotary viscometers or tube viscometers have been used. Recently, in-line real-time measurement of rheological properties has become possible using an Ultrasound Velocity Profiling and Pressure Drop (UVP+PD) technique.

Rotary viscometry

Rotary viscometers have various configurations and the main types are controlled shear rate and controlled shear stress instruments. Both these can be fitted with different geometries such as parallel plate, cone and plate, and concentric cylinder systems. The torque applied to rotation is related to shear stress and the speed of rotation to shear rate. A few measuring systems are shown in Figure 4.

The concentric cylinder system has a truncated cone at the lower end to minimise end effects (Metzger, 1998).

For the Cylinder measuring system, the representative shear stress (τ) and the shear rate ($\dot{\gamma}$) is as follows according to Metzger, 1998:

$$\tau = \frac{\delta^2}{2\delta^2} \frac{T}{2\pi L \left(R_b\right)^2 c_L} \quad and \ \dot{\gamma} = \omega \frac{\left(\delta^2\right)}{\left(\delta^2 - 1\right)} \qquad (14)$$

where $\delta = \frac{R_c}{R_b}$, and c_L= the resistance coefficient for the frontal area correction. This is found empirically. This measuring system was used in this work.

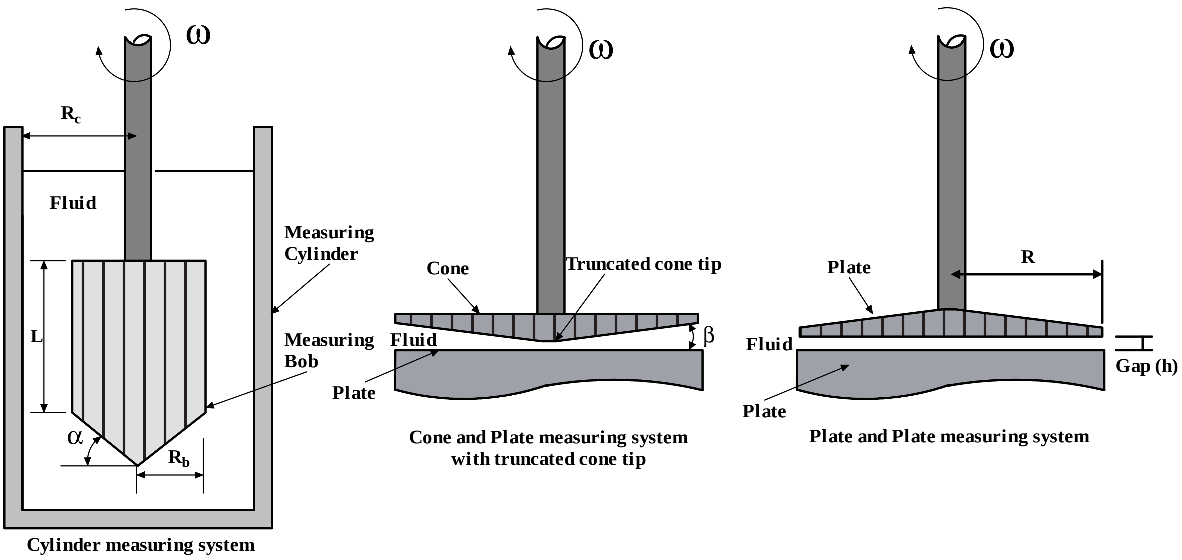

Figure 4 Rotational viscometer measuring systems

Tube viscometry

A tube viscometer is a miniature pipeline and therefore geometrically similar. For this reason some authors prefer these for non-Newtonian slurries (Wilson et al.,1996 and Slatter, 1994). In rotary viscometers lower shear rates can be obtained. Our group has been using tube viscometers extensively.

In a tube viscometer the relationship between wall shear stress τ_w, the volumetric flow rate Q and the shear stress τ is as follows:

$$\frac{Q}{\pi R^3} = \frac{1}{\tau_w^3} \int_0^{\tau_w} \tau^2 f(\tau) d\tau \qquad (15)$$

$\tau_w = \frac{R}{2}\left(-\frac{\Delta p}{L}\right)$ and $\left(-\frac{\Delta p}{L}\right)$ is equal to the pressure drop per unit length of tube.

The shear stress at any radius r is:

$$\tau = \frac{r}{2}\left(-\frac{\Delta p}{L}\right) \qquad (16)$$

A plot of $\frac{Q}{\pi R^3}$ vs τ_w will give a unique line for a given material for all values of R and $\left(-\frac{\Delta p}{L}\right)$ (Chhabra and Richardson, 2008).

As the values if 8V/D are wall shear rates for Newtonian fluids, these pseudo shear rates have to be transformed to true shear rates($\dot{\gamma}$).

According to Chhabra and Richardson, 2008 a flow curve of unknown form (Eqn. 11) will yield after some manipulation the following:

$$\left(-\frac{du}{dr}\right)_0 = \frac{8V}{D}\left(\frac{3}{4} + \frac{1}{4}\frac{d\log(8V/D)}{d\log\tau_w}\right) \qquad (17)$$

This equation exists in various forms one being the Rabinowitsch-Mooney equation:

$$\dot{\gamma}_w = \left(-\frac{du}{dr}\right)_w = \frac{8V}{D}\left(\frac{3n' + 1}{4n'}\right) \tag{18}$$

Where

$$n' = \frac{d(\log \tau_w)}{d\left(\log\left(8V/D\right)\right)} \tag{19}$$

This was used to transform the tube viscometer pseudo shear rates to true shear rates.

Ultrasound Velocity Profiling and Pressure Difference (UVP+PD) technique

Ultrasonic Velocity Profiling (UVP) is originally a medical technique for measuring an instantaneous velocity profile in liquid flow along the pulsed ultrasonic beam axis. The instantaneous velocity profile is obtained by detecting the relative time lags between pulse emissions echoed by particles contained in the fluid as a function of time. The technique was first used for general fluid flow measurements by Takeda, 1991; 1996.

When combining the UVP technique with pressure difference, in-line rheological parameters of opaque fluids with suspended particles can be determined. The UVP+PD method is described in detail by Wunderlich and Brunn 1999; Wiklund et al*.,* 2007 and Kotzé et al*.,* 2008.

With this technique the shear rate distribution is obtained from the measurements of flow profiles and the shear stress distribution from pressure difference measurement over a set distance in the pipe, similarly as in tube viscometry. However, an important advantage is that the UVP+PD technique gives the complete multipoint flow curve at one flow rate, thus making it possible to instantaneously visualise and measure flow behaviour (profiles) and fluid properties (rheology).

Measurements can be made non-invasively, in real-time, even for opaque and concentrated suspensions. This makes this uniquely applicable to process monitoring with potential in varied industrial applications such as paper pulp, foods, drilling fluids, waste water sludges and mineral suspensions to name a few.

The equation for the Herschel-Bulkley model (Eqn.12) and wall shear stress (Eqn. 2) can be combined and integrated to determine the radial velocity, shear rate and viscosity profiles in a pipe (Kotzé et al., 2008).

$$v = \left(\frac{n}{(1+n)}\right)\left(\frac{\Delta P}{2LK}\right)^{\frac{1}{n}}\left(\left(R - R_{plug}\right)^{1+\frac{1}{n}} - \left(r - R_{plug}\right)^{1+\frac{1}{n}}\right) \tag{20}$$

$$\dot{\gamma} = \left(\frac{\Delta P}{2LK}\right)^{\frac{1}{n}}\left(r - R_{plug}\right)^{\frac{1}{n}} \tag{21}$$

and

$$\mu = \frac{\tau}{\dot{\gamma}} = K\left(\frac{\Delta P}{2LK}\right)^{1-\frac{1}{n}}\left(\frac{r}{\left(r - R_{plug}\right)^{\frac{1}{n}}}\right) \tag{22}$$

R_{plug} is correlated to the yield stress as follows:

$$R_{plug} = \frac{2L\tau_y}{\Delta P} \tag{23}$$

The shear rate and viscosity at the pipe wall are given by

$$\dot{\gamma}_w = \left(\frac{\Delta P}{2LK}\right)^{\frac{1}{n}}\left(R - R_{plug}\right)^{\frac{1}{n}} \tag{24}$$

and

$$\mu_w = \frac{\tau_w}{\dot{\gamma}_w} = K\left(\frac{\Delta P}{2LK}\right)^{1-\frac{1}{n}}\left(\frac{R}{\left(R - R_{plug}\right)^{\frac{1}{n}}}\right) \tag{25}$$

A theoretical flow profile is fitted to the measured UVP profile and with the pressure drop measurement the rheological parameters are determined. A schematic of this is given in Figure 5.

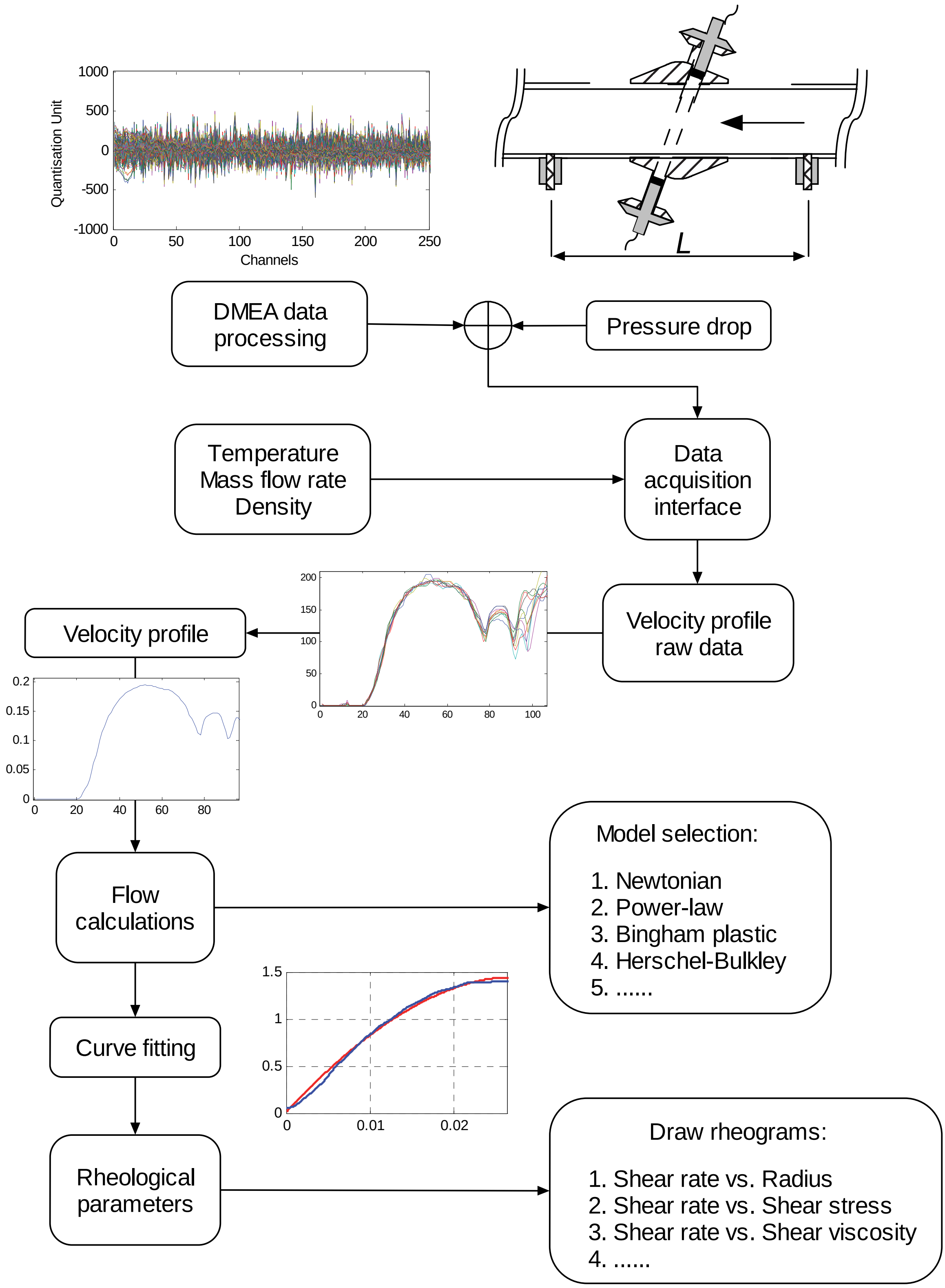

Figure 5 UVP-PD data processing structure (adapted from Wiklund et al., 2007).

The Flow Process and Rheology Centre at CPUT and their Swedish Partners at SIK – The Swedish Institute for Food and Biotechnology, Gothenburg, Sweden, have developed the UVP+PD system over many years from a research to a stable industrial system. A spin-off company, preliminary called Flow-Viz, is currently pending (registration of company planned for October 2014). Patent applications for the Flow-Viz technology has been filed in the US, European Union, Japan and South Africa. The patent applications are currently in the final stages and full protection expected during 2014.

2.4 Rheological characterisation of sludges

One of the oldest references to the use of tube viscometers was the work of Babbitt and Caldwell (1939). They describe a tube viscometer with pipes from 25-75 mm diameter. Since then a number of researchers have used real pipe lines or tube viscometers to determine the rheology of sludges (Babbitt and Caldwell, 1940; Michaelson et al., 1982; Carthew et al., 1983 and Murakami et al., 2001). As these tests are not easy to conduct because of the scale of experiment many researchers prefer rotary viscometers. We believe however that for pipeline pressure drop predictions, rheological characterisation is better done in a geometrically similar device such as a tube viscometer.

There is no agreement between researchers on which rheological model best characterises sludges. Babbitt and Caldwell, 1939 testing in a tube viscometer used the Bingham model. Carthew et al., 1983 testing raw sludges and using a tube viscometer also used the Bingham model. Honey and Pretorius, 2000 using a rotary viscometer and testing activated sludges used the pseudoplastic model. Murakami et al., 2001 tested digested biosolids, thickened and waste activated sludges in a tube viscometer and preferred the pseudoplastic model. Using a rotary viscometer and characterising activated sludges Mori et al., 2006 used the yield pseudoplastic model.

The most popular models used for sludges are the pseudoplastic, Bingham plastic and yield pseudoplastic.

Haldenwang et al., 2012 used tube viscometer data from tests done at a WWP in Stockholm Sweden and Cape flats to propose a relationship between sludge concentration and the Bingham plastic yield stress and viscosity which can be used in the prediction of pipe line pressure drop. This relationship is depicted in Figure 6.

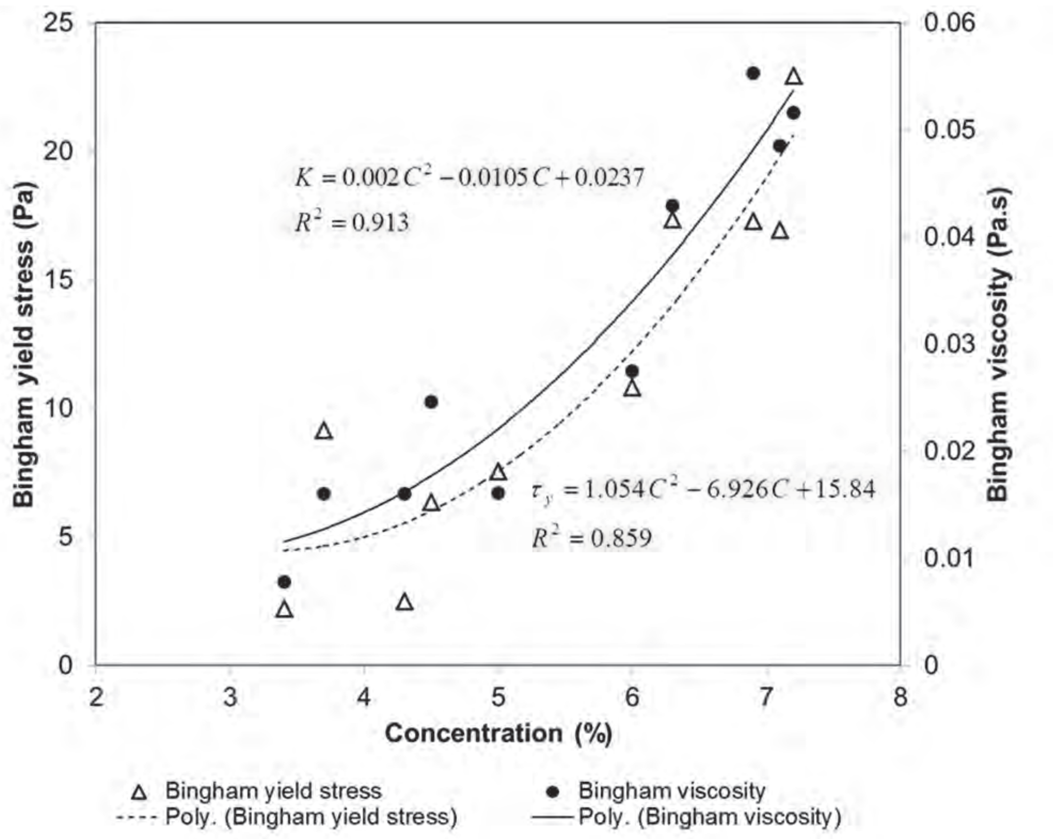

Figure 6 Relationship between sludge concentration and Bingham plastic yield stress and viscosity (Haldenwang et al., 2012)

One of the objectives of this work was to further populate this database with data obtained from local WWTPs.

2.5 Non-Newtonian Reynolds numbers

Several non-Newtonian Reynolds numbers have been proposed over the years to accommodate the different rheological models. Only two will be described in this report the first being the Metzner and Reed, 1955 and second the Slatter and Lazarus, 1993 Reynolds number.

Metzner and Reed were the first to propose a non-Newtonian Reynolds number for pseudoplastic fluids and Re_{MR} is given as:

$$Re_{MR} = \frac{\rho V^{2-n'} D^{n'}}{K' 8^{n'-1}} \tag{26}$$

For a power law fluid the values for n' and K' (and K and n in Eqn. (10)) are constant and are (Skelland, 1967):

$$n' = n \tag{27}$$

$$K' = K((3n'+1)/4n')^n \tag{28}$$

For Bingham plastic fluids n' and K' are given by Skelland, 1967 as:

$$n' = \frac{1-(4/3)(\tau_y/\tau_w)+(1/3)(\tau_y/\tau_w)^4}{1-(\tau_y/\tau_w)^4} \tag{29}$$

$$K' = \tau_w \left[\frac{K}{\tau_w(1-(4/3)(\tau_y/\tau_w)+(1/3)(\tau_y/\tau_w)^4)} \right]^{n'} \tag{30}$$

For Herschel-Bulkley fluids n' and K' are given by Desouky and Al-Awad, 1998 as:

$$n' = 1/(\lambda_1 + (\lambda_2/\lambda_3)) \tag{31}$$

$$K' = \frac{\tau_w}{\left(\frac{4n}{K^{1/n}\tau_w{}^3} (\tau_w - \tau_y)^{\frac{1+n}{n}} \left[\frac{(\tau_w-\tau_y)^2}{1+3n} + \frac{2\tau_y(\tau_w-\tau_y)}{1+2n} + \frac{\tau_y^2}{1+n} \right] \right)^{n'}} \tag{32}$$

with

$$\lambda_1 = -3 + [(1+n)/n][\tau_w/(\tau_w-\tau_y)] \tag{33}$$

$$\lambda_2 = 2\tau_w(1+n)(\tau_w + 2n\tau_w + n\tau_y) \tag{34}$$

$$\lambda_3 = (1+n)(1+2n)(\tau_w-\tau_y)^2 + 2\tau_y(\tau_w-\tau_y)(1+n)(1+3n) + \tau_y^2(1+2n)(1+3n) \tag{35}$$

For Herschel-Bulkley model fluids the following Reynolds number Re_2 was proposed by Slatter and Lazarus, 1993. This is similar to the Clapp Reynolds number reported by Torrance, 1963 but now including a yield stress.

$$Re_2 = \frac{8\rho V^2}{\tau_y + K\left(\frac{8V}{D}\right)^n} \tag{36}$$

This Reynolds number can also be used for pseudo plastic ($\tau_y=0$) and Bingham plastic ($n=1$) model fluids.

2.6 Laminar flow

For laminar flow in pipes Govier and Aziz, 1972 developed the following equation for Herschel-Bulkley fluids. This can easily be adapted for Bingham fluids by equating *n=1.* If the rheological parameters are known then the velocity for a specific wall shear stress can be determined.

$$\frac{32Q}{\pi D^3}=\frac{8V}{D}=\frac{4n}{K^{\frac{1}{n}}\tau_w}\left(\tau_w-\tau_y\right)^{\frac{1+n}{n}}\left(\frac{\left(\tau_w-\tau_y\right)^2}{1+3n}+\frac{2\tau_y\left(\tau_w-\tau_y\right)}{1+2n}+\frac{\tau_y{}^2}{1+n}\right) \qquad (37)$$

2.7 Turbulent flow

There are several turbulent models available in the literature for different rheological models but only two will be presented that both are relevant for Bingham fluids.

Torrance turbulence model

Torrance, 1963 developed for yield-pseudoplastic fluids a turbulent pipe flow model which he derived from the Newtonian turbulent model. He used a value of 0.36 n for the Von Karman constant which means that it depends on the viscous characteristics of the fluid. The average turbulent velocity for smooth pipe flow is as follows.

$$\frac{V}{V^*}=\frac{3.8}{n}+\frac{2.8}{n}\ln\left(1-\frac{\tau_w}{\tau_y}\right)+\frac{2.78}{n}\ln\left(\frac{V_*^{2-n}\rho R^n}{K}\right)-4.17 \qquad (38)$$

With the shear velocity V_*

$$V^*=\sqrt{gR_h\sin\alpha} \qquad (39)$$

Slatter turbulence model

Slatter, 1994 includes particle roughness effect in his model. He formulates a roughness Reynolds number that takes the rheology and representative particle size of the solids into account. For the slurries tested he found the d_{85} the most representative.

His roughness Reynolds number is as follows:

$$\mathrm{Re}_r = \frac{8\rho\left(V^*\right)^2}{\tau_y + K - \left(\frac{8V^*}{d_x}\right)^n} \tag{40}$$

For smooth wall turbulent flow when $Re_r \leq 3.32$ the average velocity is

$$V = V_*\left(2.5\ln\left(\frac{R}{d_{85}}\right) + 2.5\ln \mathrm{Re}_r + 1.75\right) \tag{41}$$

For fully developed rough wall turbulent flow when $Re_r > 3.32$ the flow velocity is:

$$V = V_*\left(2.5\ln\left(\frac{R}{d_{85}}\right) + 4.75\right) \tag{42}$$

The transition from smooth wall to rough wall turbulent flow is assumed to be abrupt. The rheological parameters are taken into consideration by this model.

2.8 Transition flow

This is the unstable region between laminar and turbulent flow. For water this is between $2100<Re<4000$. When dealing with non-Newtonian fluids, for both Metzner and Reed, 1955 and Slatter and Lazarus, 1993 Reynolds numbers, transition is assumed to occur at Re=2100.

3 EXPERIMENTAL PROCEDURES

The experimental work described consists of three phases. For Phase 1 which was completed in 2013 the rheological characterisation was done mainly in the portable tube viscometer. Phase 2 consisted of comparing data obtained with the ultrasound velocity profiling and pressure drop system (UVP-PD) with those of the portable tube viscometer was done in 2014. Five more sludges were tested as part of a report done for consultants with the clients being the Drakenstein municipality. Two sludges were tested with a rotary viscometer and the other three with a small tube viscometer.

3.1 Portable tube viscometer

This tube viscometer was designed and built in-house at the FPRC and has been used for tests both locally and in Stockholm Sweden. It has been designed to fit into a 6 m container for easy transport.

The test rig consists of a 1/100 L tank feeding an ITT Flygt 4.2 kW 4/3 submersible centrifugal pump (impeller diameter 153 mm) fitted with an ABB variable speed drive. The tube viscometer consists of three tubes of 63.8, 52.2 and 26.8 mm ID pipes. High and low range differential pressure transducers are fitted to each pipe and flow rates are measured with a 50 and 25 mm magnetic flow meters. From the pressure drop and flow rates in the different pipes flow curves are established and the laminar flow data is then used to establish the rheological parameters. The schematic of the test rig is shown in Figure 7.

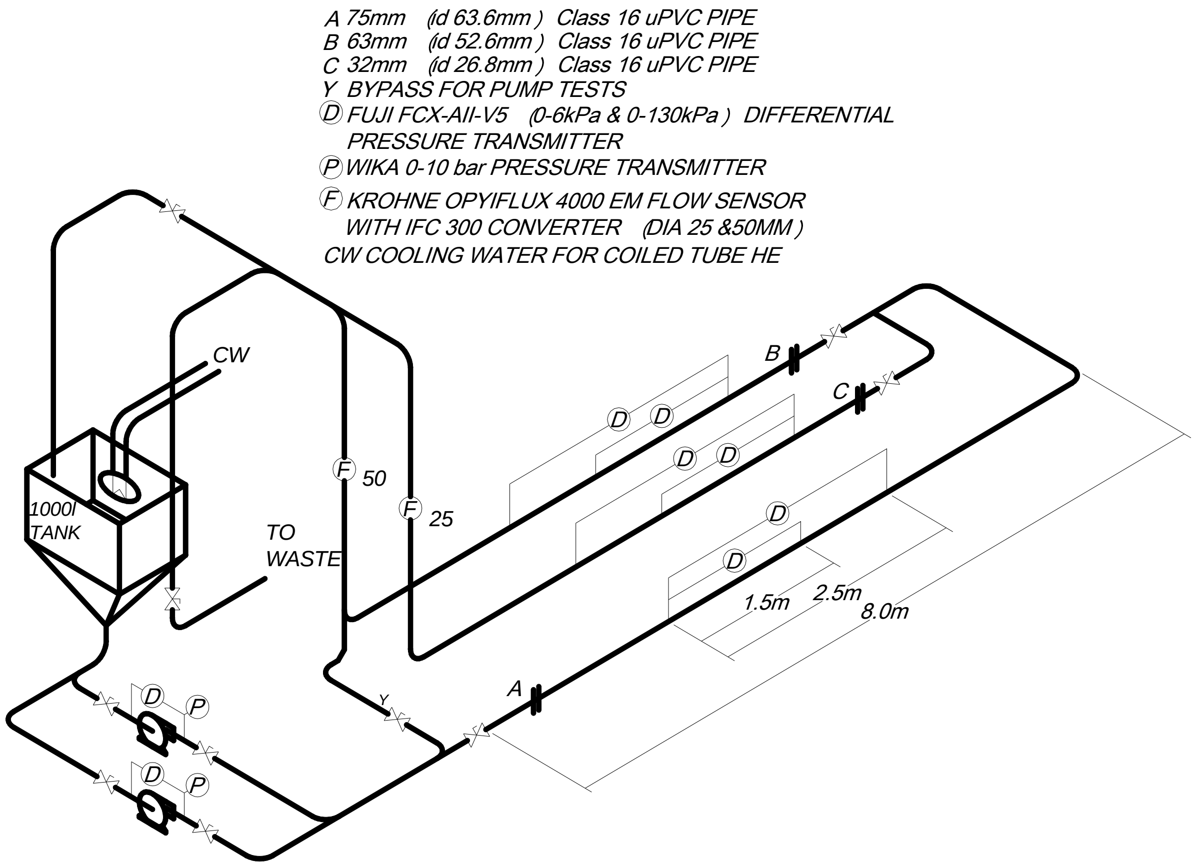

Figure 7 Portable tube viscometer

To calibrate the tube viscometer water tests were conducted. The pressure drop and flow rates over a wide range were measured and the experimental values for wall shear stress and velocity are compared with the wall shear stress derived from the Colebrook-White prediction of friction factor for turbulent Newtonian flow (Chhabra and Richardson, 2008). The calibration curves for the tube viscometer are depicted in Figure 8 and Figure 9. The Colebrook White equation (Equation 8) was predict the friction factor *f*. Pressure drop over using two different pipe sections for each pipe were used using 2 differential pressure transducers (DPT).The results show that over the flow rates used the maximum deviation from the prediction is within +/- 10% as shown by the broken lines. The only exception is the high flow rates for one DPT in the 63 mm pipe.

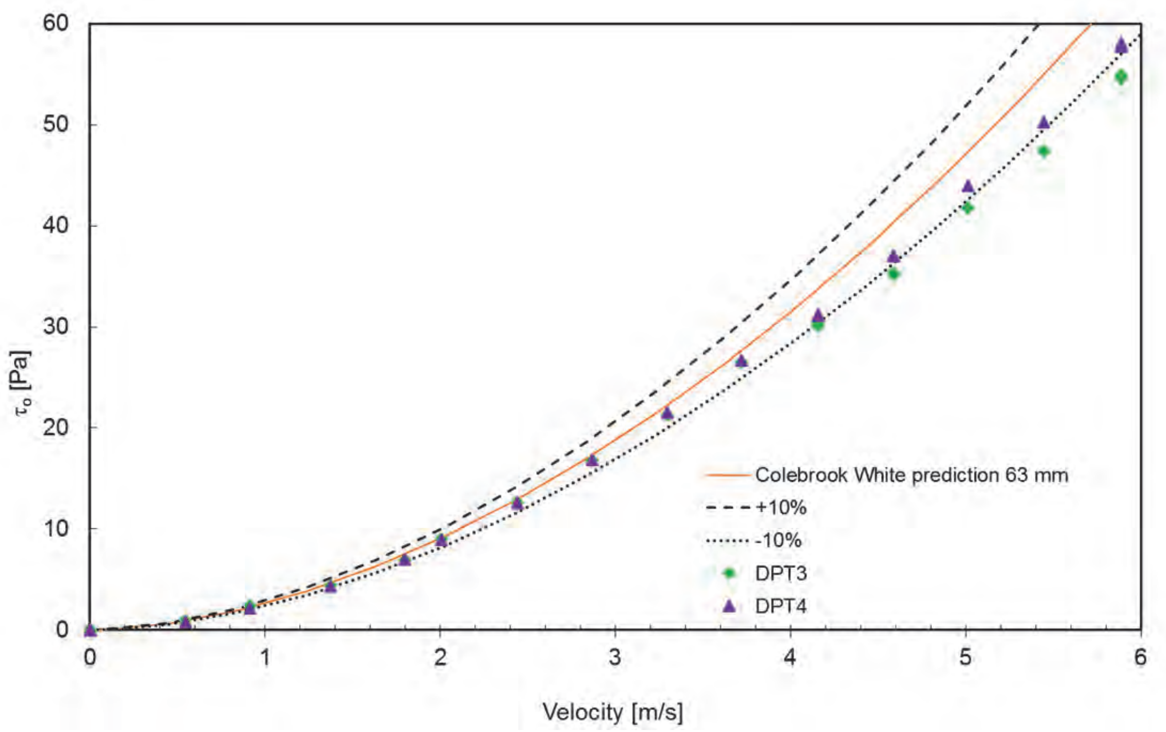

Figure 8 Water test comparison with Colebrook-White equation for 63 mm pipe

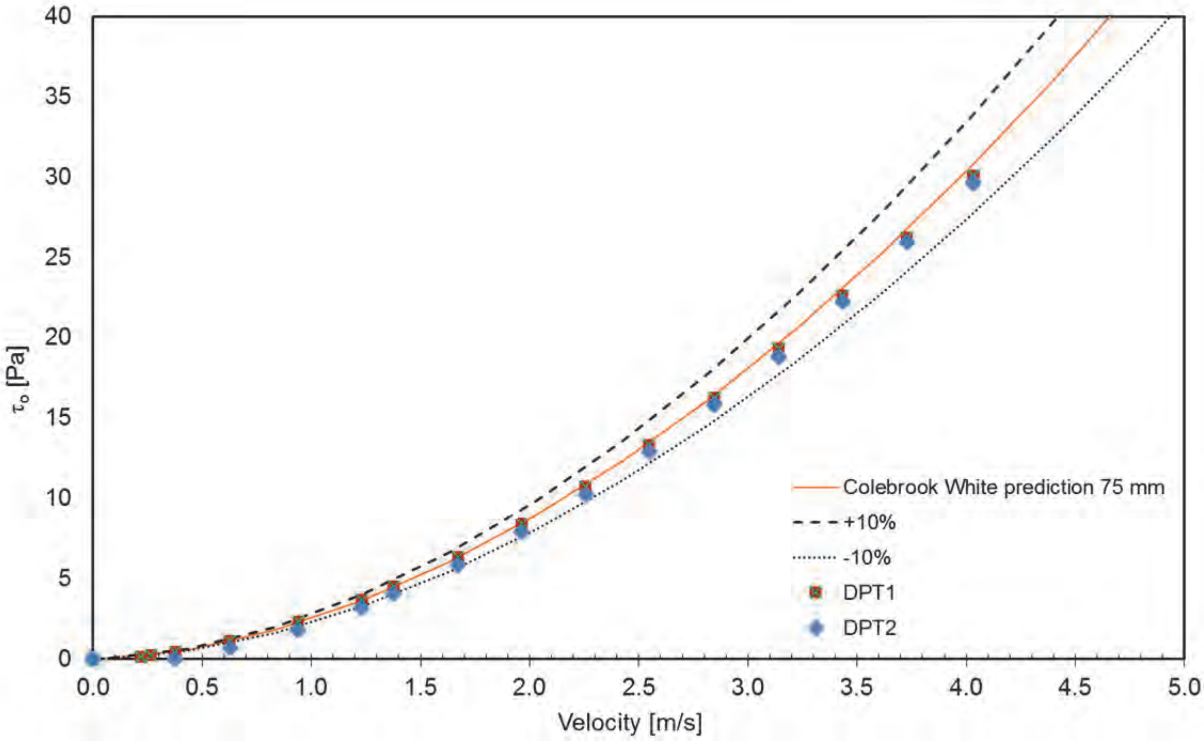

Figure 9 Water test comparison with Colebrook-White equation for 75 mm pipe

3.2 UVP+PD system

The UVP+PD system which has been developed by CPUT and SIK was used. Some of the theory is described in Section 2.3.

A new in-line fluid characterisation system and method for complex industrial fluids and suspensions, known as Flow-Viz, has been developed at CPUT and SIK. The Flow-Viz system is now made commercially available through a pending spin-off company, temporarily named "Flow-Viz AB". The patent pending system allows continuous, non-invasive flow visualization and rheological characterization of complex, non-Newtonian industrial fluids in-line, in real time under true processing conditions.

However, the Flow-Viz system is a new enhanced multi-datapoint version that does not only use volumetric flow rate measurement to get the average shear rate. Instead it uses a pulsed ultrasound method that allows true multi-point measurements i.e. to determine instantaneous velocity profiles (velocity distribution) in real-time. The instrument is thus not limited to shear thinning fluids and provides on a continuous base, complete viscosity vs. shear rate distributions, i.e. flow curves and rheograms as well rheological model parameters (such as the flow index, n, and consistency index, k).

Measurements are done non-invasively through industrial grade stainless steel pipes under realistic field conditions. The method is also non-destructive, thus not affecting the current flow and the system gives no additional pressure drop. The Flow-Viz method can be used for process monitoring and control and for continuous evaluation and optimization of industrial processes. The Flow-Viz system is packaged inside a sensor unit that is attached in-line with the current pipe plus an electronics box with user-friendly control software. Every part of the method has been improved and optimized with over 10 years of research, resulting in a unique solution. No similar solution exists on the market. Figure 10 shows the prototype version used during the August 2014 tests.

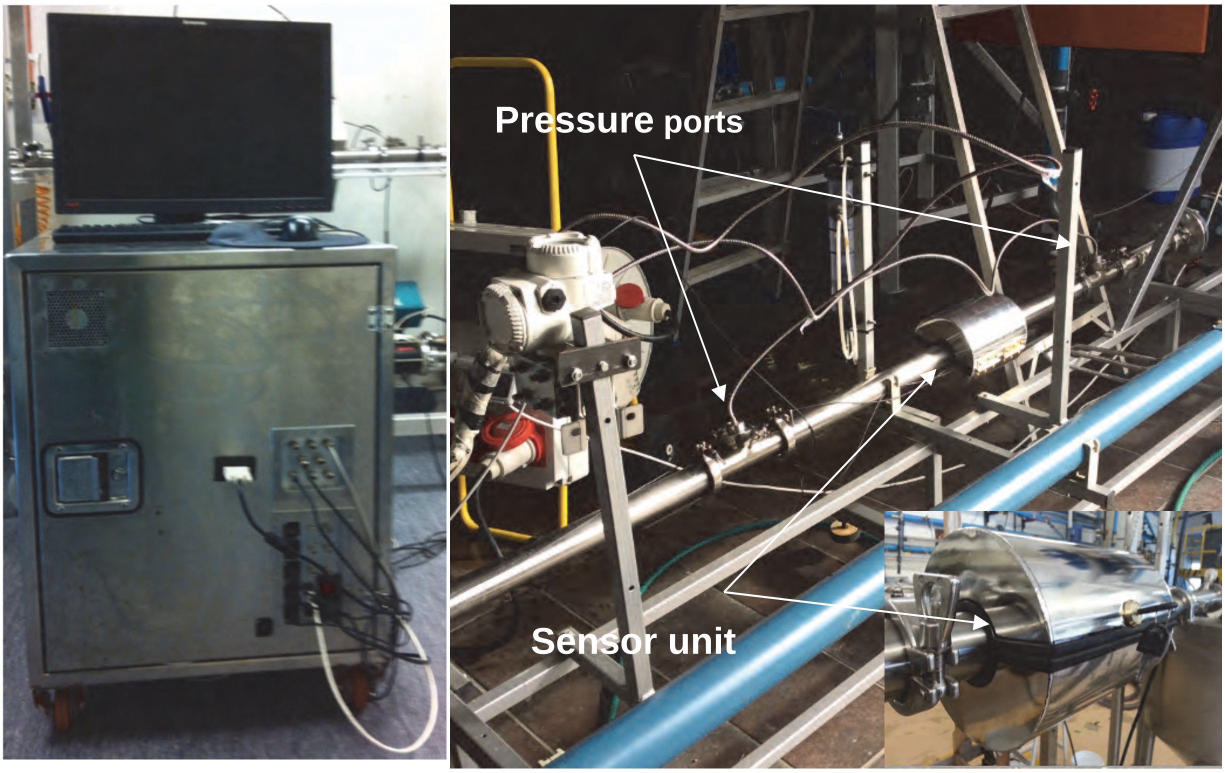

Figure 10 The prototype version of the Flow-Viz system (left: electronics box; right: non-invasive sensor installed in the flow loop)

Flow-Viz capabilities:

- Profiles measured in all fluids, one exception of air needed in system.
- Completely non-invasive (no energy losses)

Measured parameters (real-time, continuous data):

- Flow Visualisation (Velocity profile, complex flow measurements)
- Doppler spectrums (Measurement confidence, artefacts, wall positions)
- Rheology (Viscosity, yield stress, fitted rheological parameters, etc.)

- Sound speed (concentration of solids, air in system, cleaning cycle monitoring)
- RF echo plots (liquid displacement, viscous fingering, cleaning cycle)
- Volumetric flow rate (integration of profile, accurate reading)
- Pressure drop variation (differential pressure)
- Temperature

The next generation / commercial version of the Flow-Viz system

The first industrial version Flow-Viz 1.0 system based on the UVP+PD-combination is now available. All aspects have been carefully optimised; the sensors, the signal processing and the algorithms. This result is an effective method, able to:

- Produce and visualise complete flow profiles in high resolution
- Describe in detail how the flow behaves (rheology)
- Visualise and characterise non-Newtonian liquids in complex geometries (pipe bends and pumps)
- Continuously measure the flow in real-time (it only takes a few milliseconds to send a pulse, receive it and analyse it)
- The Flow-Viz method can handle all types of liquids, emulsions and suspensions (except distilled water since there are no particles that can echo the pulses). It can even handle non-transparent liquids and liquids with very high particle concentrations, e.g. cement based grouts. The method is not suitable for gas/steam due to the relatively low velocity of sound in gas/steam.

The industrial version of the Flow-Viz 1.0 system consists of three components:

- Sensor unit – contains measuring section, including ultrasound transducers and pressure sensors. A wide range of sensor units are available to cover different pipe sizes, from 10 mm up to 150 mm pipes or larger.
- Operator's Panel – pulser-receiver, DAQ, signal conversion modules, power supply and master PC.
- Software – data acquisition, signal processing, visualization and post processing of data.

The components are packaged into a sensor unit, which is installed/attached in-line with the pipe, plus an operator's panel. The sensor unit does not affect the current flow. The equipment can be packaged in a way to endure harsh weather conditions to be used outside all year round. The equipment will be modularised, allowing different versions of the product aimed at different types of applications. The equipment is designed to comply with hygienic design criteria as well as different IP- and EX- classifications. More detailed information can be found in Appendix B.

Figure 11 The industrial version of the Flow-Viz system (more information is available in Appendix B or on www.flow-viz.com)

Major improvements with next generation / commercial version of the Flow-Viz system

- More than 10 times spatial resolution (small pipes, highly detailed flow measurements)
- High refresh rate (fast, transient flow measurements)
- New user interface (simple and easy to visualize measurements)
- New sensor unit technology (integrated, minimize signal artefacts)
- New operators control panel (integrated touch screen, 4-20 mA outputs, etc.)
- Access to RF data, simultaneous sound speed monitoring (detailed flow images, high sample rate)
- Sing-around ToF measurements (volume flow rate, self-calibration)

3.3 Rotary Viscometer

The rotary viscometer used was an Anton Paar MC-1 rheometer with a cup and measuring cylinder attachment. The viscometer can measure both torque and speed. From the torque measurement the shear stress is derived and from the rotational speed the shear rate. The diameter Rc of the cup is 50 mm and the radius of the measuring cylinder is 46 mm. Therefore the gap is only 2 mm. A schematic of the measuring system used is depicted in Figure 12.

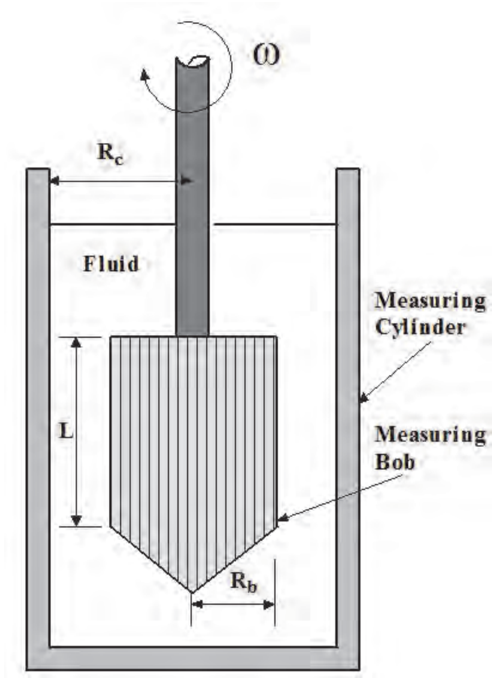

Figure 12 Rotary viscometer measuring system.

The MC1 was calibrated using a Newtonian calibration oil. The measured viscosity of this test oil was within 5% of the specified viscosity. The viscosity versus shear rate curve of the calibration oil is given in Figure 13 and shows a constant viscosity over the shear rate used in the tests. The viscosity value obtained was 3.7% higher than that given by the suppliers of the oil (0.488 vs 0.47 Pa.s)

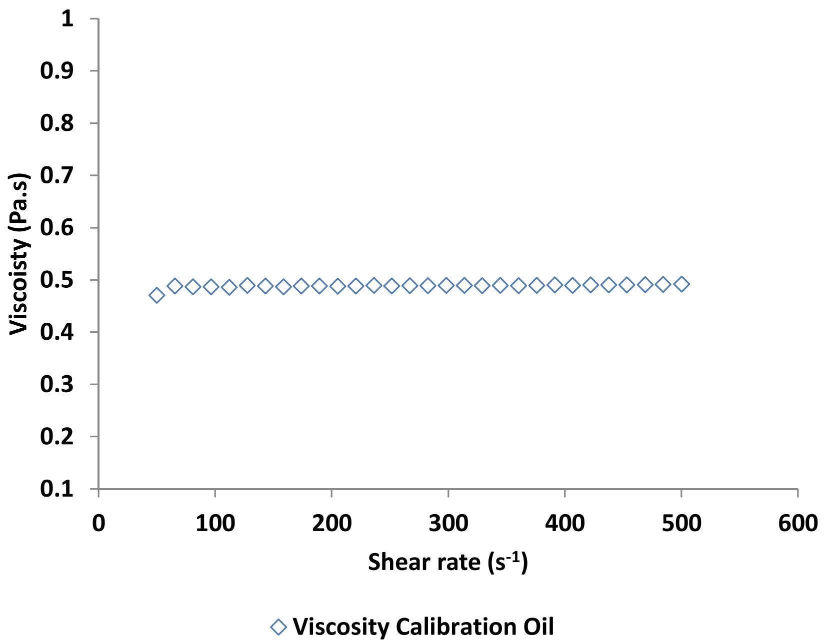

Figure 13 Viscosity versus shear rate curve of calibration oil

3.4 Small tube viscometer

Due to problems with the rotary viscometer where grit in the sludge jammed the bob a small tube viscometer situated in the FPRC laboratories at CPUT in Cape Town was used. The tube viscometer comprises 13 and 16 mm ID tubes fitted with pressure sensors, and a mass flow meter which also measures the in-line density. The sludge is recirculated with a progressive cavity, positive displacement pump fitted with a variable speed drive and pressure drop (Pa/m) and flow rate (L/s) measurements are taken over a suitable range of flow rates. A schematic of the tube viscometer is shown in Figure 14. The advantage of this small loop is that only about 40 L of fluid is required. The disadvantage is that the minimum shear rate is not very low due to the small size of the tubes.

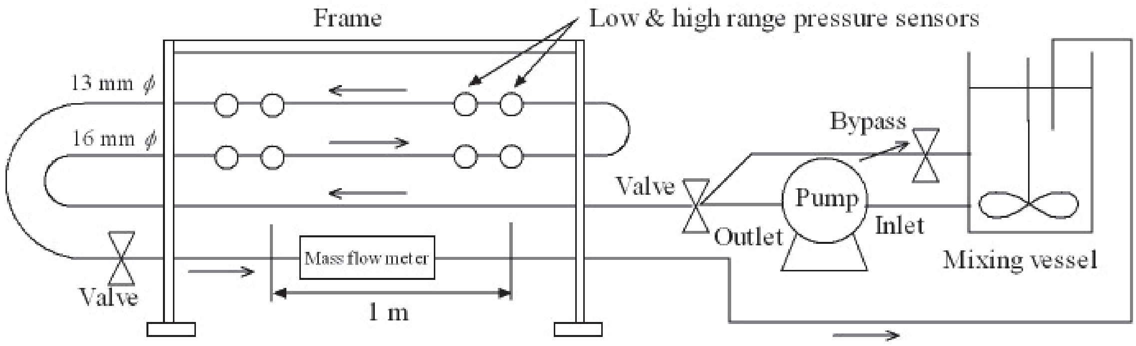

Figure 14 Small tube viscometer (FPRC laboratories)

4 RESULTS, TREATMENT OF RESULTS AND DISCUSSION

4.1 Sludges tested

The sludges tested as part of this project are from Potsdam, Melkbosstrand and Wesfleur WWTPs in Cape Town. The tests were all conducted at Potsdam and the sludges from Melkbosstrand and Wesfleur were transported by truck to Potsdam.

A schematic process flow diagram of the WWTP at Potsdam is given in Figure 15. Sludges were sampled at the filter belt press where the filter cake originated from both primary and secondary sludges. Primary sludge from the belt press dewatering process contains 25-30% solids concentration, also known as dry cake.

Secondary sludge from belt press dewatering process contains 12-15% solids concentration, also known as dry cake. These sludges had the highest concentration and were then diluted with effluent to lower concentrations for testing.

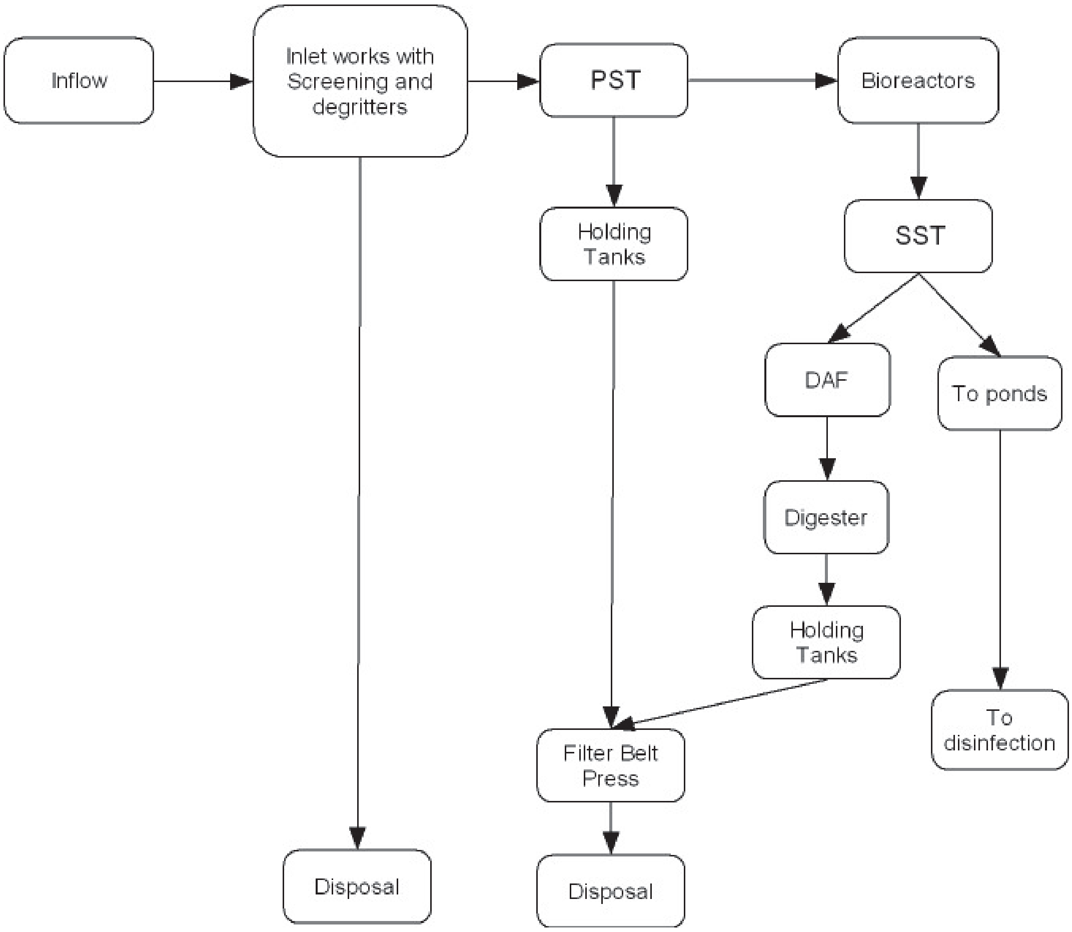

Figure 15 Potsdam WWTP – process flow diagram

The Melkbosstrand WWTP is situated at Melkbosstrand road in Cape Town on the West Coast. A schematic process flow diagram is given in Figure 16. At Melkbosstrand low solid concentrated sludges from bioreactors were found and high concentration sludges of more than 10% are found on sludge drying bed. This sludge was transported to Potsdam for testing.

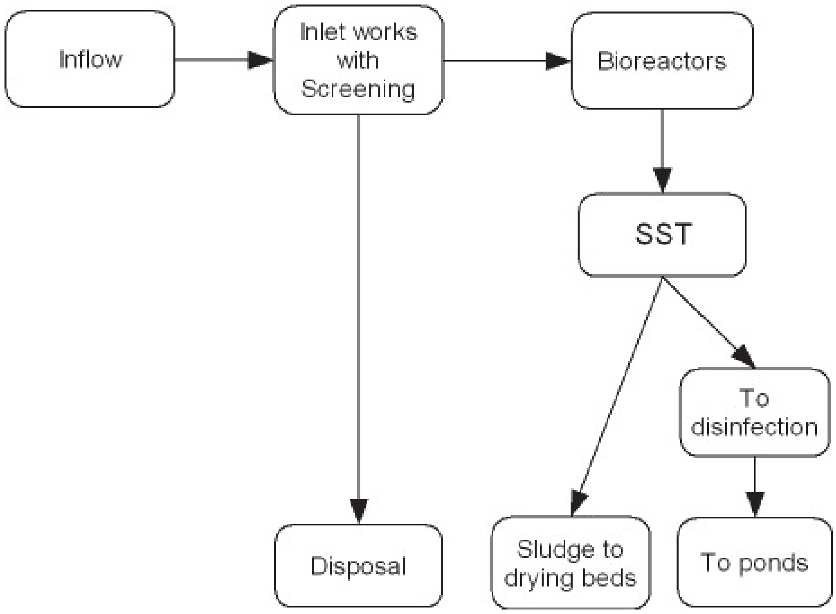

Figure 16 Melkbosstrand WWTP – process flow diagram

The WWTP at Wesfleur is situated at Dassenberg road in Atlantis on Cape Town's west coast. The process is the same as in Melkbosstrand as shown in Figure 16. The drying bed sludges were transported to Potsdam where they were tested in the tube viscometer.

4.2 Tube viscometer test results

The tube viscometer conducted at Potsdam in 2013, are depicted in the following section. During this period 14 concentrations of sludge from Potsdam, Melkbosstrand and Wesfleur were tested. For the flow curves as shown in Figure 17-Figure 30, the relationship between wall shear stress (τ_w)and shear rate ($\dot{\gamma}$) is depicted. The wall shear stress is obtained from the pressure drop measurement by (Eqn.2) and the pseudo shear rate (8V/d) from the flow rate measurement. To obtain the true shear rate ($\dot{\gamma}$) the Rabinowitch-Mooney (Equation 17) is used. A mathematical fit through the data will describe the relationship between wall shear stress (τ_w) and shear rate ($\dot{\gamma}$). The Bingham model (Eqn.12) was used to describe this relationship. The slope of the fit is the Bingham viscosity (*k*) and the y-intercept is the value of the Bingham yield stress (τ_Y). With an increase in concentration the values of yield stress and viscosity increase resulting in an increase in pipe-flow resistance. The values of concentration, Bingham viscosity and Bingham yield stress of the Phase 1 results of Potsdam, Wesfleur and Melkbosstrand WWTP sludges are presented in.Table 1

Table 1 Summary of rheology results – tube viscometer

Phase 1 sludges. Aug 2013 Potsdam, Wesfleur & Melkbosstrand	Solids Concentration %	Bingham yield stress τ_y(Pa)	Bingham viscosity *K* (Pa.s)
Potsdam secondary sludge PD 1	3.47	8.6	0.026
Potsdam secondary sludge PD 2	3.73	4.2	0.028
Potsdam secondary sludge PD3	4.13	9.6	0.032
Potsdam primary sludge PD 4	3.59	3.7	0.006
Potsdam primary sludge PD 5	3.89	2.9	0.017
Potsdam secondary sludge PD 6	3.69	8.2	0.022
Potsdam secondary sludge PD 7	4.66	13.8	0.047
Potsdam secondary sludge PD 8	5.80	34.3	0.055
Melkbosstrand drying bed sludge MB 1	4.92	16.7	0.046
Melkbosstrand drying bed sludge MB 2	4.15	10.9	0.022
Melkbosstrand drying bed sludge MB 3	3.32	2.7	0.027
Wesfleur drying bed sludge WF 1	6.99	13.7	0.041
Wesfleur drying bed sludge WF 2	7.78	27.0	0.079
Wesfleur drying bed sludge WF 3	6.03	11.1	0.024

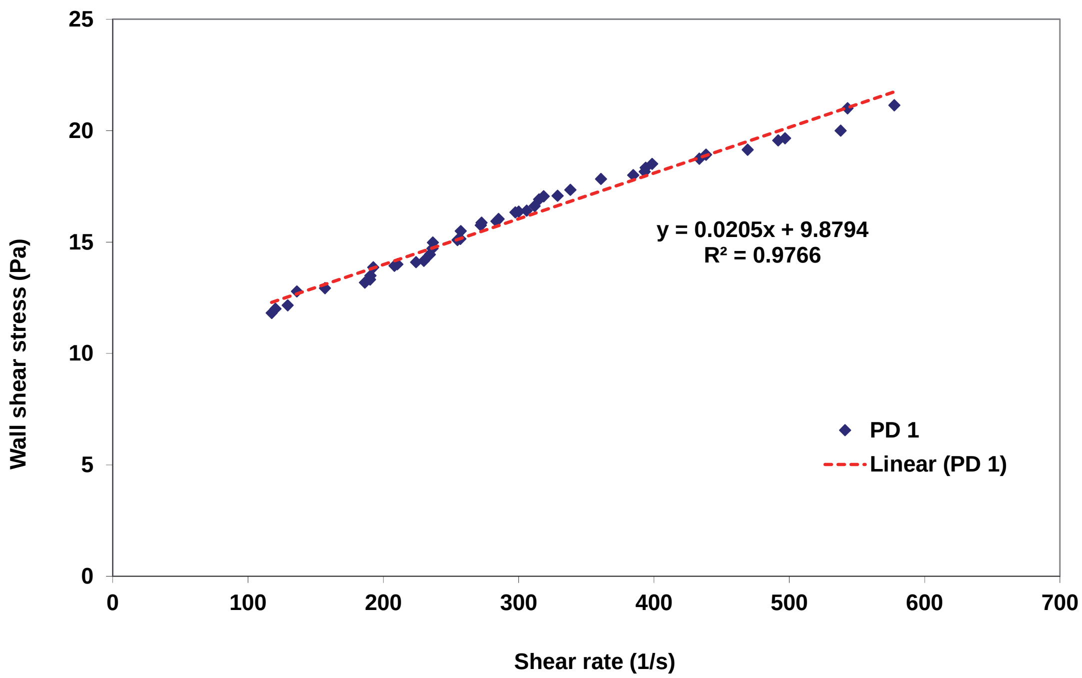

Figure 17 Potsdam WWTP secondary sludge 1 (PD 1 – 3.47%) Flow curve

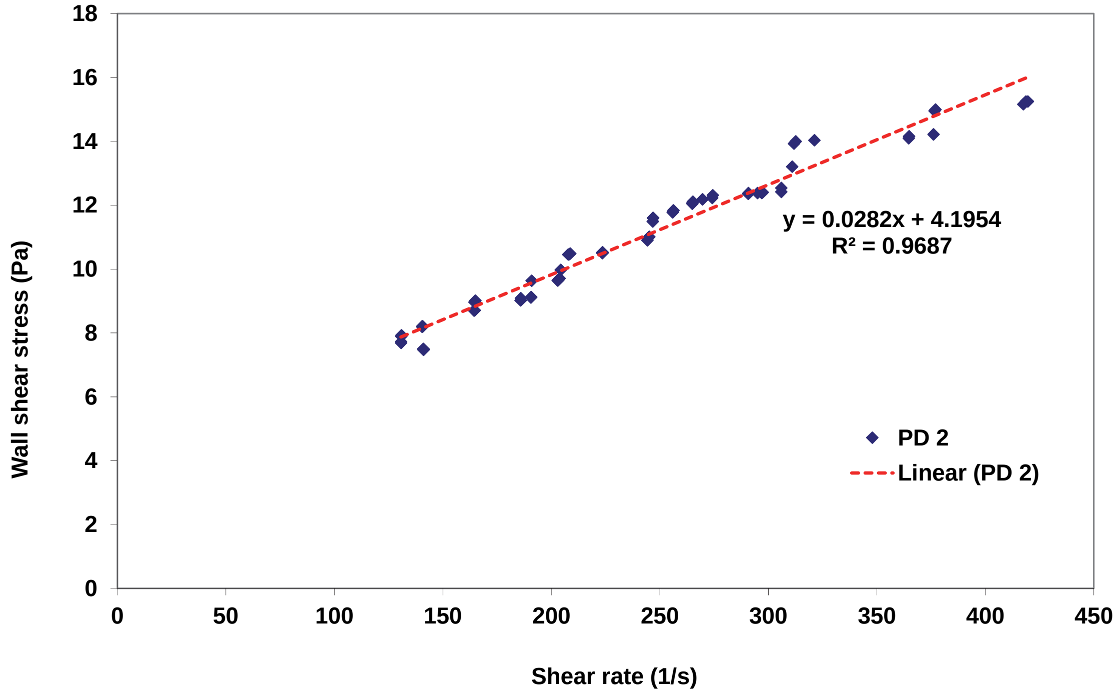

Figure 18 Potsdam WWTP secondary sludge 2 (PD 2 – 3.73%) Flow curve

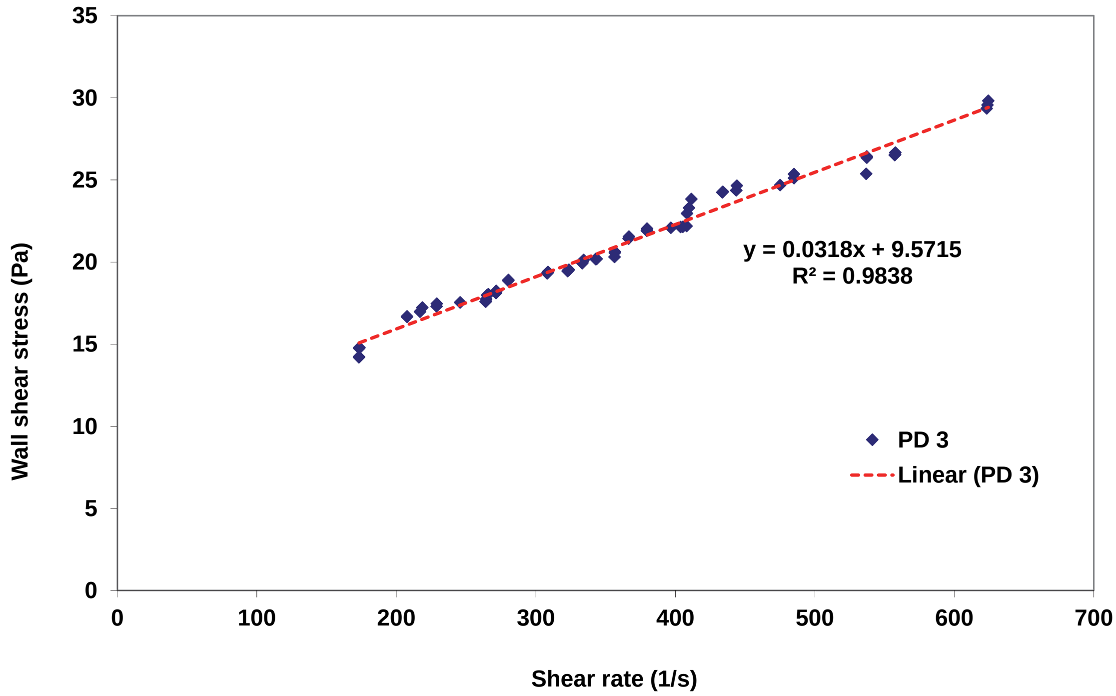

Figure 19 Potsdam WWTP secondary sludge 3 (PD 3 – 4.13%) Flow curve

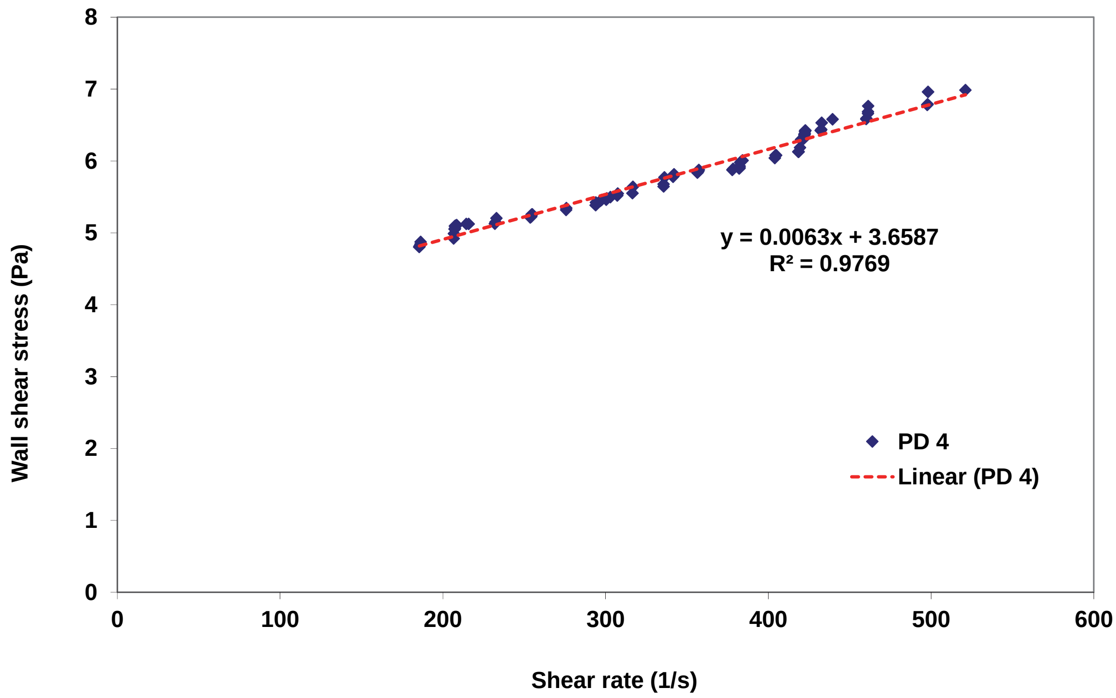

Figure 20 Potsdam WWTP secondary sludge 4 (PD 4 – 3.59%) Flow curve

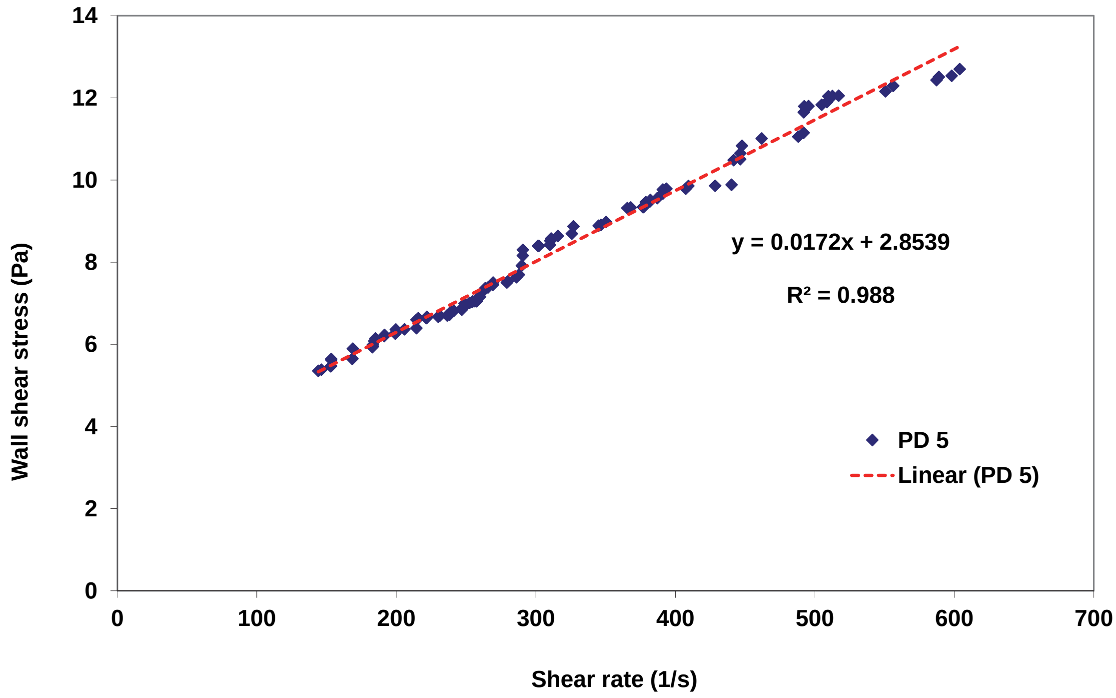

Figure 21 Potsdam WWTP secondary sludge 5 (PD 5 – 3.89%) Flow curve

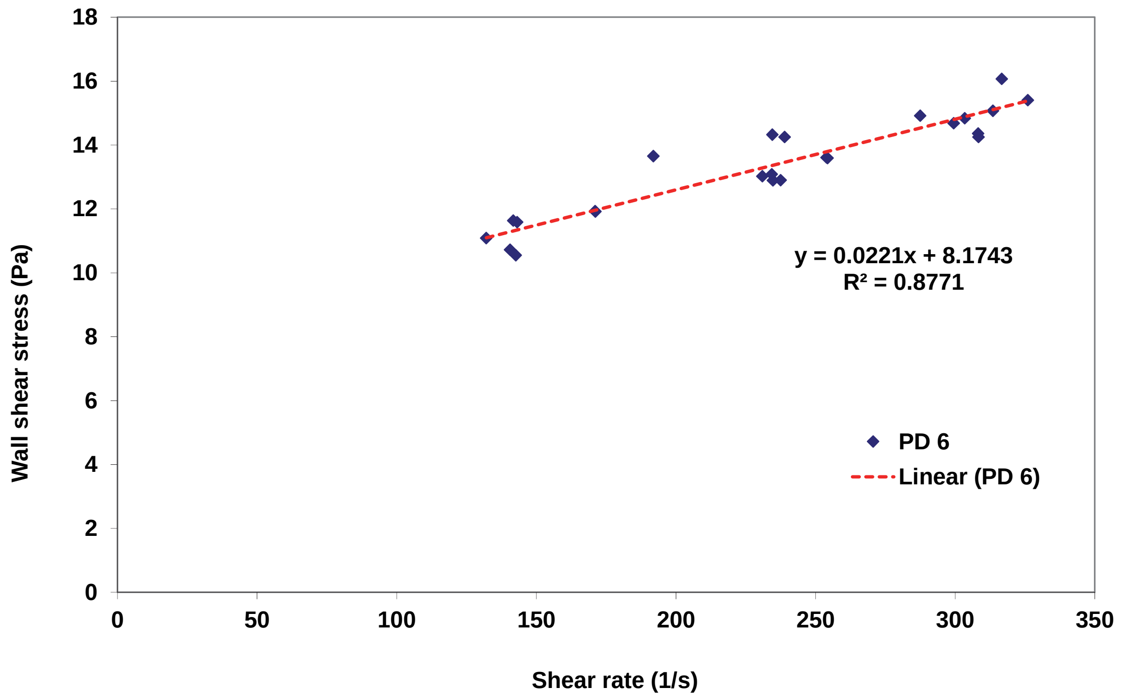

Figure 22 Potsdam WWTP secondary sludge 6 (PD 6 – 3.69%) Flow curve

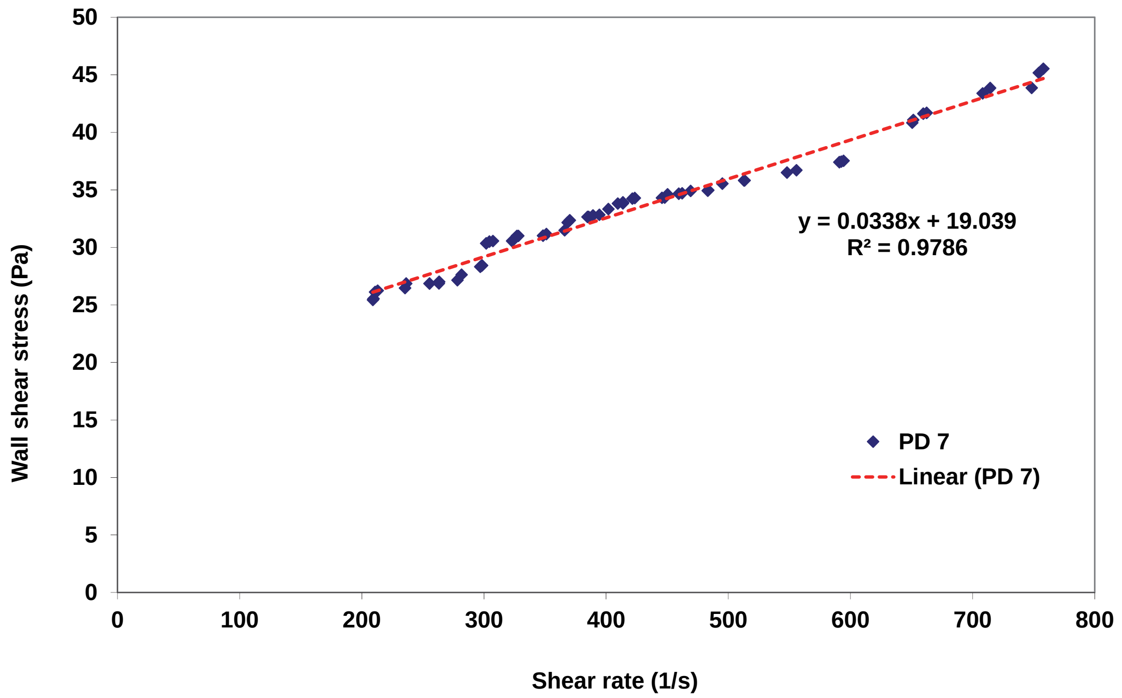

Figure 23 Potsdam WWTP secondary sludge 7 (PD 7 – 4.66%) Flow curve

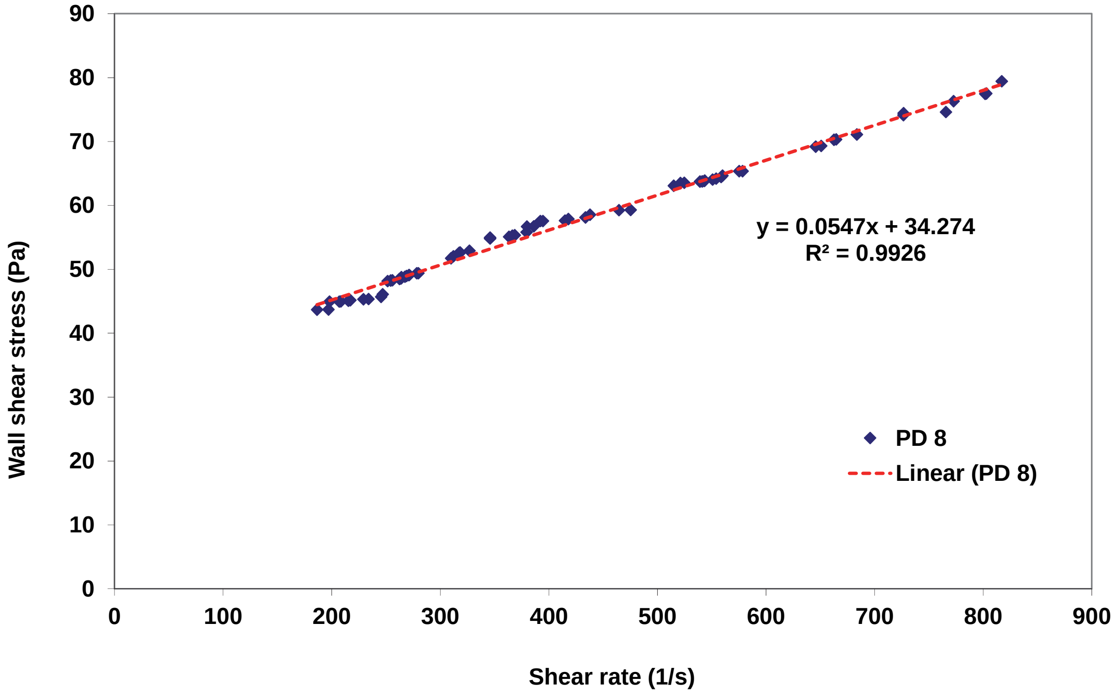

Figure 24 Potsdam WWTP secondary sludge 8 (PD 8 – 5.8%) Flow curve

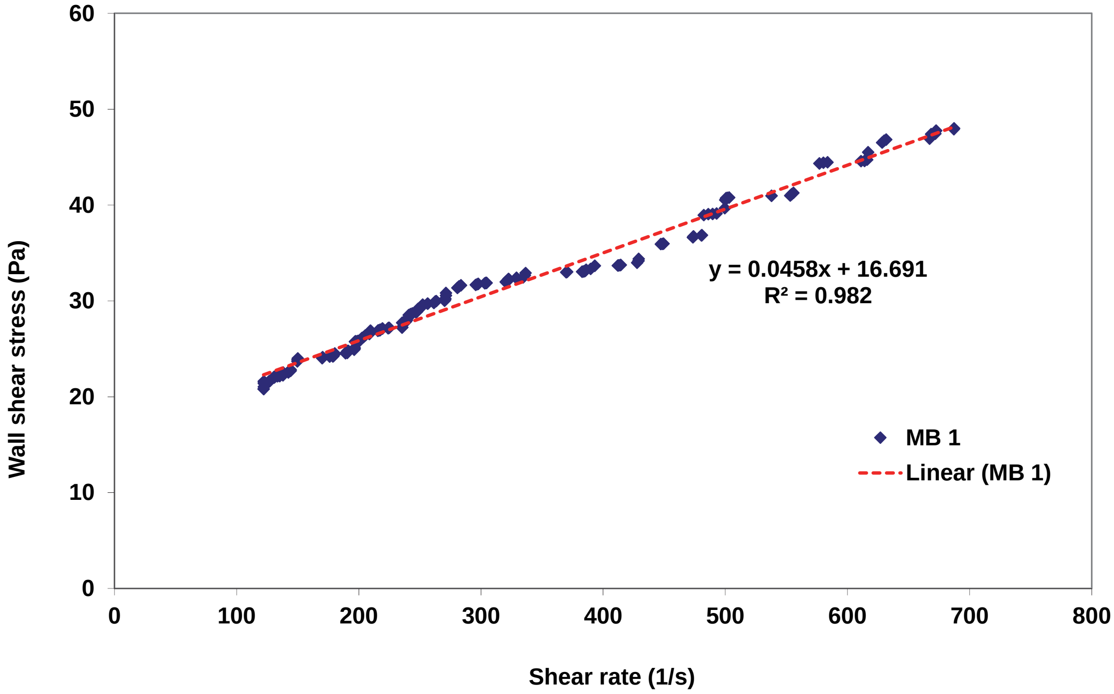

Figure 25 Melkbosstrand WWTP Sludge 1 (MB 1 – 4.92%) Flow curve

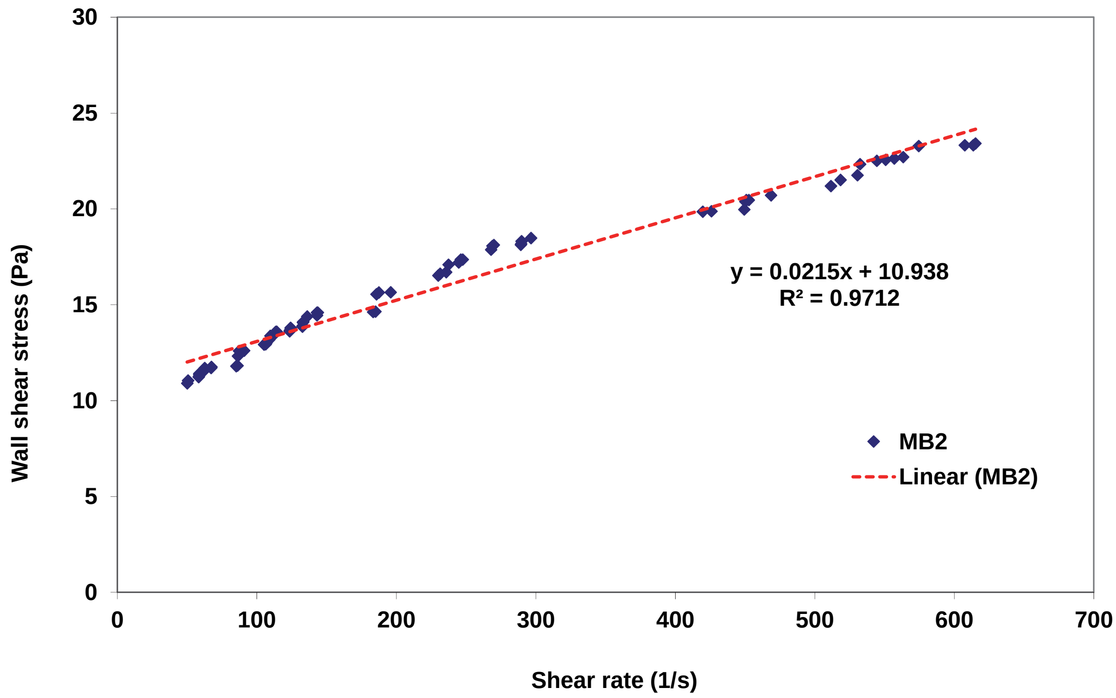

Figure 26 Melkbosstrand WWTP Sludge 2 (MB 2 – 4.15%) Flow curve

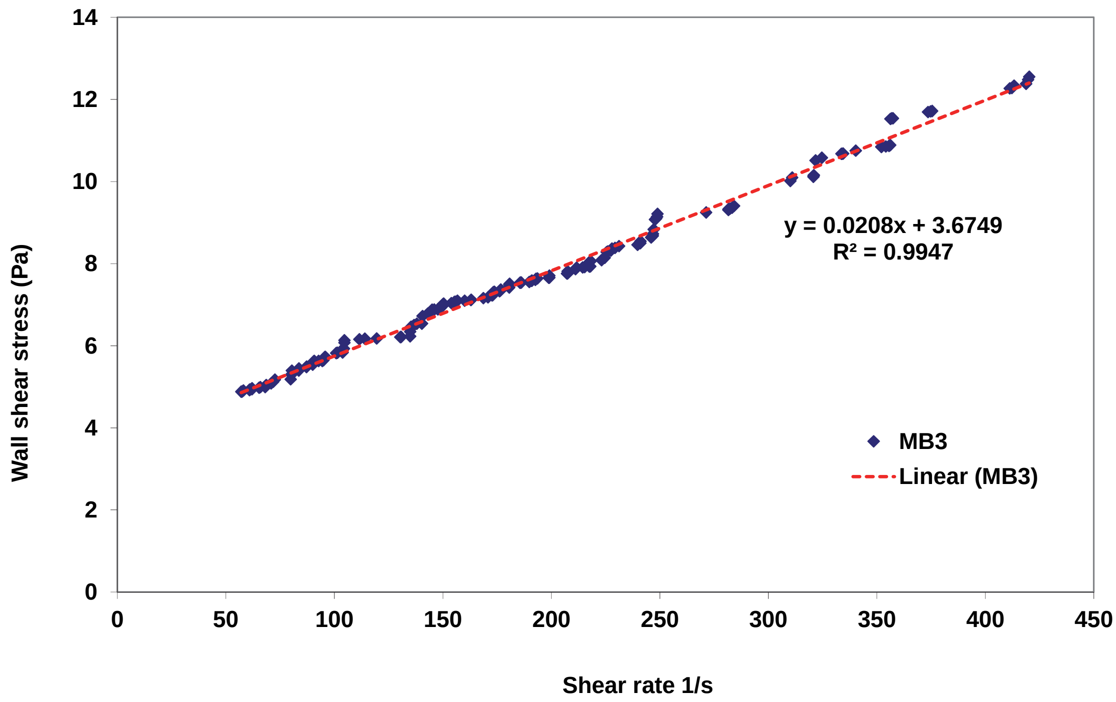

Figure 27 Melkbosstrand WWTP Sludge 3 (MB 3 – 3.32%) Flow curve

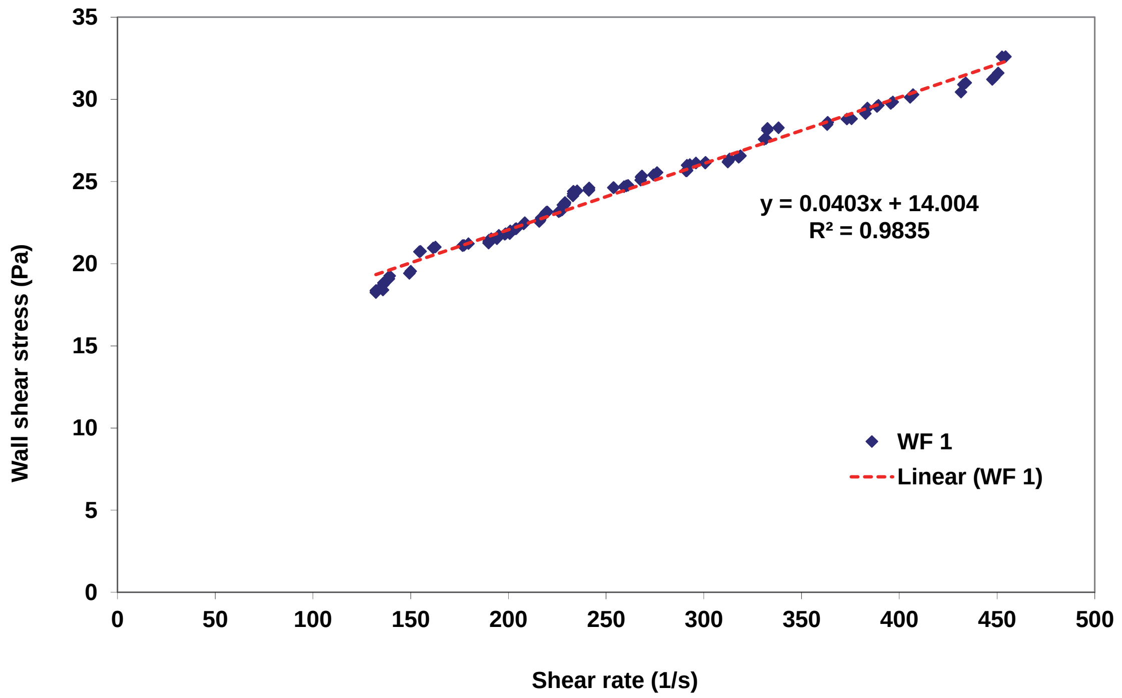

Figure 28 Wesfleur WWTP sludge 1 (WF 1 – 6.99%) Flow curve

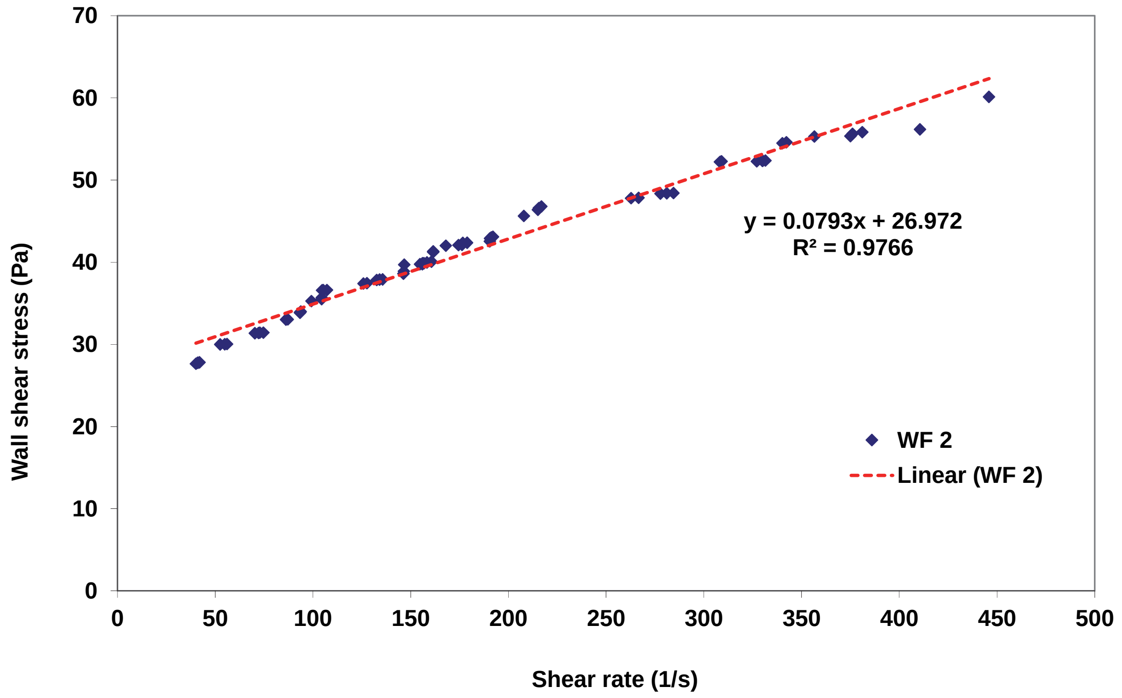

Figure 29 Wesfleur WWTP sludge 2 (WF 2 – 7.78%) Flow curve

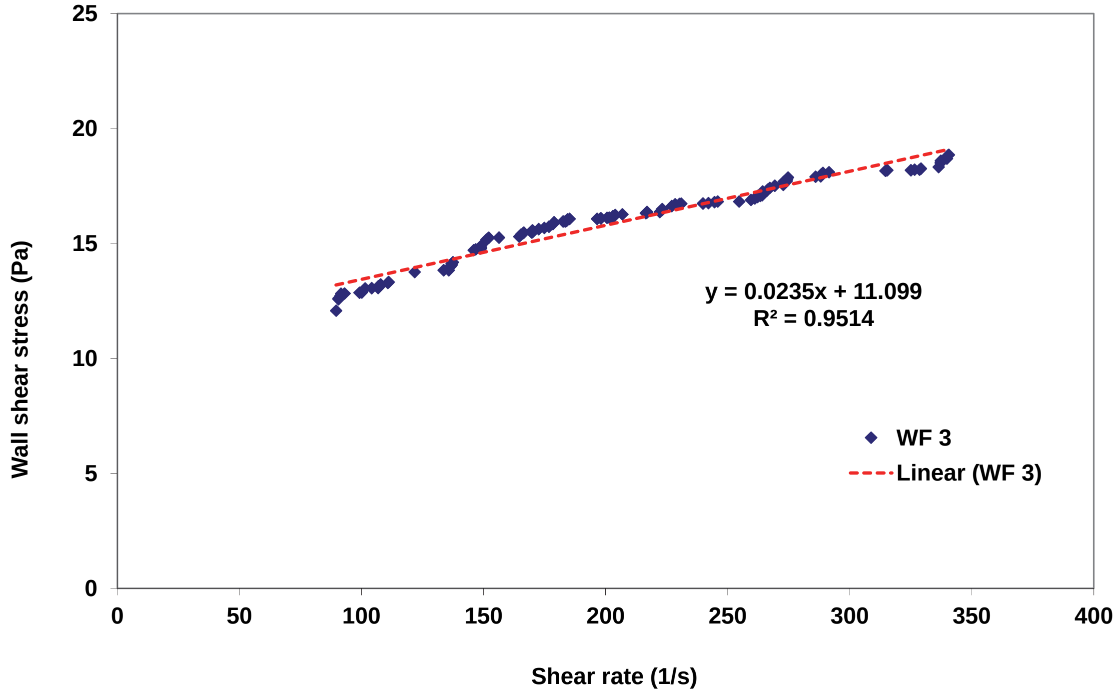

Figure 30 Wesfleur WWTP sludge 3 (WF 3 – 6.03%) Flow curve

4.3 UVP+PD results

During May 2014 the portable rig was again transported to Potsdam to facilitate the in-line measurement of sludge rheology using the Flow-Viz system and comparing these with the results obtained with the tube viscometer.

Three concentrations secondary sludge obtained from the filter belt press at Potsdam were used. The tube viscometer tests were done as described in Section 3. For each of the three sludges the UVP results and the fitted velocity profiles are depicted in Figure 31, Figure 33 and Figure 35. The results obtained from both UVP and tube viscometer systems are depicted in Figure 32, Figure 34, and Figure 36. The summary of the results is given inTable 2.

Table 2 Summary of rheology results – comparison between UVP-PD system and tube viscometer

Potsdam Secondary sludges May 2014	Concentration (%) (previously tested Potsdam sludge)	Yield stress τ_y(Pa)	Bingham viscosity K(Pa.s)	Yield stress τ_y(Pa)	Bingham viscosity K (Pa.s)
		UVP-PD	UVP-PD	Tube Visco	Tube Visco
Sludge PD 9	4.6	21.65	0.037	20.38	0.042
Sludge PD 10	3.6	7.82	0.021	8.34	0.024
Sludge PD 11	3.3	5.29	0.019	4.98	0.021

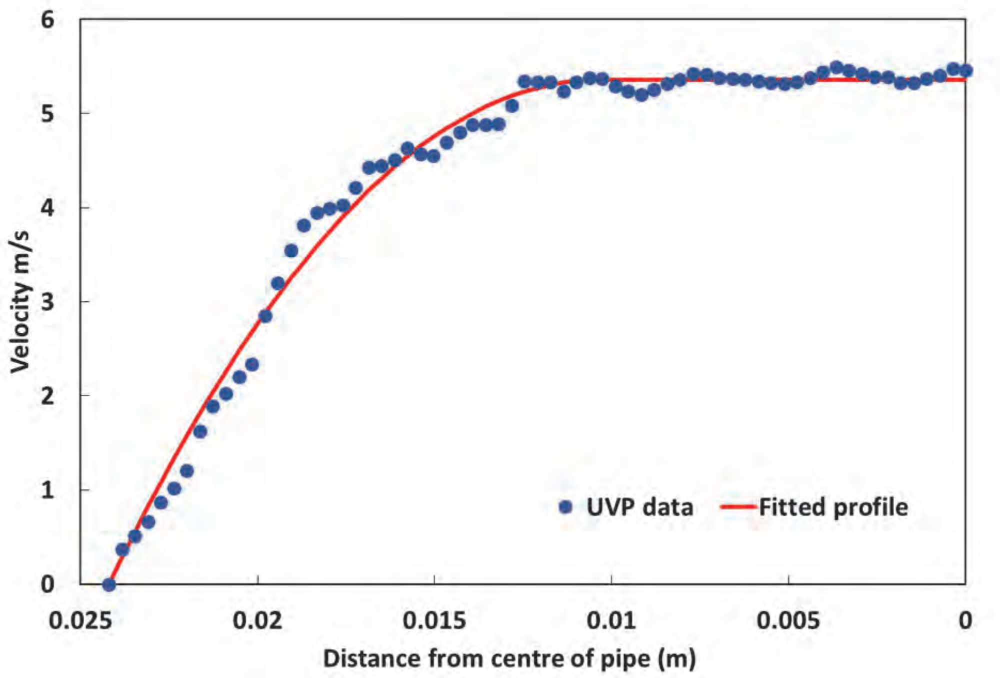

Figure 31 UVP measured data and fitted velocity profile for sludge PD9

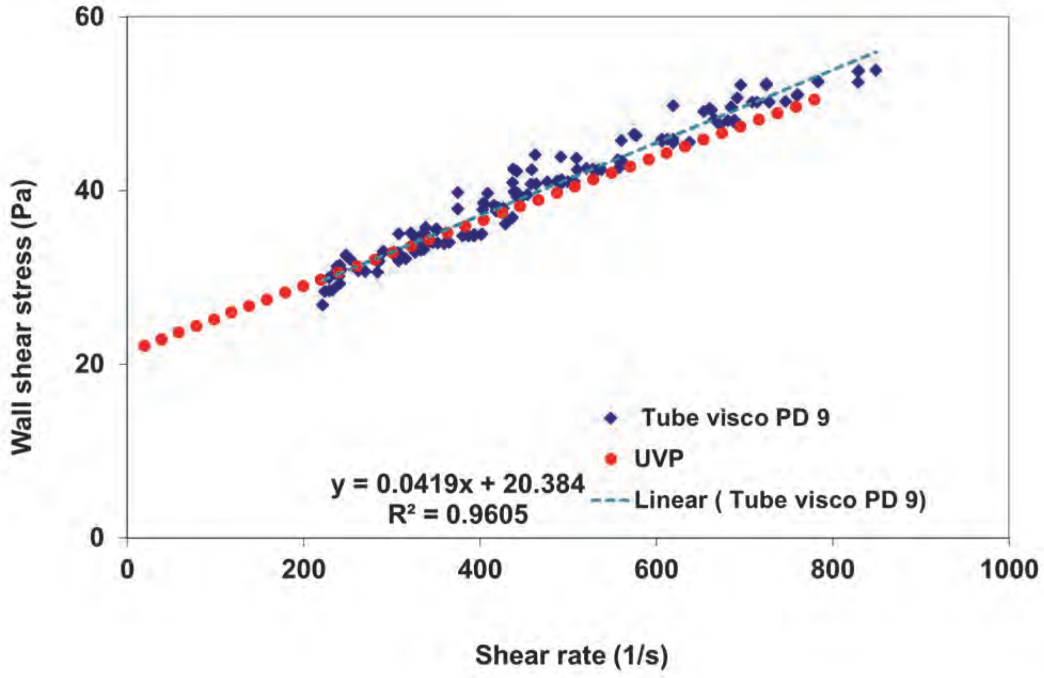

Figure 32 Potsdam secondary sludge PD9 Comparison of rheology- UVP with tube viscometer

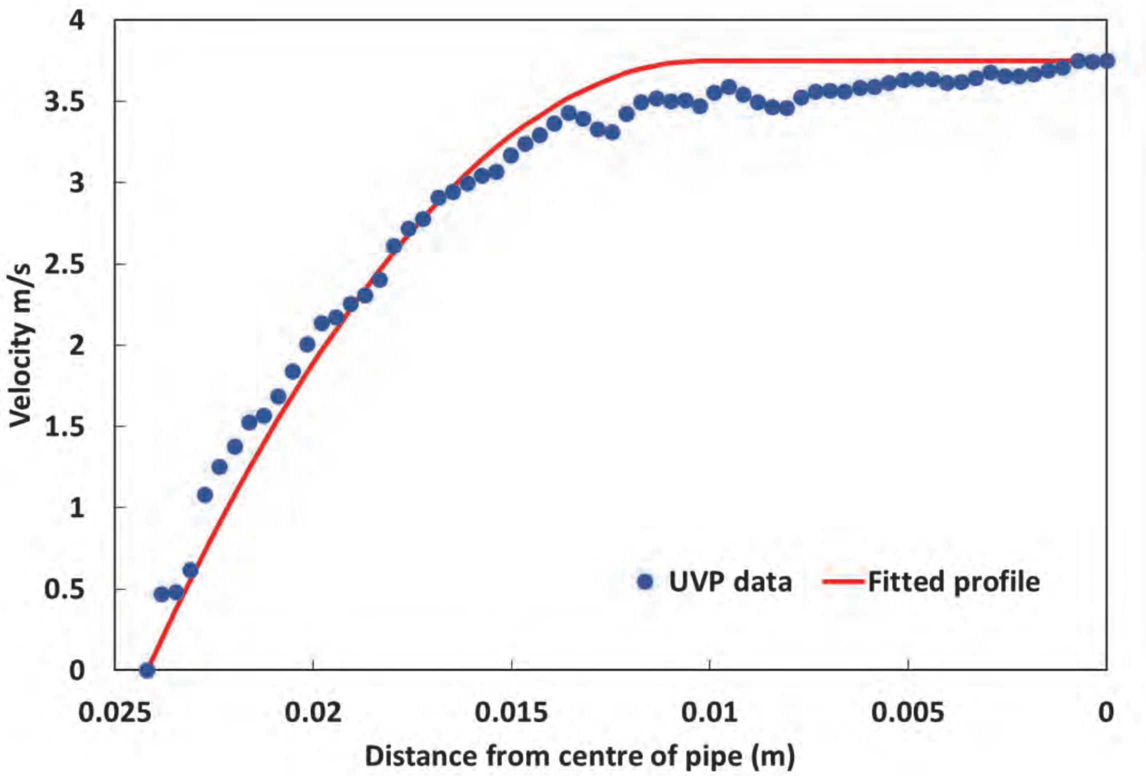

Figure 33 UVP measured data and fitted velocity profile for sludge PD10

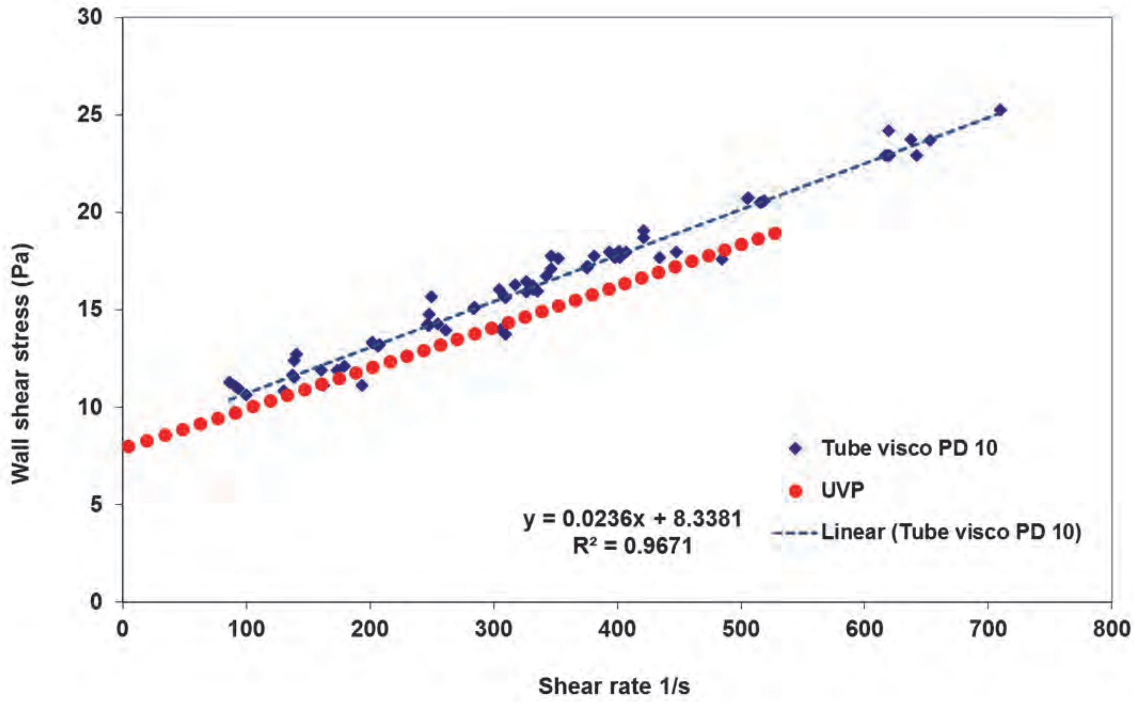

Figure 34 Potsdam secondary sludge PD10 Comparison of rheology- UVP with tube viscometer

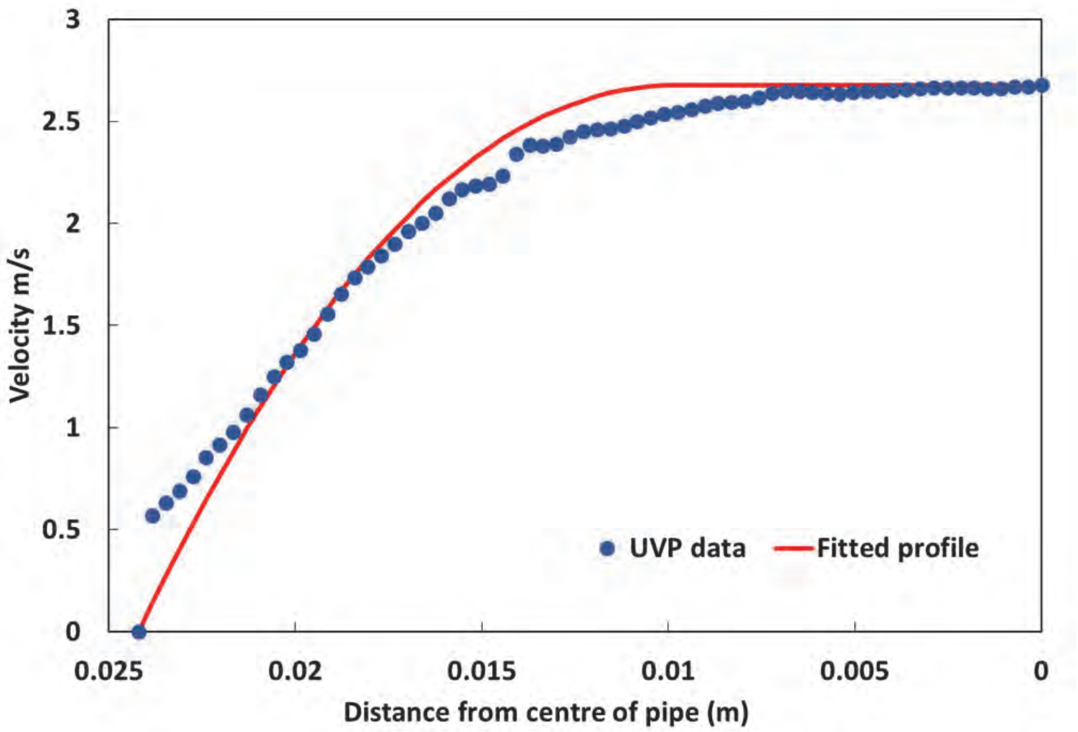

Figure 35 UVP measured data and fitted velocity profile for sludge PD11

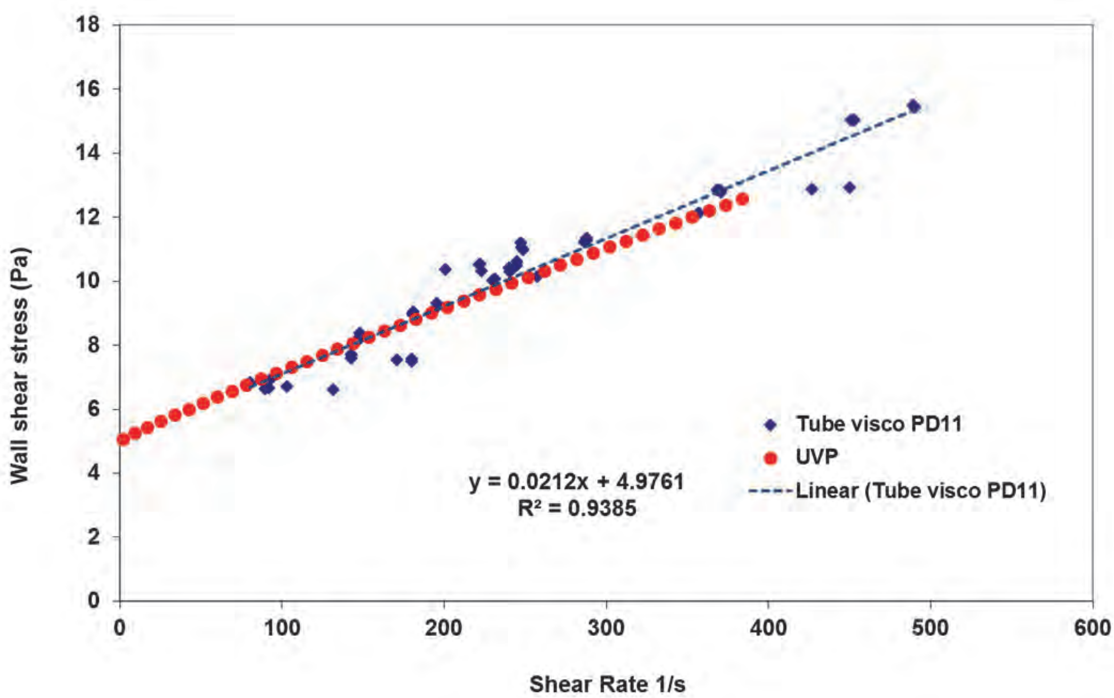

Figure 36 Potsdam secondary sludge PD11 Comparison of rheology- UVP with tube viscometer

The main objective of this part of the project was to compare the UVP+PD results with those obtained from the tube viscometer over a range of concentrations. There was a problem obtaining the sludge concentrations for the three sludges. Even though the rheological parameters were significantly different, concentrations of 3.94, 3.89 and 4.01 were obtained for sludge PD9, PD10 and PD11. From the flowcurves, it is clear that these sludges matches PD7, PD6 and PD2 which results in concentrations of approximately 4.6% for PD9, 3.5% for PD10 and 3.3% for PD11. This is in our opinion a reasonable assumption. This data was not used to populate Figure 43 and Figure 44.

The maximum difference between the values obtained by the tube viscometer and the UVP system for yield stress is 6% and for the viscosity 12%. The comparison is very good especially since the tube viscometry takes 30-60 minutes to complete whereas the UVP measurement is taken over a very short time (less than one minute) at one flow rate.

This comparison also verifies that the UVP+PD system and method (Flow-Viz) is an accurate technique for rheological characterisation of wastewater. The in-line rheology is of much more use as it is an instantaneous flow characterisation.

4.4 Tube and rotary viscometer data done for Drakenstein municipality

The following data sets are included to expand the database. These tests were done for a pipeline design project and the Drakenstein Municipality gave us permission to include these in the report. Primary and secondary sludges were sampled at Wellington Paarl and Stellenbosch WWTPs. The flow curves are presented in Figure 37, Figure 38, Figure 39 and Figure 40. A summary of the rheological parameters is given inTable 3. The tests for Wellington sludges 1 and 2 were done in a rotary viscometer and the others in the small tube viscometer.

Table 3 Summary of rheology results for Wellington, Paarl and Stellenbosch sludges

Description	Solids Concentration (%)	Yield stress τ_y(Pa)	Bingham viscosity K(Pa.s)
Well 1 Waste sump sludge	4.65%	8.34	0.01
Well 2 Waste sump sludge	3.24%	7.36	0.011
Well 3 Waste sump sludge	3.1%	0.91	0.005
Paarl 1 Primary sludge	3%	1.1	0.008
Stell 1 Primary sludge	?	12.63	0.032

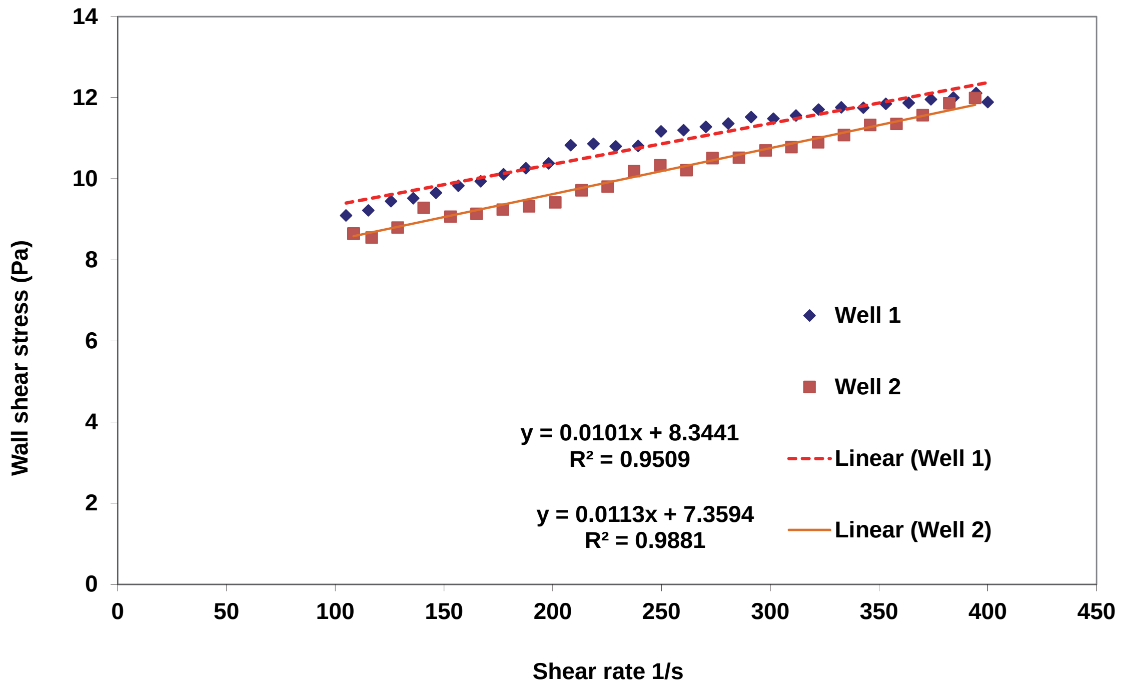

Figure 37 Wellington waste sump sludge (secondary) (Well 1 – 4.65%, Well 2 – 3.24%) Flow curve, Tests done with rotary viscometer

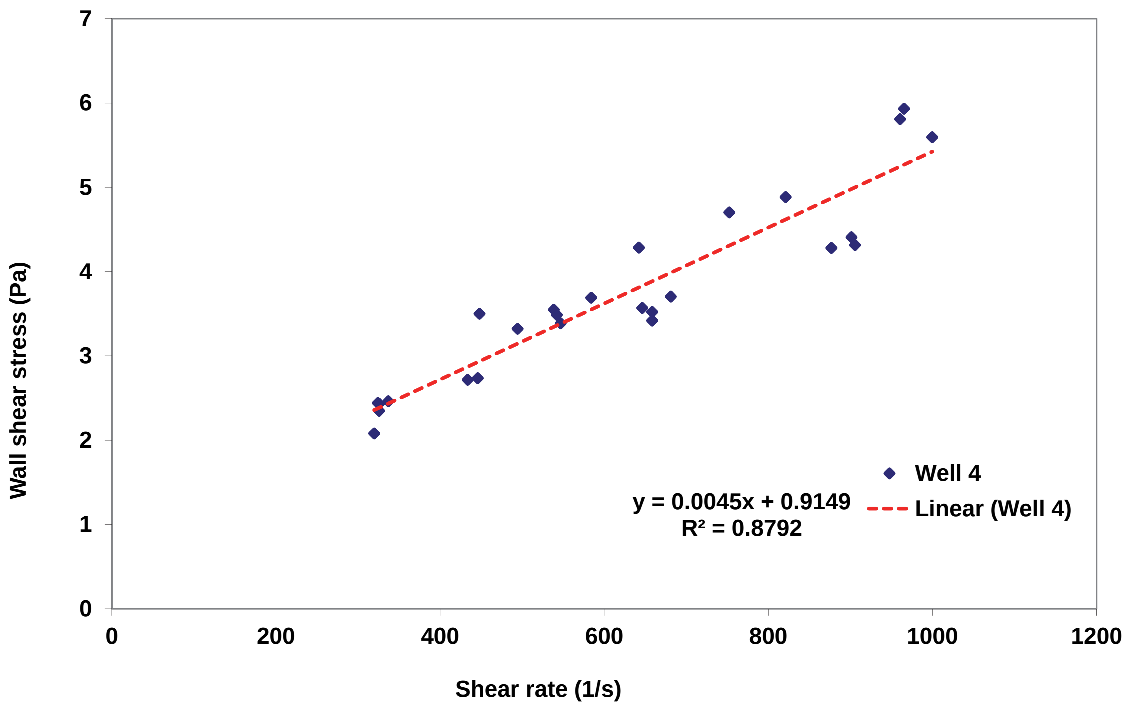

Figure 38 Wellington primary sludge (Well 3 – 3.1%) – Small tube viscometer

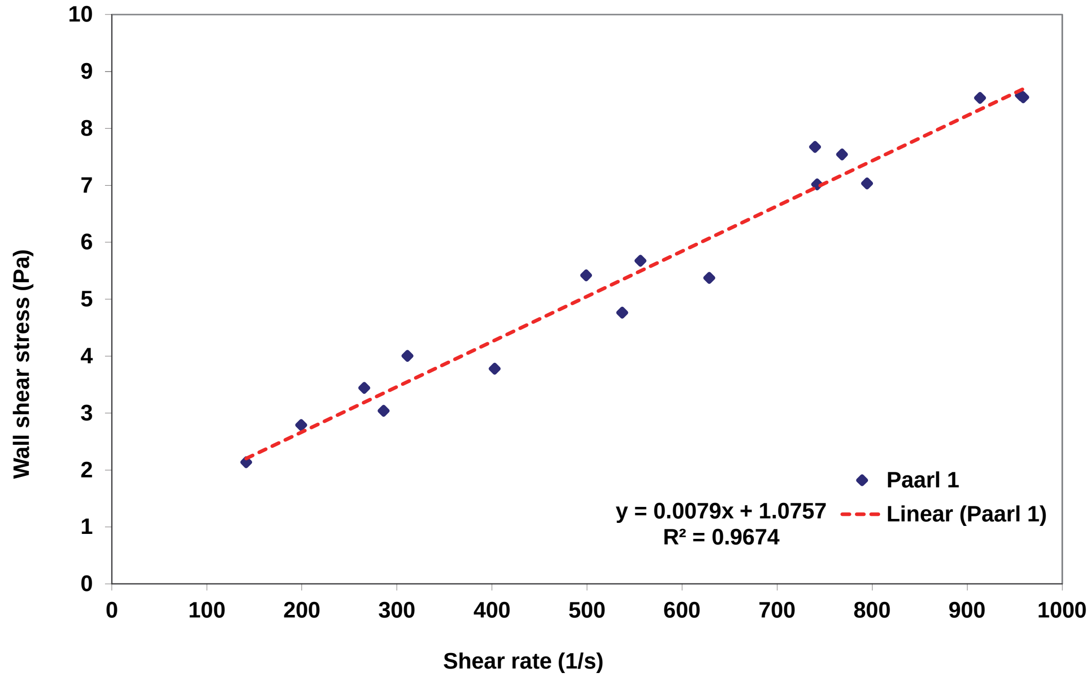

Figure 39 Paarl primary sludge (Paarl 1 – 3%) – Small tube viscometer

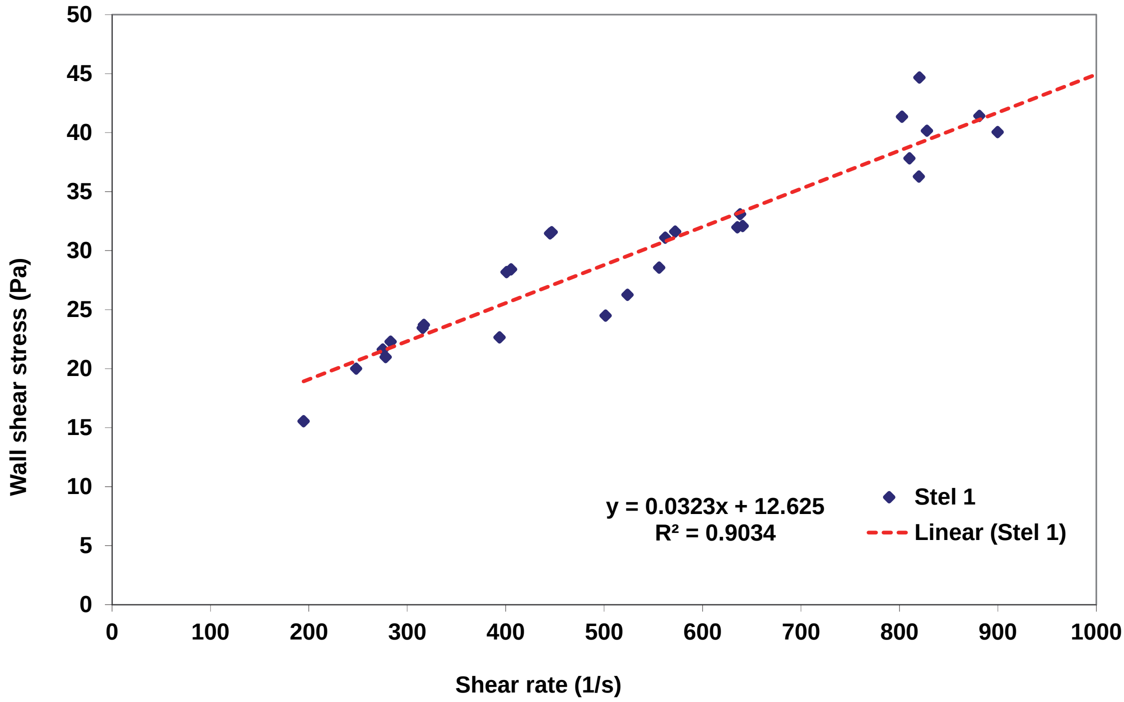

Figure 40 Stellenbosch primary sludge (Stell 1) – Small tube viscometer

5 DISCUSSION

Figure 41 presents a comparison of all the flow curves, representative of the pressure drop data, obtained for all sludges tested. Small changes in concentration can result in a significant increase in the wall shear stress. For example, at a shear rate of 300 1/s, the difference between the lowest and highest wall shear stress is 50 Pa, the lowest which will be nearly Newtonian at 5 Pa and the highest at 55 Pa. The difference in solids concentration is approximately between 3.5% and 8%.

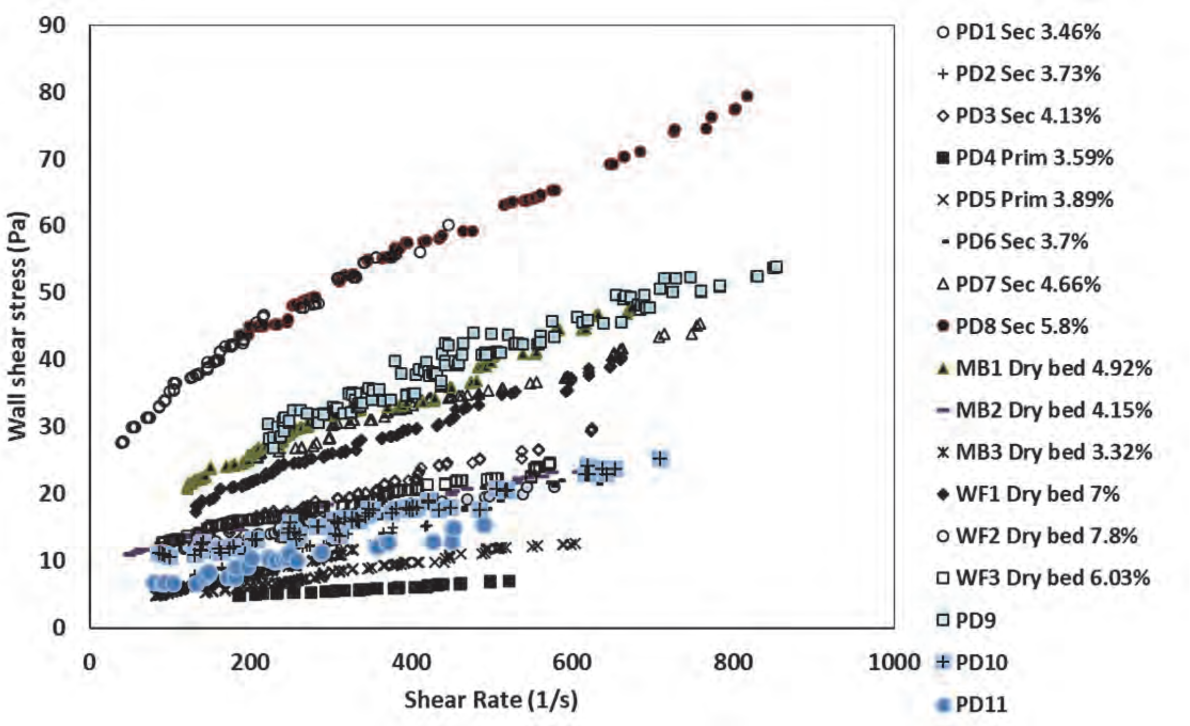

Figure 41 Summary of all the flow curves (Phase 1)

The increase of yield stress with increase in concentration is well known for sludges and mineral tailings. In both it has been recorded that at a certain concentration the yield stress will increase drastically (Mori et al., 2005; Foster, 2002: Zhou et al., 1999). This has a great influence on the pumping predictions for pipeline design.

Figure 42 shows a plot of Bingham yield stress versus solids concentration to determine the critical solids concentration for sludge in the Western Cape. Data from Paarl and Wellington sludges were also incorporated.

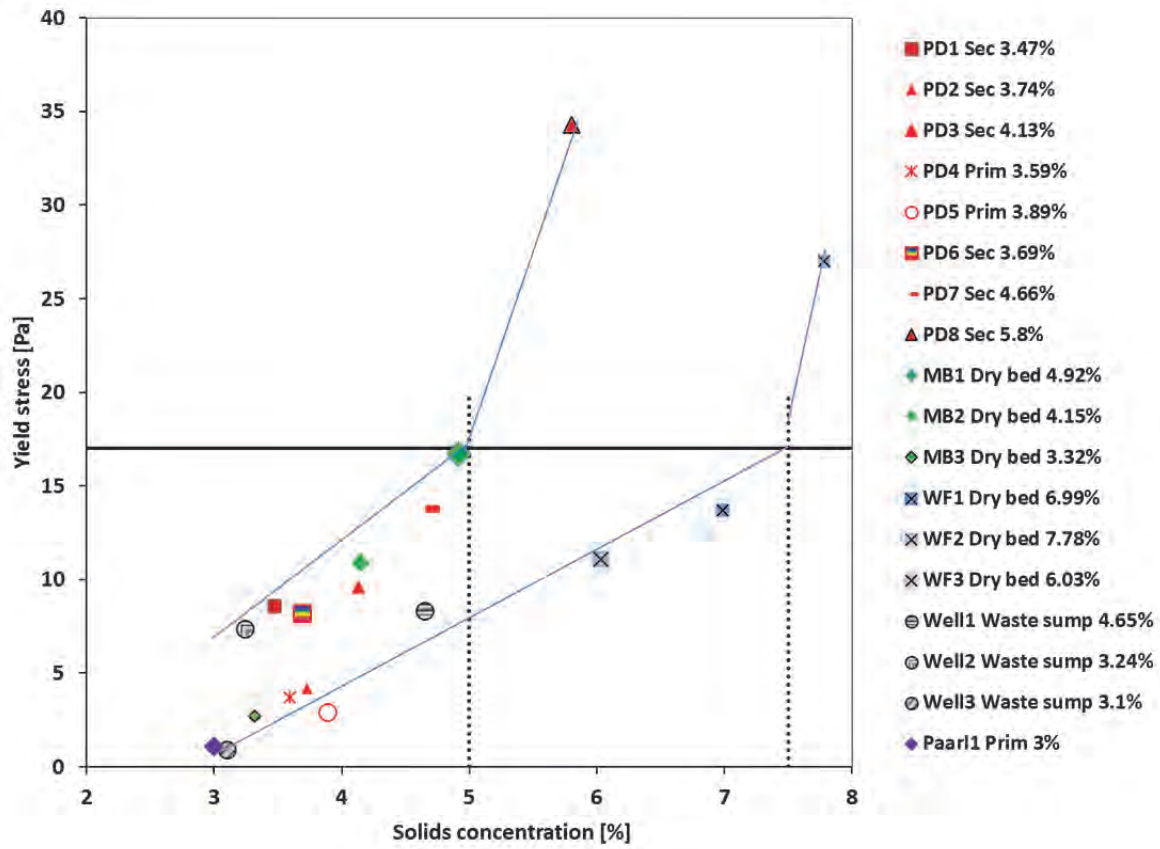

Figure 42 Effect of solids concentration on Bingham yield stress

Apart from a few anomalies, two distinct trends were observed. Firstly, a difference is observed between primary and secondary sludge from Potsdam. The primary sludge has lower yield stresses at the same concentrations than the secondary sludge that was diluted from the filter belt press. The sludge from the drying beds from Melkbosstrand showed similar behaviour to the Potsdam sludge. The Paarl primary sludge, Wellington waste sump sludge and the Wesfleur drying bed sludge followed a similar trend to that of the Potsdam primary sludge. The Wesfleur drying bed sludge trends offer higher critical concentrations (7.5%) compared to the trend obtained by the Potsdam secondary sludge (5%). The critical concentration is important as this is the point after which the yield stress increases exponentially.

The critical yield stress corresponding to the critical concentrations is approximately 17 Pa. Beyond this point, minor changes in concentration will result in significant increases in the yield stress and subsequent pumping requirements. Unfortunately there are not sufficient data in the high concentration range. However, greatly scattered results are common with wastewater sludge and trends should be verified. Furthermore, the floc structure should be evaluated in addition to the concentration to have a better understanding of the behaviour of wastewater sludge as a function of concentration. These rheological parameters will be compared with previous results to ascertain if a universal model can be established for predicting rheological parameters with solids concentration.

5.1 Combining all the tube and rotary viscometer data

If all the rheological parameters of the sludges tested as in Table 1 and Table 3 are combined with that published by Haldenwang et al., 2012, the relationship between Bingham yield stress and concentration is as given in Figure 43 and the relationship between Bingham viscosity and concentration is given in Figure 44.

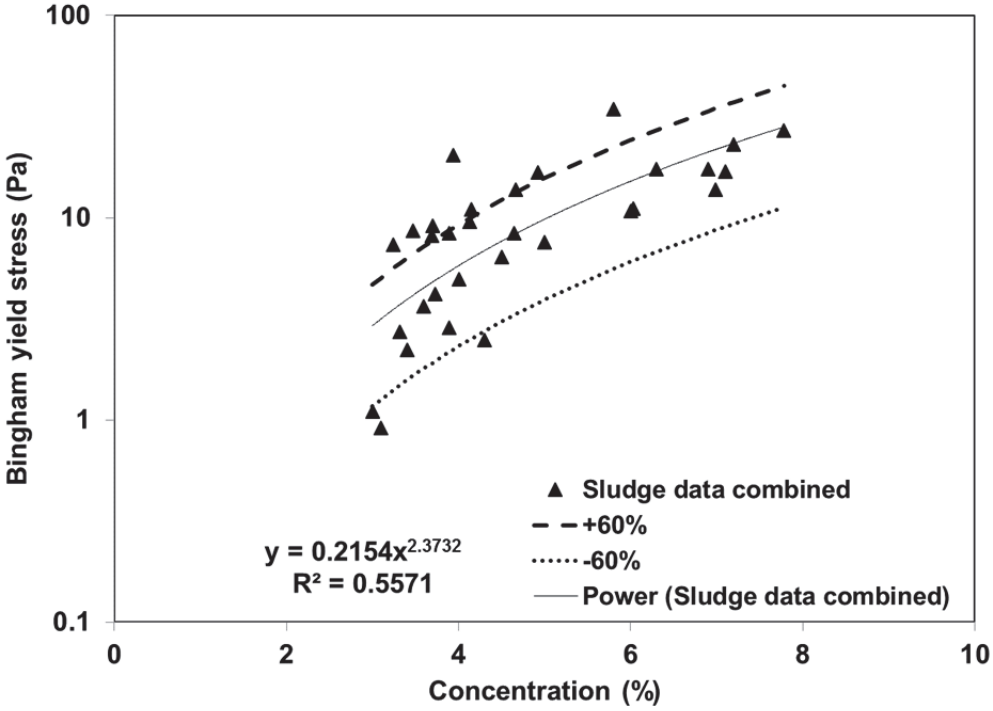

Figure 43 Relationship between Bingham yield stress and sludge concentration: combined current and Haldenwang et al., 2012 data

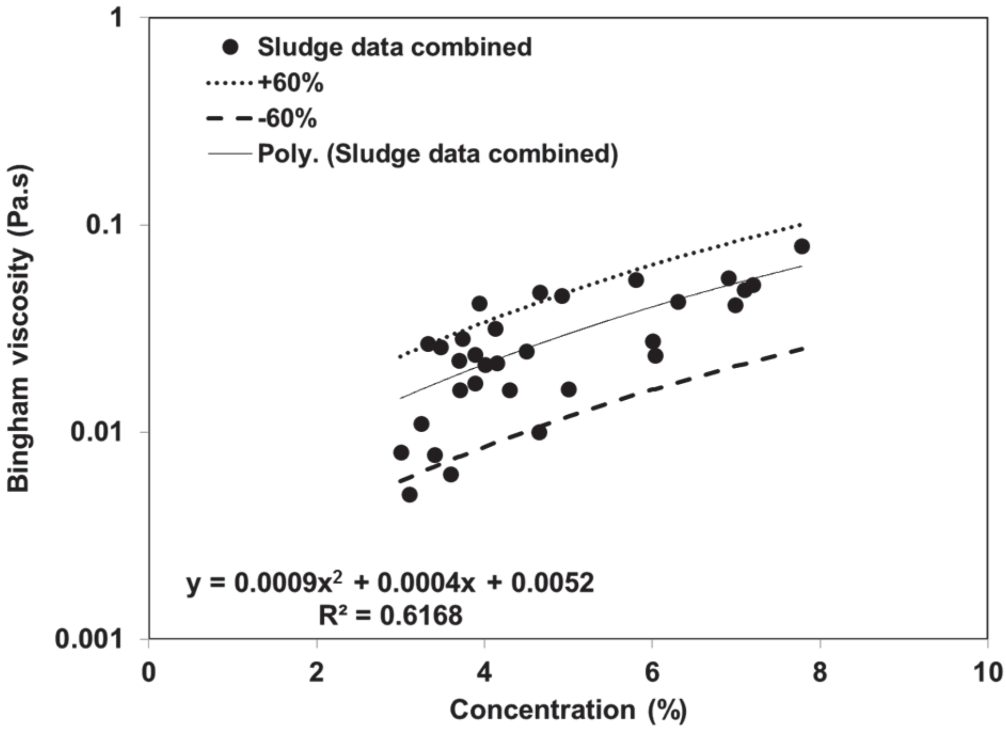

Figure 44 Relationship between Bingham viscosity and sludge concentration: combined current and Haldenwang et al., 2012 data

The relationships between Bingham yield stress and concentration as well as Bingham viscosity and concentration are not better than that proposed by Haldenwang et al., 2012.

However, more local data has been made available. This relationship can be used to predict pressure drop for sludges in pipelines.

6 CONCLUSIONS

The rheological properties of 21 sludges from six WWTPs in the Western Cape were tested ranging in solids concentration between 2% and 7.8%. Most tests were done in tube viscometers which are really small pipelines. The sludges were primary and secondary diluted from a filter belt press, secondary sludge diluted from a drying bed and from a waste water sump.

The rheological properties of these sludges varied hugely with Bingham yield stresses varying between 1 Pa and 34 Pa and the Bingham viscosity from 0.005 to 0.079 Pa.s.

The effect on pressure drop predictions is significant as can be seen in example shown in Appendix A.

The data was combined with that previously published by Haldenwang et al., 2010 and new predictions for both Bingham yield stress Figure 43 and Bingham viscosity Figure 44 were compiled. Using the new predictions developed the data can only be predicted in a range of +/- 60% certainty.

The effect of rheology on the prediction of pipeline pressure drop is shown in an example for 4% sludge (Appendix). This shows clearly that head loss can be greatly under-predicted if the rheology of the sludge is not known. Therefore extreme care must be taken when designing long pipelines transporting viscous sludges.

It was envisaged that the results would be closer grouped because of the fact that all the tests were done in the same tube viscometer. This was however not the case and again shows how complex sewage sludges are. The rheological parameters such as Bingham yield stress and viscosity cannot only be linked to concentration. There are many other factors that influence the behaviour of these sludges, such as the process, flocculation pre-shear history, etc.

This again confirms the fact that when designing pipelines to transport viscous sludges great care should be taken when estimating the rheology of such sludges. This will become more and more important as plants are trying to increase concentrations in the processes and the viscous properties increase. It will take some time before more accurate predictions will become available due to the complex nature of sewage sludge.

A new ultrasound transducer which can measure non-invasively through high grade stainless steel pipes has been tested with sludges for the first time. The Flow-Viz system (UVP+PD) was successfully tested with three concentrations secondary sludge and the results were compared with the tube viscometer. The fact that one can now determine the rheology of sludges in-line and in real-time, has huge potential for process control in the waste water treatment industry. Furthermore, the Flow-Viz system can accurately measure volumetric flow rate and monitor the flow regime of sludge transportation, e.g. the transition between laminar and turbulent flow can be visualised and identified. By monitoring the actual flow profile of the fluid inside the pipe the user has access to more information that can be used to gain a better understanding of these complex flows.

7 RECOMMENDATIONS

It is recommended that rheology be tested if sludge is available when scale up is required. When sludge is not available at the time of design, the models developed in this work can be used as an estimate, but an allowance of 60% should be included to account for variability.

The more sludge rheology data is made available the more accurate pipeline pressure drop predictions will become. A large sludge rheology database will facilitate more accurate pipeline pressure drop predictions for efficient and sustainable design of waste water treatment systems. With the Flow-Viz system this becomes now easier as the time taken for testing is much shorter and we have built a much smaller portable rig which could be used in future.

A detailed study of floc structure formation and its effects on the rheological behaviour of sludge at the same concentration is required for microstructural control of rheology. In the absence of such understanding, monitoring of the sludge in-line in real time becomes essential.

The feasibility of using the Flow-Viz system for measuring the rheology of sludges in-line has been proven. This has huge potential for optimisation of polymer dosing if one can link the rheological parameters of the sludge to the optimum polymer concentration. This should be investigated.

The study of non-Newtonian fluid mechanics and rheology is not that well known and more students should be exposed to this field of study at universities.

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APPENDIX A: PIPELINE PRESSURE DROP PREDICTION EXAMPLE

The effect of the significance of the variation of sludge rheology is illustrated by the following example.

A 10 km pipeline with an inner diameter of 250 mm is required to transport a sludge with concentration of 4% by weight. What would the pressure drop be?

From Figure 45and Figure 46one can extract for the minimum and maximum values of yield stress and viscosity for a 4% sludge. These values are depicted in Table 4.

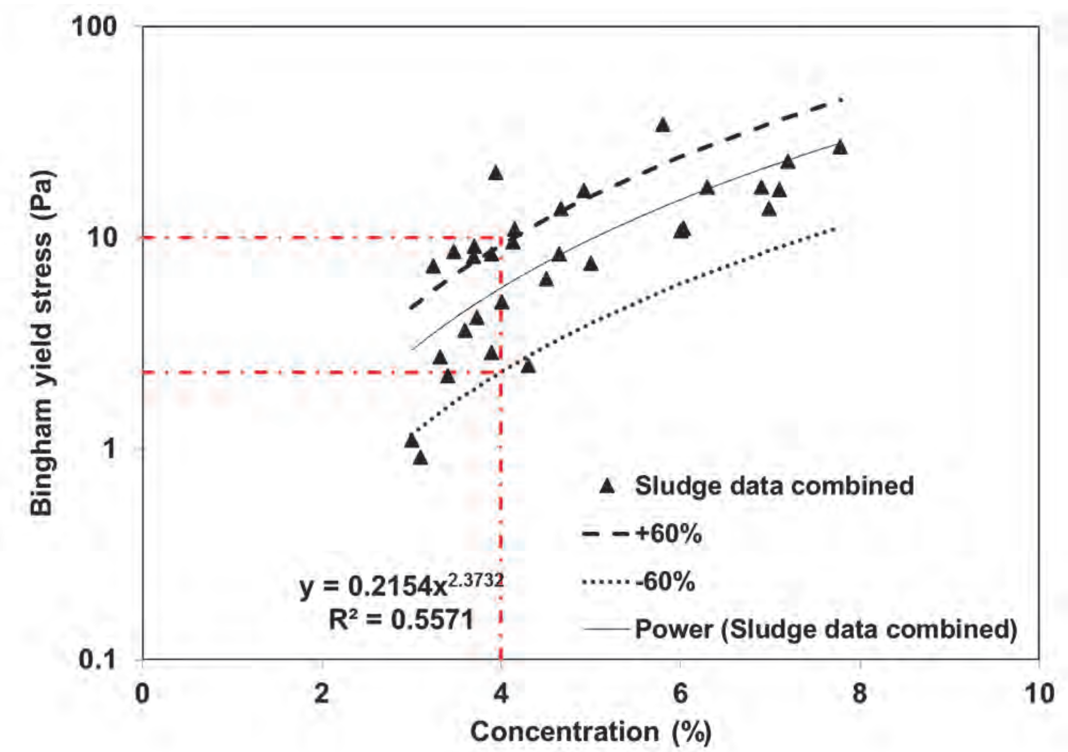


Figure 45 Estimate of maximum and minimum values of Bingham yield stress for a 4% sludge

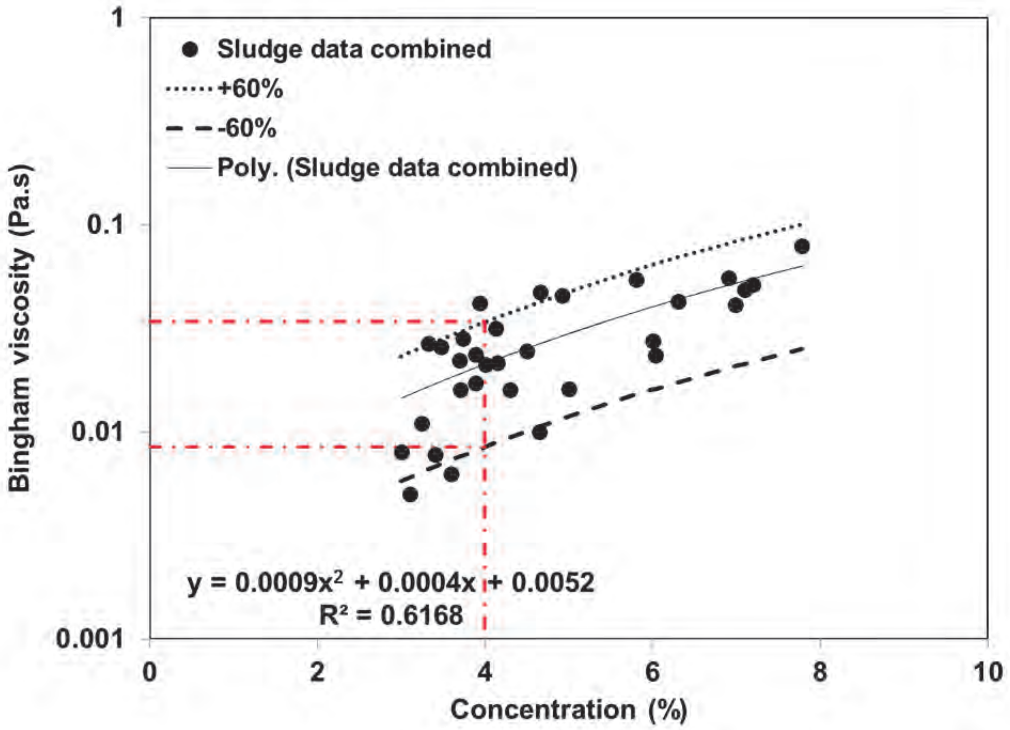


Figure 46 Estimate of maximum and minimum values of Bingham viscosity for a 4% sludge

Table 4 Rheological parameters used for pipeline pressure drop predictions.

Description	Solids Concentration (%)	Yield stress τ_y(Pa)	Bingham viscosity K(Pa.s)
WWTP sludge (Max rheology)	4 %	10	0.042
WWTP sludge (Min rheology)	4 %	3	0.006

The system curves for water and 4% sludge at maximum and minimum rheological parameters in laminar and turbulent flow for a 10 km 0.25 ID pipeline is shown in Figure 47. The effect of rheology on the head, both in laminar and turbulent flow, is obvious. Even for the minimum rheology of the 4% sludge the increase in head at 40 l/s is from 24-57 m.

The max difference is between the water and the max rheology data at 40 l/s which is from 24-208 m. This shows clearly that extreme care must be taken when predicting head loss in pipelines when viscous sludges are transported. It is important that the rheology of the sludges be measured accurately. A summary of the results is shown in Table 5.

Table 5 Effect of 4% sludge rheology pipeline pressure drop predictions (Example).

Description	Pt	Lam/Turb	Head loss (m)	Power (kw)
Water 40 l/s	A	Turbulent	24	9.5
Water 70 l/s	D	Turbulent	74	51
4% Sludge (min rheology) 40 l/s	B	Laminar	57	23
4% Sludge (max rheology) 40 l/s	C	Laminar	208	82
4% Sludge (min rheology) 70 l/s	E	Turbulent	97	67
4% Sludge (max rheology) 70 l/s	F	Laminar	227	157

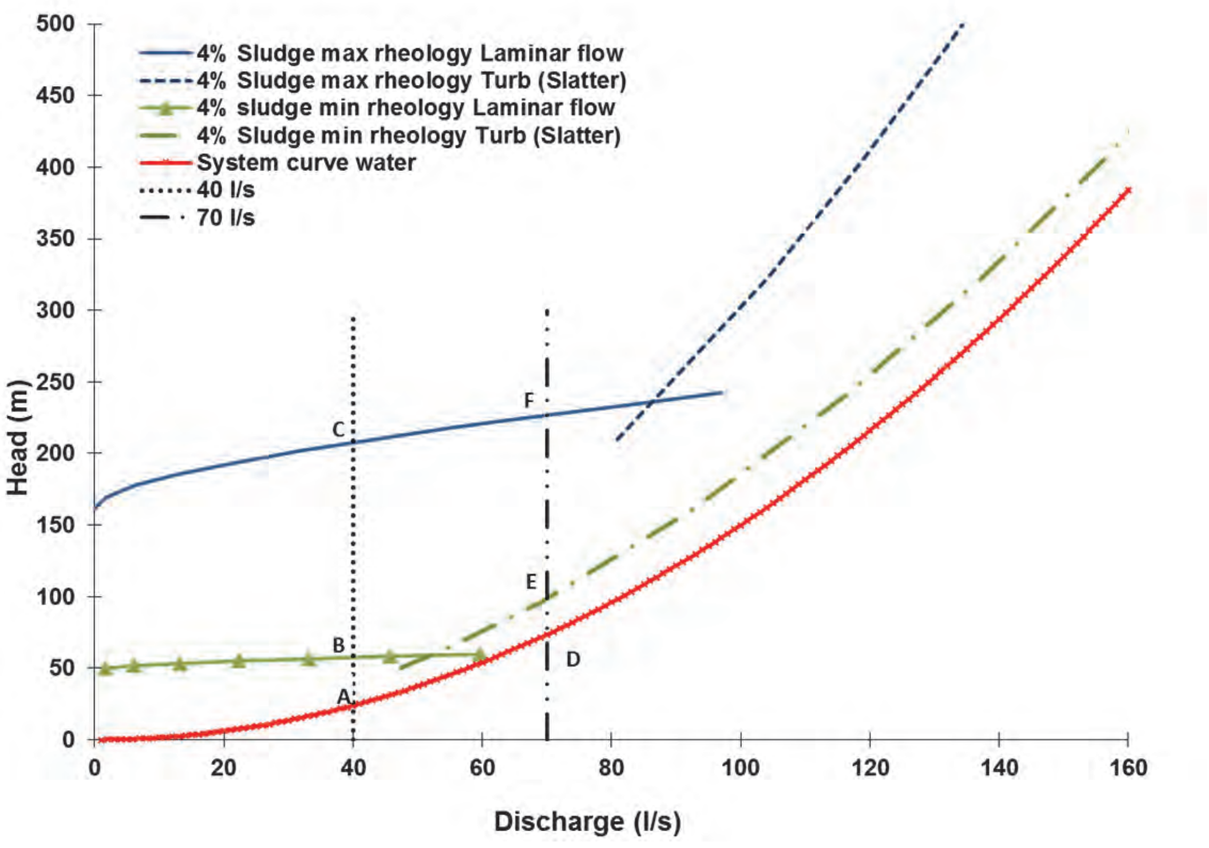


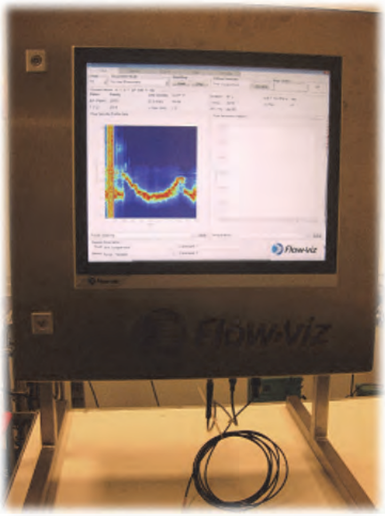
Figure 47 System curve for 4% sludge pipeline pressure drop prediction.

APPENDIX B: FLOW-VIZ SYTEM

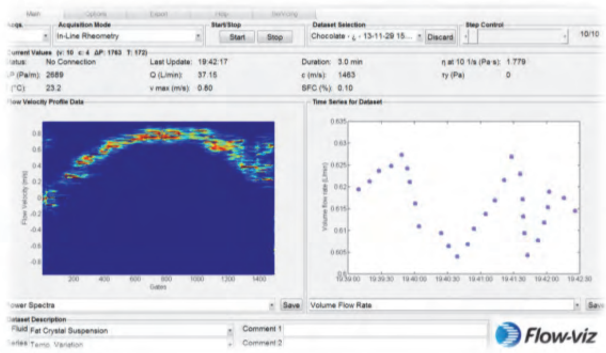
Flow-Viz

Brochure

Fluid Visualization & Characterization System

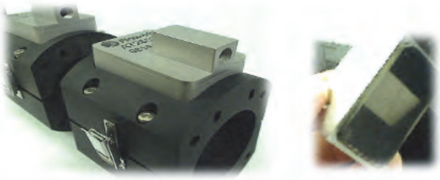


Operator's control



Easy-to-use

In-line, non-invasive sensor unit



Key Features

- Multipoint measurements are made in-line and in real-time
- Visualize complete flow profiles in high resolution
- Characterize in detail the flow behaviour and fluid properties (rheology)
- Applicable to opaque, non-Newtonian industrial fluids & suspensions
- Non-invasive & hygienically safe
- Flow-Viz software – complete on-line and off-line data processing package
- Provide continuous feedback to your process for enhanced efficiency & productivity

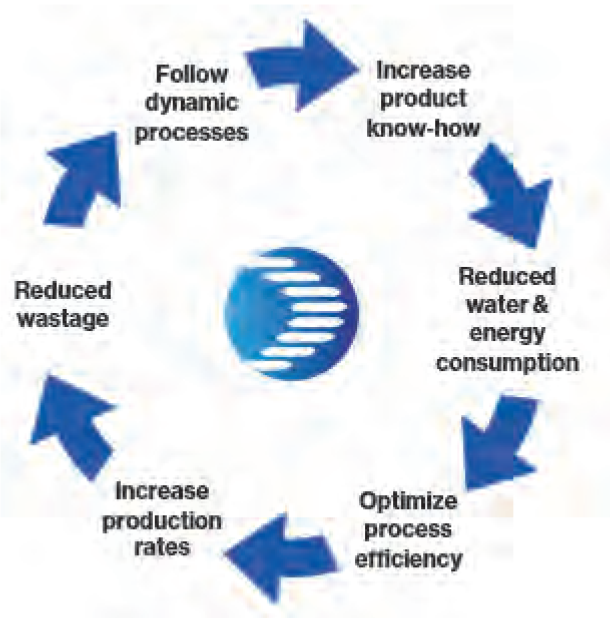
Sik your Science Partner

SP your Science Partner

Cape Peninsula University of Technology

Company pending

Product Benefits & Features



Real-time monitoring/measurement of fluid flow, rheology and transient processes makes it possible to adjust parameters directly while processing is taking place. As the system allows measurements at several points, it is possible to optimise the processes and increase production rates. Continuous measurement makes it possible to follow product changes, pasteurization, crystallization processes, CIP cleaning etc. in real-time. Measuring directly in-line provides new know-how about the product and the process. This offers a greater understanding of product features and how these are affected by the processes. Product quality can be optimized and novel products can be developed. Increased productivity and reduced water and energy consumption result due to more rapid product changes, more efficient washing, reduced wastage and optimized heat treatment processes. Inaccurate and time-consuming sampling and off-line sample analysis are now eliminated.

- REAL-TIME MONITORING — Monitor dynamic process live with continuous feedback and visualization.
- PROCESS INTEGRATION — Link user requirement parameter outputs to your process, 4 - 20 mA, 0 – 10 V DC.
- NON-INVASIVE SETUP — Non-contact installation for full hygienic and industrial compliance.
- MULTIPLE MEASUREMENTS — Measure several properties simultaneously, no need for multiple measuring tools.
- ZERO DOWNTIME — Continuous monitoring of complex flow and processes with no interruptions.
- CUSTOM SOLUTIONS — Custom modification and system design for your process and user application.
- ECONOMY & ENVIRONMENT — Knowing necessary fluid properties will give you more control, less waste and enhanced product quality.

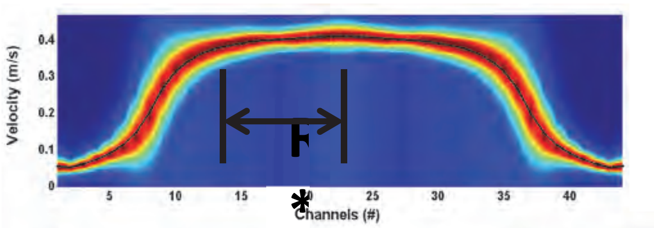
Applications Examples

- Food processing

Rheological characterization was achieved for tempered and un-tempered chocolate suspensions. By monitoring the viscosity the degree of temper can be determined in-line and in real-time.

- Construction industry

Grout suspensions of up to 0.4 water / cement ratio were rheologically characterized in-line and in real-time. This information will ensure that correct flowability of grout is achieved in order to completely seal cracks and crevices in e.g. tunnels.

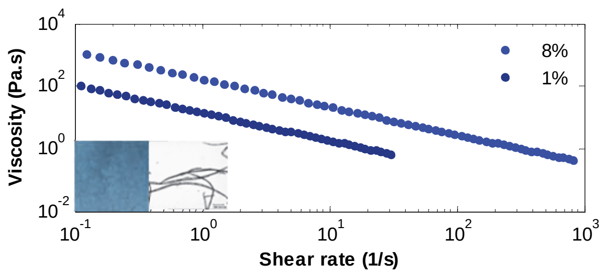


- Concentrated mineral suspensions

The Flow-Viz system was successfully evaluated in concentrated, non-Newtonian mineral suspensions. For example, bentonite 10% w/w with a yield stress of 80 Pa was successfully characterized. Bentonite is typically used as a drilling mud.

- Paper Pulp

The Flow-Viz system was used to measure velocity profiles and complex rheological properties, such as yield stress, directly in-line in highly concentrated paper pulp suspensions. The yield stress could be determined directly from the obtained plug radius, R*.



Other Applications:

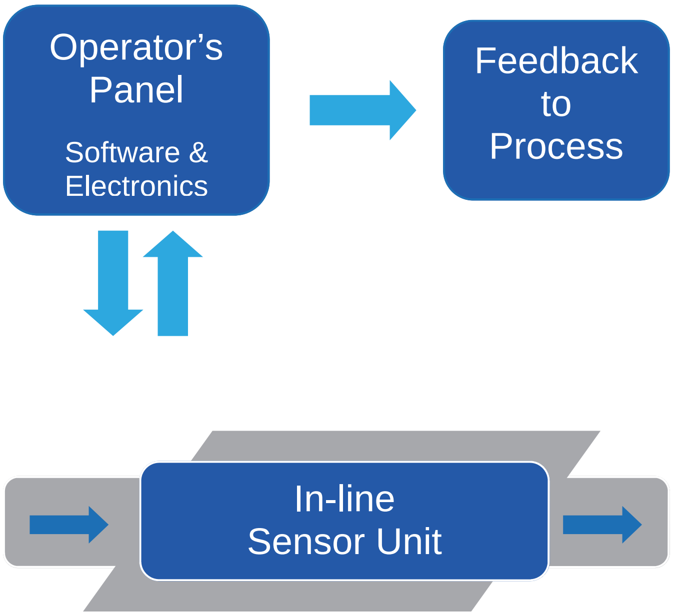
- Biochemicals
- Beverages
- Cosmetics
- Explosive emulsions
- Wastewater
- and more …

Cape Peninsula University of Technology

Company pending

System Overview

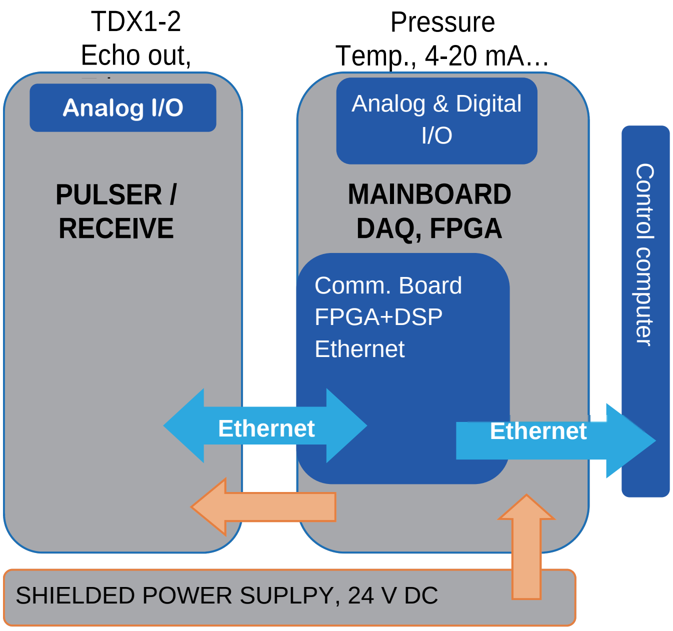
The Flow-Viz system uses an Ultrasonic Velocity Profiling (UVP) technique in order to measure an instantaneous velocity profile in a fluid containing particles across the ultrasonic beam axis. Newly designed sensor technology is used in transmitting and receiving mode to measure velocity profiles in pipe flow through stainless steel. A pressure difference measurement is used in combination with the velocity profile to determine shear viscosities and rheological model parameters. In parallel with obtaining radial velocity profiles, a data acquisition module continuously monitors the pressure and temperature (or other user selectable channels) and therefore is able to accurately visualize the flow, determine the flow-rate, rheological properties and concentration of solids, all in real-time. Specific measured parameters set by the user can be linked to an output analog signal and fed back in order to control and optimize a specific process.



Electronics Architecture

The system consists of two main parts: pulser-receiver and the mainboard. These are physically separated featuring a more compact measurement unit. The pulser-receiver is used to control and optimize the acoustic measurements (velocity profiles). The mainboard features the analog and digital data acquisition module (DAQ), high speed DSP (digital signal processor), FPGAs (field programmable gate arrays) and main communications board. Communication between both parts (and control computer) uses a **Fast Ethernet network**. An advanced, shielded power supply provides stable and efficient power to the system in order to ensure no loss of data and protection against electromagnetic noise and/or power spikes.

A **fast DSP and FPGA** is implemented within the acquisition part, combined with a special buffer system and fast A/D converters. The latter allows fast processing of large data sets, permitting the handling of large velocity profiles at high sampling rates and monitoring of fast transient flows.



Measurement Outputs

- VELOCITY PROFILE & SPECTRAL IMAGES
- SHEAR VISCOSITY / SHEAR STRESS VS. SHEAR RATE (FLOW CURVE)
- YIELD POINT & PLASTIC VISCOSITY
- VOLUMETRIC FLOW RATE
- TEMPERATURE
- DIFFERENTIAL PRESSURE
- RHEOLOGICAL MODEL PARAMETERS (OPTIONAL MODELS)
- ACOUSTIC PARAMETERS (VELOCITY OF SOUND & ATTENUATION GIVING E.G. SOLIDS %)

Services Available

- TECHNICAL SUPPORT
- APPLICATION SUPPORT
- INSTALLATION AND SETUP
- HARDWARE SUPPORT
- MAINTENANCE
- SOFTWARE UPDATES
- GUARANTEED WARRANTY
- TRAINING AND COURSES

Talk to us about a solution for your process

Technical Specifications

Parameters	Specifications	Comments
Instrument		
Velocity Measurement Range	0.1 m/s – 3 m/s	Bulk velocity
Temperature Measurement Range	-40°C to 150°C	See operating temperature
Pressure Measurement Range	0 – 2.55 bar	See operating pressure
Media	Compatible with flow element material	
Accuracy		
Flow	± 5% of true value	Media dependent
Temperature	± 1°C	
Pressure	± 0.5% of span	
Distance from instrument to pipe	< 3m	Can be extended
Enclosure	Stainless steel, IP66	IP67 pending
Flow Element (Sensor Unit)		
Material of Construction	316L stainless steel	
Operating Pressure	< 40 bar	Flange / tri-clamp connection: per rating
Operating Temperature	-40°C to 140°C	
Pipe Diameters (DN)	12.5 mm – 150mm (1/2” – 6”)	Inquire for application sizes outside the range
Process Connections	Tri-Clamp / Flange	(ANSI or DIN)
Flow element length	1m	Allow 10 nominal diameters in flow direction
Enclosure	Stainless steel, IP66	IP67 pending
Electronics (Control Panel)		
Processor	Intel Dual Core I7 1.5 GHz	Upgrades are available to fit customer need
Memory	2 GB DDR3	
Storage	USB FLASH	
Remote Control Interface	Ethernet 100 base-T	(RJ-45 remote connector)
Display	19”, 1280x1024 DVI/USB	Multi-touch display
AC in	110 / 240 V 60/50 Hz	
Operating Temperature	-25°C to 60°C	

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Technical Specifications

Parameters	Specifications	Comments
Electronics (Ultrasonics)		
Number of Tx / Rx channels (3-wire)	2	Non-simultaneous
Transducer impedance	50 ohm	
Emission voltage	30 – 250 $V_{p\text{-}p}$	Application dependent
Frequency range Tx/Rx	0.5 – 7 MHz	Application dependent
Rx amplification	7 – 55 dB	Linear in dB
Switch between single ended & balanced transducers		Switch via zero resistor
Two analog outputs (Tx & Rx)		After amplification
Clock frequency	45 - 150 MHz	Adjustable
Time of flight measurements		Automatic switching
Buffer memory	64 Mb	
Tx memory (for AWG)	4096 word, 14 bit digital to analog conversion	
DDS to configure sinusoidal signals		Optionally windowed
Demodulation	RF to IQ format	
FFT of IQ signal		On board processing
Two debug modes		
Power section synchronization		
PRF output connection		
Acquisition time window output		
Time Gain Compensation (TGC)		
TXRAM upload for AWG		
FFT mean extraction		Real-time velocity estimation

Contact Details

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