Rheological characterization of centrifuged thickened waste excess activated sludge (EAS): the maceration effect on sludge pumpability

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Rheological characterization of centrifuged thickened waste excess activated sludge(EAS): the maceration effect on sludge pumpability

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Abstract: The purpose of this study is to determine how the rheological characterization of centrifuged thickened waste excess activated sludge (EAS). Wastewater treatment plants (WWTP) contain a number of transport operations of suspensions with special flow characteristics. Flow characteristics, in particular viscosity related effects, vary from very water-like to strongly non-Newtonian.

This study uses a flow loop (or on-line apparatus) for pumping the EAS. The pressure loss versus flow rate measurement along a circular straight pipe (tube viscometer) provides the rheological data. As a complement, a rotational rheometer, Physica by Anton-Paar, was used to perform constant shear rate (CR) measurements on sludge samples.

Depending on the flow rate, but within the laminar flow regime, the reduction in pressure loss is order of $30-40\%$*. As expressed in the apparent viscosity this result in a ten times reduction, similar result reported in [4]. The obtained result indicate that a macerated EAS TS-content value may be chosen* $1-2\%$ *higher than the reference sludge with remaining pumpability and laminar flow condition.*

Biogasmax is a project aiming to reduce the use of fossil fuels in Europe providing that biogas is a good technical, economical and environmental alternative as vehicle fuels. The specific aim for Stockholm Water is to increase the biogas production at the existing waste water treatment plant in Henriksdal, Stockholm. This report is a part of an evaluation study of a method for disintegration of waste activated sludge aiming at an increased biogas production potential.

Contents

Nomenclature

acronym	units	Description
μ	Pas	shear viscosity
ρ	kg/m^3	density
σ	Pa	shear stress
$\dot{\gamma}$	s^{-1}	shear rate
D	m	pipe diameter
Δp	Pa	pressure drop
L	m	pipe length
U	m/s	velocity
f	$-$	friction factor
RE	$-$	Reynolds number
K	Pas^n	consistency coefficient
n	$-$	flow behaviour index
P	W	power
Q	m^3/s	flow rate

Index

$_{pseudo}$	pseudo
$_{app}$	apparent
$_{MR}$	Metzner-Reed definition

1 Introduction

Wastewater treatment plants (WWTP) contain a number of transport operations of suspensions with special flow characteristics. Flow characteristics, in particular viscosity related effects, vary from very water-like to strongly non-Newtonian, as the solids content increases in concentration and complexity, and as the flow conditions move from turbulent to laminar. In general, non-Newtonian fluids exhibit a non-linear relationship between the shear rate and the shear stress, and their viscosity cannot be described by a single number, but possibly by a curve or a set of curves.

The sewage sludge in WWTP is a water-based suspension with various concentrations of suspended particles and fibres, and dissolved substances. The characteristics of the sewage sludge vary depending on its origin and history. Municipal sludge differ between themselves, and from industrial sludge. The wastewater and sludge treatment processes influence sludge characteristics; chemical additives like polymers or mechanical operations like thickening affect sludge properties. All these factors will influence the fluid behaviour and sludge handling, [6].

The purpose of this study is to determine the rheological characteristics of centrifuge thickened waste excess activated sludge (EAS). In particular, the effects of total solids concentration (TS) content and of post-maceration (disintegration) by a mechanical option mounted on the centrifuge outlet are considered.

The objective is to increase the TS-content in the thickened sludge. However, volumetric and digestion process gains must be balanced against a potential increase in pumping power requirement as well as the power requirement of operating the centrifuge at another duty point, with a macerator installed. The installed pumping performance for the pipeline is an additional limiting factor.

The general understanding of pumping of thickened WAS in full-scale systems in WWTP is also improved.

Biogasmax is a project aiming to reduce the use of fossil fuels in Europe providing that biogas is a good technical, economical and environmental alternative as vehicle fuels. The specific aim for Stockholm Water is to increase the biogas production at the existing WWTP in Henriksdal, Stockholm. This report is a part of an evaluation study of a method for disintegration of waste activated sludge aiming at an increased biogas production potential.

2 Experimental design

This study uses a flow loop (or on-line apparatus) for pumping the fluid. By either operating a valve or by varying the pump frequency, different flow conditions can be obtained. The pressure loss versus flow rate measurement along a circular straight pipe (tube viscometer) provides the rheological data and system characteristics to be studied, during shear flow condition. The measurements concerns mainly pumpability of different types of EAS on the pressure side of a pump, for different flow conditions and TS content. Consequently, this study gives restricted information of the impact of different EAS on the suction side of a pump, *i.e.* the initial startup of pumping, also known as extensional rheology, [3].

As a complement, a rotational rheometer, Physica (MC1+) by Anton-Paar, was used to perform constant shear rate (CR) measurements on sludge samples. A configuration of concentric cylinder of both *small* gap and *wide-gap* geometry were used. The rheometer tests were complementary in data as well as in sampling flexibility, since significantly reduced amounts of sludge sample was needed to obtain a set of data, [2].

2.1 Flow loop: on-line measurement

The flow loop used consists of a closed flow loop of acrylic pipes (diameter 100mm) and a container (450 litres), a dry-mounted Flygt N-pump 3102, and a ball valve to change the flow rate. The closed flow loop is equipped with static pressure taps upstream and downstream of the pump (pressure head) and in both return legs of the loop, see Fig.1. The latter taps are used for pressure loss measurements along a straight pipe for the rheological characterisation (tube viscometer). The return pipe length is approximately $3m$ and the two pipe diameters are $53mm$ and $27mm$. Due to the length/diameter ratio, fully developed pipe flow is not expected for most of the flow rates $(0 - 25l/s)$. However, the pressure loss measurements are used to obtain a relative rheological measure for water and for the different sludge samples in the flow loop. A magnetic inductive flow-meter (Danfoss, Magflow 3100) was mounted 10 pipe diameters ($100mm$ pipe) downstream of the pump outlet. A second flow meter (Krohne, IPC110) was used in the $27mm$ return pipe, which allowed improved flow measurement in the low flow rate regime, *i.e.*$< 2l/s$. The pump power supply used a variable frequency drive (VFD, ABB ACS800-15kW) that also monitored electric input pump power required ($4.4kW$) as well as pump drive frequency. The pressure readings were obtained with Rosemount 3051-series transducers: CD2 ($0.25bar$) and CD3 ($2.5bar$)(total performance $\pm 0.15\%$ of FS). The pump temperature was recorded with a thermocouple device and the fluid was at ambient room temperature.

The data acquisition system was a Labview based program with a sampling rate of 20 Hz and 200 samples in order to obtain statistic ensemble average values of the relevant quantities (power, pressure and flow).

In all tests, the procedure included a warming up sequence of the pump for at least 15 min. The pressure tubing was re-flushed with water frequently in order to maintain water as a pressure carrier at any time, and avoid sludge fouling in tubing or air bubble entrainment, that would corrupt the pressure data.

2.2 Waste excess activated sludge

The sludge obtained for the test is separated into centrifuge thickened waste access activated sludge (EAS), hereafter named "reference" EAS, and the centrifuge thickened sludge macerated by the Lysatec device, named disintegrated/macerated/"lysed" EAS. The centrifuge thickened WAS is then further differentiated by total solid concentration (TS-content) value. The TS-content value of WAS is affected by the incoming TS-content upstream the centrifuge and the centrifuge differential rotational speed (diff-rpm). There is a variation in the incoming TS-content in the range of $0.6\% - 1.2\%$ due to WWTP loading. The differential rotational speed is controlled manually for each centrifuge unit, in the approximate interval $7 - 21rpm$. The TS-content value of sludge samples was determined by the conventional 105 degree C method by mass. The used centrifuges are of type Alfa-Laval XMNX-4565.

In the on-line flow loop test, the EAS is pumped through a feed PC-pump (Netzsch NM105SY02S08B) from the process into the container. The test is performed and the sludge is returned to the sludge process. In the rotational rheometer test, a sludge sample is taken closely to the outlet of the centrifuge or in the flow loop container before, under and after flow loop operations. Such a sludge sample is of the order of one litre, whereas in the flow loop a few hundred litres are needed.

2.3 Rheometer tests

The rheometer tests are performed by a sequence of sludge samples for different TS-content value, of reference and lysed sludge. The test procedure consists of subjecting the same sample to two consecutive constant shear rate(CR) mode tests, *i.e.* monotonic ramping up-and-down in the interval $10 - 700rpm$ and measuring the torque-values. The results can be directly evaluated in the torque-rotational speed space, but with some transformation the material characteristic shear stress-shear rate curve can also be obtained. The rheometer test is performed in two geometries: a bob-cup-DIN45(small gap) and in a paddle-jar (wide-gap)$d = 45mm$, see Fig.3.

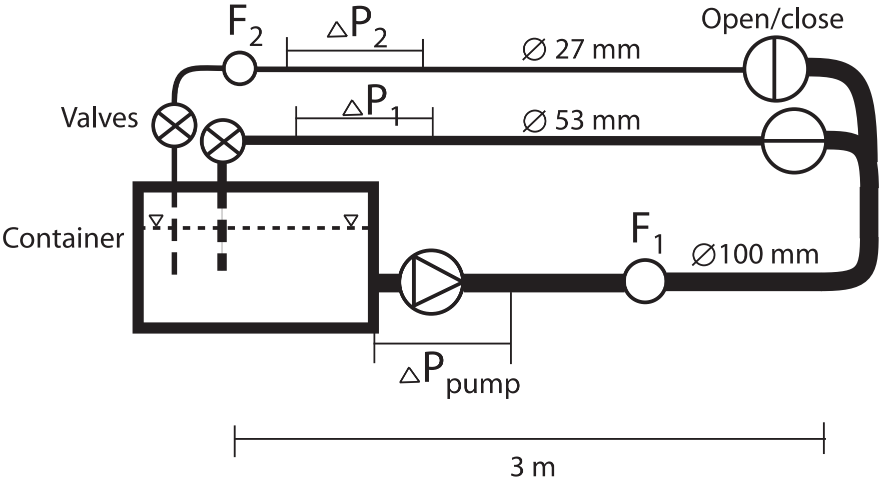

Figure 1: An illustration of the flow loop- online measurement.

The small gap geometry exhibits some well-known difficulties, such as unwanted influence of particles of the same order size as the gap. This could for instance violate the non-slip condition assumed for the method. With this in mind, still the bob-cup geometry was used for the centrifuge thickened EAS in this study.

In the case of paddle-jar geometry, a four-vane-paddle and jar of $600ml$ was used. A non-slip condition at the cylindrical surface circumscribing the paddle-vane is assumed in the test. The wide gap and larger volume compared to other geometries also reduces the secondary flow, or pumping effect, which may otherwise corrupt the measurement. However, there is a restriction in upper rotational speed. Exceeding the upper limit results in a solid body rotation. Although possible to observe in the rheometer result, it is difficult to predict *a priori*.

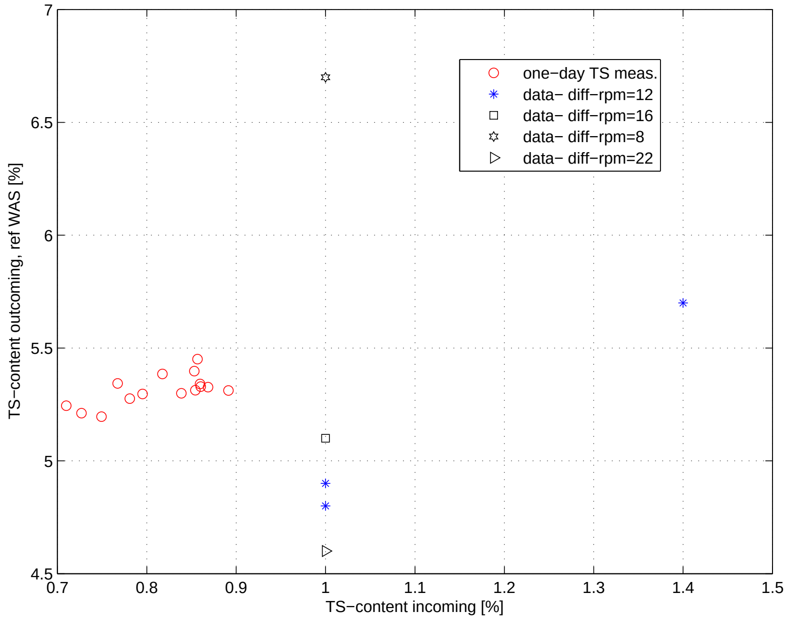

Figure 2: The TS-content value of reference EAS, from a one-day measurement and values obtained during the data acquiring, for different centrifuge settings.

Figure 3: The different rheometer inserts (bob and vanes) and cup. N.B. the smaller vane was used *here*.

3 Method for rheological analysis

The pipe pressure loss data is evaluated using the pseudo-shear stress (Eq.1) and pseudo-shear rate(Eq.2) in order to compare the centrifuge thickened macerated EAS (Lysed-EAS) to the centrifuge thickened EAS (Reference-EAS). The pseudo-shear stress and shear rate are obtained from the expressions

$$\sigma_{pseudo} = \frac{D}{4}\frac{\Delta p}{L} \tag{1}$$

$$\dot{\gamma}_{pseudo} = 8\frac{U}{D} \tag{2}$$

the subscript pseudo will drop out but implied in the following analysis.

A non-linear curve fitting is based on the *power law* model and applied to the experimental data. This model is deemed appropriate as the uncertainties of flow rate measurements of approximately $< 2litre/s$, corresponding to pseudo shear rates $< 20s^{-1}$, need to be suppressed. Thus the model is forced through the origin and a curve-fitting of the upper laminar region is in fact of a greater importance for this investigation. Other measurements techniques would be more appropriate for the lower region, when for example yield stress. The power law model and its parameters (to be obtained) are expressed as

$$\sigma = K\dot{\gamma}^n \tag{3}$$

where K is known as the fluid consistency parameter and n the fluid behaviour index. For shear-thinning fluids, the index $0 < n < 1$ in the laminar region. The smaller the value of index n, the greater is the degree of shear-thinning, [3].

The friction force based on pressure loss measurements are defined as

$$\frac{\Delta p}{L} = \frac{2f\rho U^2}{D} \tag{4}$$

and the modified Reynolds number, based on the power law model is thus

$$RE_{MR} = \frac{\rho U^{(2-n)} D^n}{K 8^{(n-1)} (\frac{3n+1}{4n})^n} \tag{5}$$

In Fig.4 the pseudo-shear rate and shear stress is presented and for comparison a turbulent water flow curve is shown. The shear stress is close to collapsing at large shear rates, as expected no rheological impact in turbulent flow for EAS. The overall shear stress in the turbulent regime is the similar order of magnitude as in the case of turbulent water flow. However, the difference is due to that the theoretical turbulent water curve assumes smooth pipe wall roughness. A significant difference at lower shear rates indicates a laminar flow of EAS compared to the turbulent water pipe flow. In the laminar flow regime, the shear-thinning behaviour ($n < 1$) of EAS is clearly seen.

A break-point model *e.g.* in pseudo shear stress/shear rate is a way of presenting a laminar to turbulent flow regime transition. The increase in shear stress represents a significant change in the pressure loss data. A difference based model $(p_{i+1} - p_i)/(v_{i+1} - v_i))$ is used and even if this is a conservative approach in obtaining the start of the transition region, all data is evaluated consistently.

4 Results

The results consist of several data sets. The first set contains the pipe pressure loss, versus the flow rate for different TS-content value of thickened EAS. The second set contains the total pressure head developed by the pump and the pump input power, all as a function of the flow rate. This represents the pump performance. The third set consists of rheometer data for the centrifuge thickened EAS, and provides a complementary view of the sludge rheology.

In order to compare the rheological effect on pipe flow of the centrifuge thickened EAS the equivalent water flow is used, however under turbulent flow condition. The procedure to extract absolute rheological data from this set can be applied, although its validity is questionable, cf. above.

4.1 Pipe pressure loss data and rheological study of EAS

In Fig.5 the difference of lysed and reference EAS is observed in the shear stress for laminar pipe flow. A rather consistent increases in shear stress and in the transition shear rate are seen for increasing TS-content values of the different EAS. It is further noticed a significant difference between the lysed EAS and reference EAS, of $TS = 5.6 - 5.7\%$. A reduction of factor 2 is observed in the laminar region. In the turbulent region, pipe pressure loss data collapse on same curve. The turbulent pressure loss of water in the flow loop is included for comparison. Furthermore, an un-physical result, not in pressure loss, rather in the zero shear rate is observed due to difficulties to determined the flow rate close to zero.

In Fig.6 the pressure loss per unit length for different TS-content of ref-EAS and lysed-EAS is shown. The equivalent pipe average flow velocity (based on pipe diameter) gives an indication of the laminar to turbulent flow condition due to the incremental change in pressure loss. For pipe velocity ($> 6m/s$)all pressure loss data collapse and no difference of TS-content are obtained. For pipe velocity ($< 4m/s$), the pressure loss increases with increasing TS-content consistently. For ref-EAS, here ranging from ($TS = 4.9 - 5.1 - 5.7\%$, there is a significant shift in pressure loss in comparison to the lysed-EAS ($TS = 3.7\% - 4.4\% - 5.6\%$). In a comparison of same TS-content(at a velocity $3m/s$) there is approximately 40% pressure loss reduction in lysed-EAS compared to ref-EAS. At a velocity $1m/s$, the equivalent reduction is (35%).

In Fig.7 the apparent viscosity for ref-EAS and lysed-EAS clearly shows a shear thinning behaviour, both seen in the data as well as in the power law model. Interesting to notice is that in the case of low TS-content value ($TS < 4\%$), the power model suggest a constant viscosity, thus a Newtonian behaviour. Partly, this is due to tuning the model to the data in upper shear rate region. In the case $TS = 5.6 - 5.7\%$ the lysed-EAS shows a 10 times reduction of apparent viscosity in the upper shear rate region compared to reference-EAS. This is observed within the laminar flow regime.

In Fig.8 the analysis of different TS-content EAS, as well as for macerated/lysed EAS, shows a somewhat constant fluid behaviour index, exponent ($n = 0.5$). In one case the variation in the model is presented in the *min-max* approach, ($TS = 4.4\%$).The most conservative approach is used for the open marker, whereas the filled ones represent a manual adjustment in the non-linear threshold limit of curve fitting: a smoothing filter. Thus, this

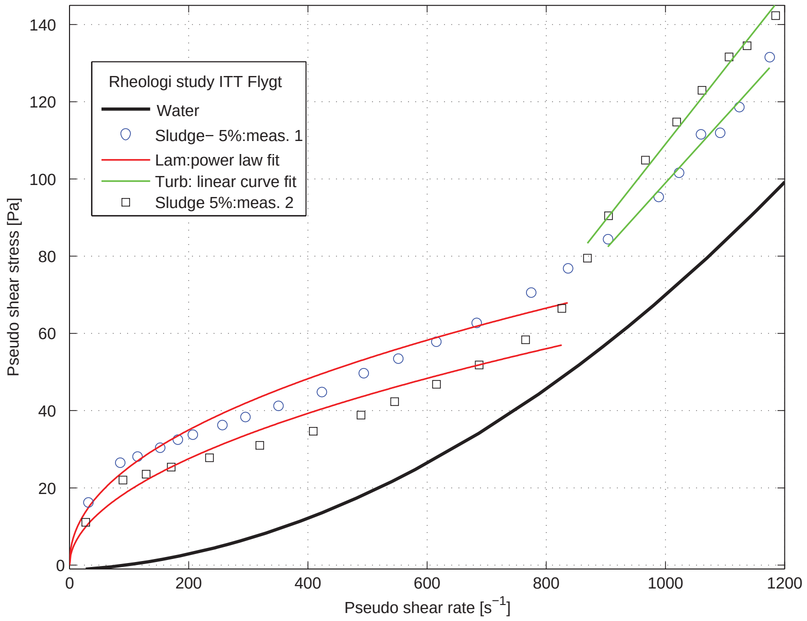

Figure 4: The pressure loss data represented in pseudo-shear stress and rate. The laminar region is evaluated by a non-linear curve fit, and the turbulent regime by a linear curve fit. For comparison,the pressure loss for turbulent pipe flow of water in the same experimental set up is shown.

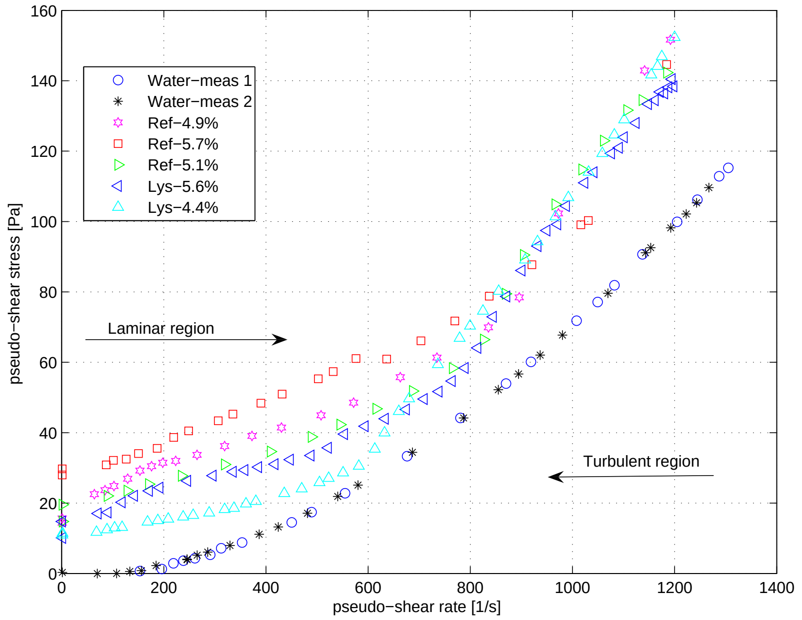

Figure 5: The pseudo shear stress - shear rate diagram pipe pressure loss data ($53mm$). The different TS-content for both macerated EAS (Lys) and reference EAS, laminar and turbulent regions. In turbulent regime, the data collapse on each other whereas differences are seen in the laminar region.

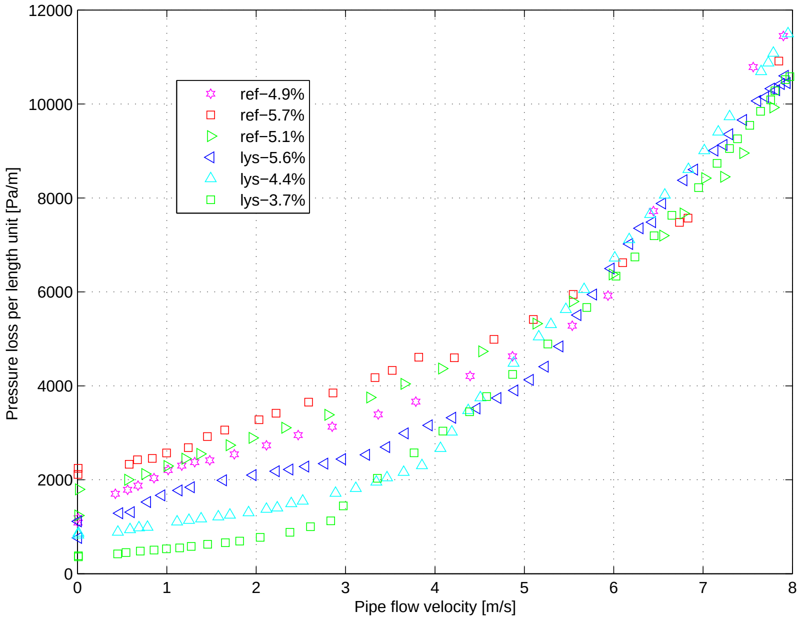

Figure 6: The pressure loss per length for different reference EAS and lysed EAS.

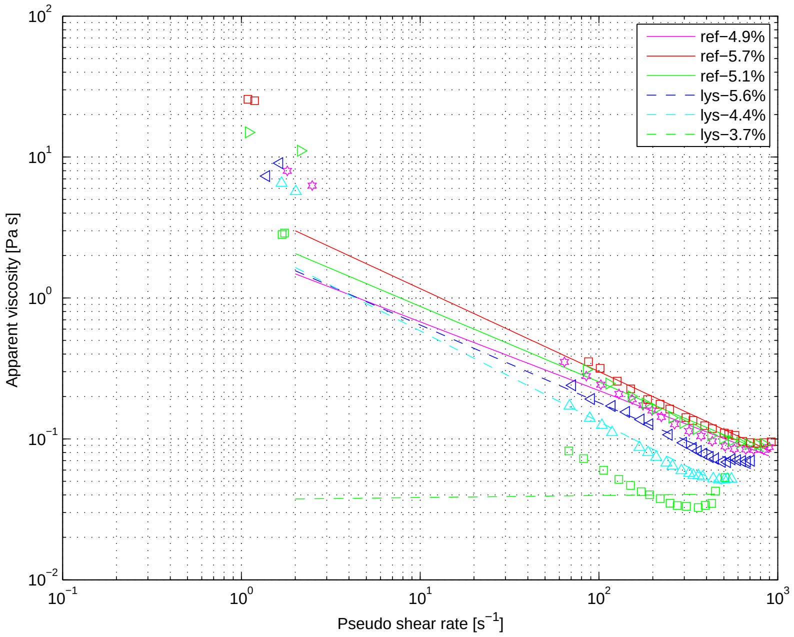

Figure 7: The apparent viscosity, with experimental data for different reference EAS and lysed EAS.

indicates that an even narrower band of data is possible but *here* a conservative way of presentation is used. However, using the conservative approach, a rheological change in fluid behaviour index is not observed in lysed or in reference centrifuged thickened EAS for different TS-content values.

In Fig.9 the rheological consistency (K) shows a dependency in TS-content for both macerated EAS and reference EAS. The macerated EAS exhibits a reduction in consistency K for TS-content increase than consistency change of reference EAS. A structural change in the lysed EAS could be an explanation, that influence the consistency number (K). In the case of $TS > 5\%$ there is observed a reduction by about half of the consistency value for macerated/lysed EAS compared to reference sludge at comparable TS-values. However, this conclusion has to be qualified further. In $TS < 5\%$ the result do not show any significant difference of lysed or reference EAS, but an overall consistency K increase with increasing TS-content.

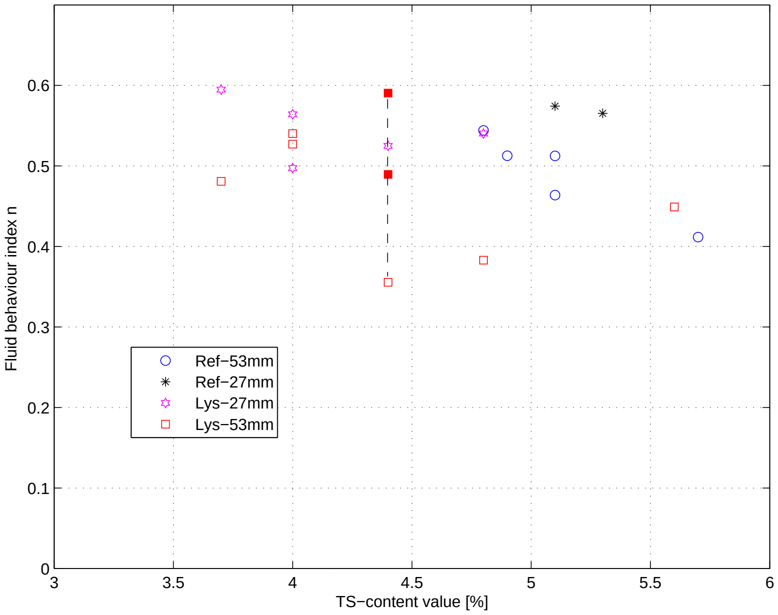

Figure 8: The fluid behaviour index, exponent (n) for macerated EAS (lysed sludge) compared to reference EAS. A variation is shown for ($TS = 4.4\%$) due to a smoothing filter, filled marker.

In Fig.10 the diameter difference in break-point is shown as well as the dependency on TS-content to obtain the shear rate break-point value. In the 53mm pipe diameter, the macerated EAS reaches a transitional regime at a lower shear rate than for reference EAS. Since the pipe diameter influences the obtained shear rate at a certain flow rate, this may result in a absence of laminar-turbulent transition, which is in the case of reference EAS in pipe diameter 27mm. In lysed EAS in 27mm diameter, a transitional shear rate is obtained for different TS-content values.

In Fig.11 the equivalent pseudo-shear stress for laminar-turbulent transition is presented. There is non-geometrical dependency expected in transitional shear stress, but may indicate

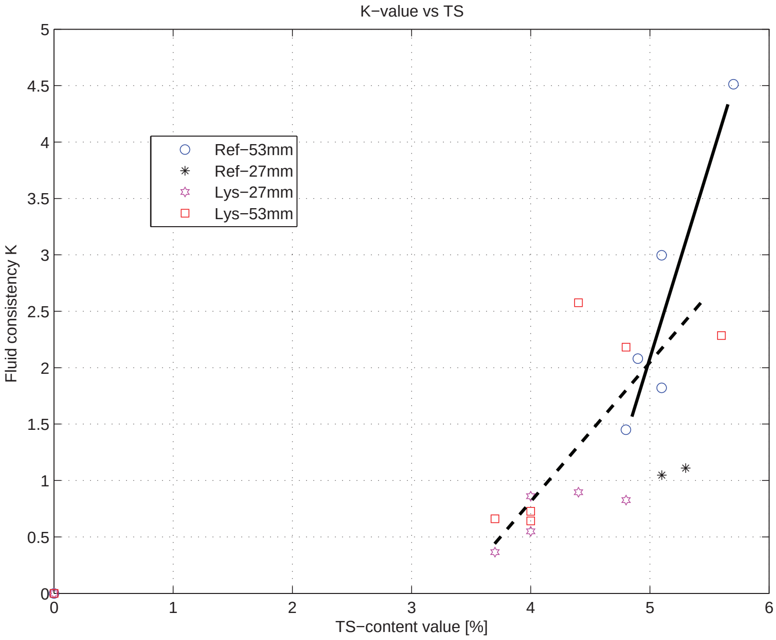

Figure 9: The fluid consistency,(K) for macerated EAS (lysed sludge) compared to reference EAS. For $TS > 5\%$, an significant difference in K of macerated EAS as compared to reference EAS is shown, indicating a possible structural change in the sludge.A estimation of change in K showed in dashed lines for macerated EAS and solid line for reference EAS.

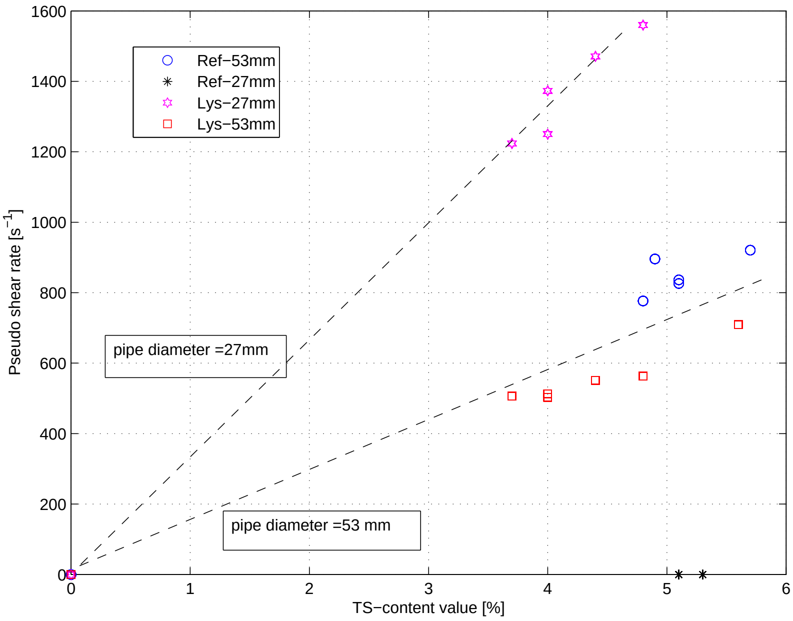

Figure 10: The break-point model shown for pseudo shear rate. The diameter dependency is shown in dashed lines with an increasing break-point value for increasing TS-content.

a change of fluid consistency. The influence of increasing TS-value shows are somewhat similar increase for both lysed and reference EAS, but the level is different. The lysed EAS shows a reduction by half in transitional shear stress compared to reference EAS. This may be a result due to a change in the fluid consistency observed earlier of the lysed EAS.

The turbulent regime is studied by a linear-curve fitting method and the obtained curve-slope is shown in Fig.12. The change due to increase in TS-content is marginal for lysed and reference EAS of pipe diameter $53mm$. The curve-slope data of tested EAS tends to the value of 2, a value seen for turbulent water, a turbulent pipe flow is presumably obtained.

In the case of pipe diameter $27mm$ the laminar flow seems to dominate the tested flow range. In the case of macerated EAS where a weak transitional regime were indicated, are presented in Fig.12 but shows a spurious result. This is due to to the limited number of data points available in the turbulent regime. In reference EAS there is no transitional regime developed, and showed as zero-values here and also in both figures, Fig. 10 and Fig.11.

An approach to validate the data, in the laminar regime, is by using friction factor theoretical value to obtained data. In Fig.13 the friction coefficient based on the pressure loss versus the modified Reynolds number show a collapse of the data on the theoretical curve. Data from both pipes are presented as well as for lysed and reference sludge. As expected no difference is detected.

4.2 Pump performance in centrifuge thickened EAS.

The pump performance is evaluated using the data of the pump pressure head and power for different TS-content values. In Fig.14 the power required for the Flygt N-3102 pump installed in the on-line pump loop for sludge compared to water as pumping medium.Pump performance is frequently presented in best efficiency point (BEP), for water in submersible condition. In this case best efficiency point is flow rate $16l/s$ and pressure head $16m$water with an overall efficiency of 52%. The power is shown for both macerated EAS and reference EAS of different TS-value content. The de-rating due to TS-content is within the estimation of the general assumption for ITT W&WW, *i.e.* power increases simply with TS-value $(100 + TS\%)$ compared to water power requirements, [5]. In the figure, two water curves are included, that unfortunately refers to two different cases. The "water-meas1" and "ref-4.9%" are related and consequently the other curves are related to "water-meas2". In reference EAS of $TS = 5\%$ the power requirement for pumping in the flow loop showed a increase seen by the general assumption. But in macerated/lysed EAS the power demand significantly decreased, by the order of the suggested de-rating. This is due to the reduction in pipe pressure loss (decrease in apparent viscosity), reported earlier in this study. In $TS = 4.4\%$ and lysed EAS an increased power demand is not observed over the flow range tested. This indicates a negligible non-Newtonian effect on the pump performance. In the data uncertainties for flow rate $< 2l/s$ is observed in experiment. This could actually be related to the flow meter measurements, but has to be further evaluated.

In Fig.15 the equivalent result of pressure head to flow rate for same set of EAS as in previous power curve is shown. In using the generally suggested impact of sludge on pressure head de-rating, $(100 - TS\%)$ of the obtained pressure head for water. The pressure head difference between macerated EAS and reference EAS is not that pronounced on the head performance nor the general de-rating of TS-content value. The satisfying result is that the

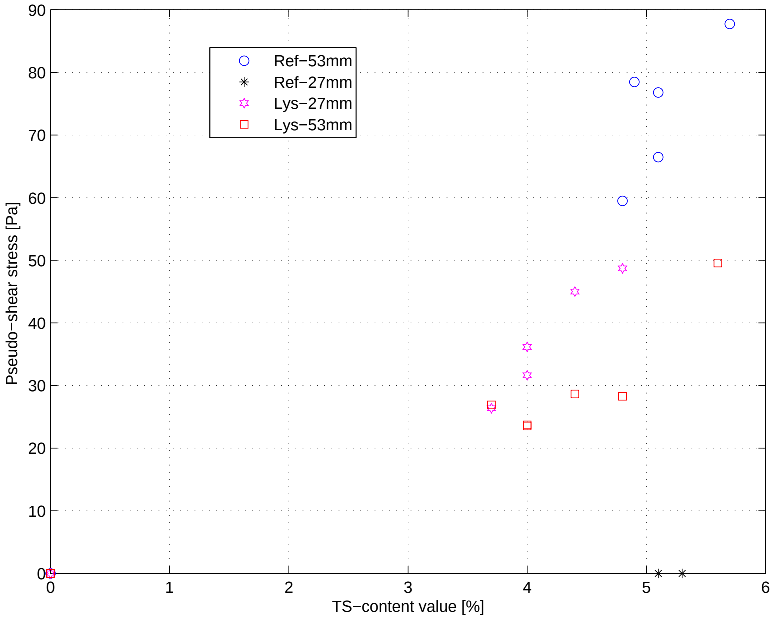

Figure 11: The break-point model presented as pseudo-shear stress indicating the laminar-turbulent transition.

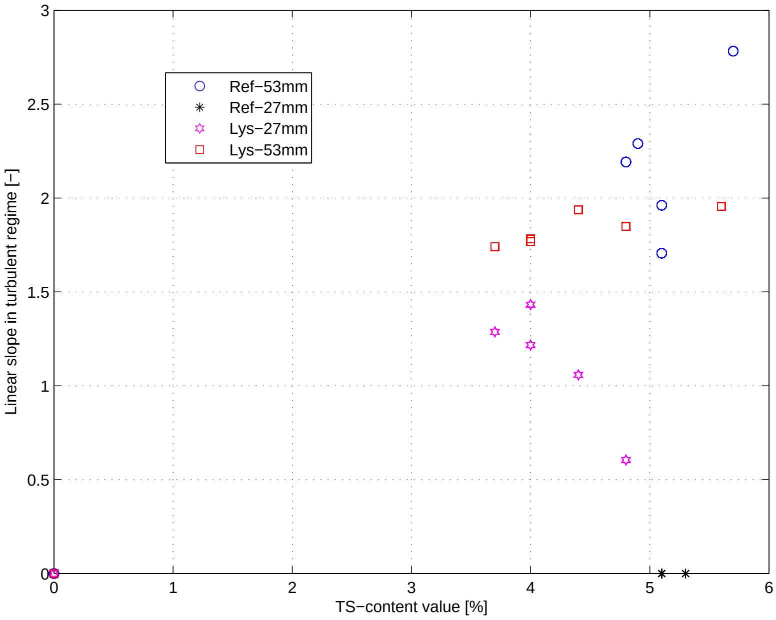

Figure 12: The linear curve-fitting slope in the turbulent pipe flow regime.

pressure head is maintained when pumping different sludge, a condition of importance for system design. There is a leveling out at flow rate $< 4l/s$, this is not a physical case, rather an artifact of the pressure transducer reaching its upper limit for recording. In the other extreme, maximum flow rate, a reduction is observed in comparing water to sludge test, that is a consequence of system curve limitation when pumping sludge, seen in earlier similar test of ITT W&WW.

4.3 Rheometer test result of centrifuge thickened EAS.

There is a possibility to use the two configurations, with the standard geometry and wide gap geometry, in order to perform rheometer curve result.

The challenging part is the transformation of the rheometer data from rotational speed -torque into the shear rate-shear stress.In the case of bob-cup configuration this is performed under the assumption of small gap, so called *small gap approximation.*

In Fig.16 the flow curve obtained from the rheometer, bob-cup configuration, data show an increase in shear stress for increasing TS-content value. The concluding result indicate a difference in $TS = 1-2\%$ between reference EAS and macerated EAS, for approximately collapsing shear stress- shear rate curves. The difference for same TS-content value is observed to be order of $20\% - 30\%$ in shear stress of reference EAS and macerated EAS.

Similar to pipe pressure loss, the rheology characteristics of sludge is presented as a fluid consistency and a fluid index, based on power law model. The possibilities to extend the TS-content range compared to the range in the flow loop, gives indication of sludge behaviour. As expected the consistency increases and even if there is a difference in the actual consistency value compared to pipe loos measurements, the relative value seems to increase by a factor 2-3.There are no significant differences observed between the reference EAS or macerated EAS, in the rheometer method of the consistency aspect.

The fluid behaviour index, Fig.18 indicating a decrease trend, however, contradictory to earlier result of a rather constant index for different TS-content values. This has to be further studied in order to explain.

The equivalent result for the paddle-jar configuration show similar result as the pipe pressure loss measurements and bub-cup rheometer test. However, the transformation to shear stress-shear rate is not achieved, rather data are shown in torque-rotational speed. In Fig.19 the break-down of the rheometer method is clearly seen as a sudden dramatic change in curve due solid body rotation occurring in the jar. The reason for a paddle is to maintain no-slip condition and avoiding jamming effects.

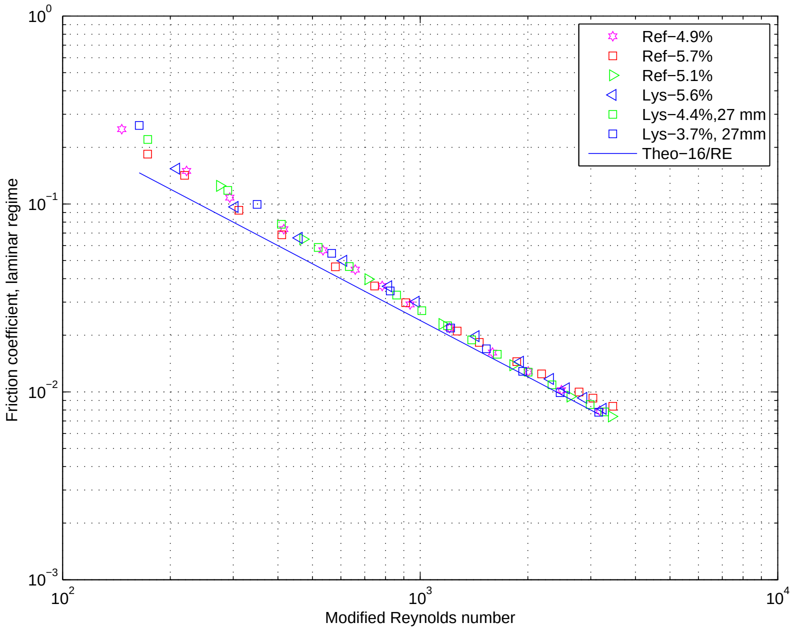

Figure 13: The change in friction coefficient vs modified Reynolds number, for lysed and reference EAS and different pipe diameters in the laminar pipe flow regime. The theoretical expression is shown as a solid line.

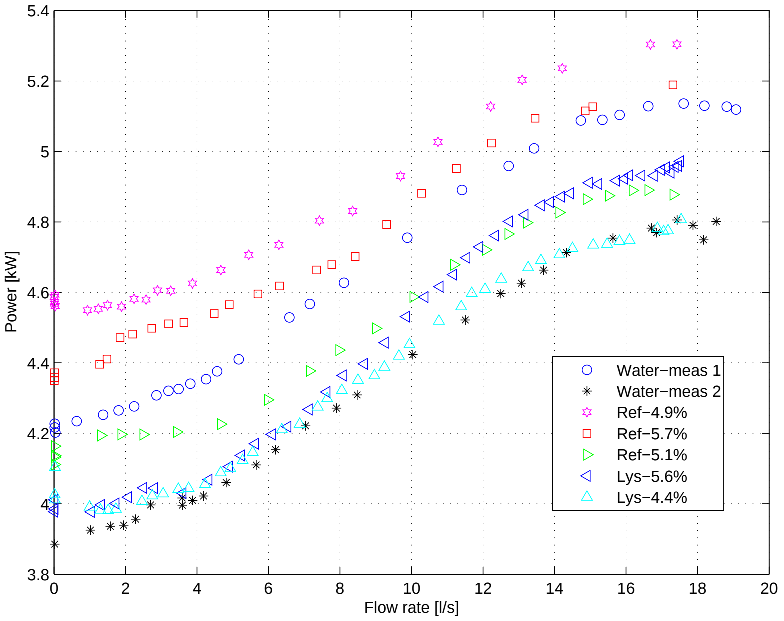

Figure 14: The power vs flow rate for the Flygt N-3102 pump in the flow loop, pipe diameter 53 mm. BEP-values in water and in submersible condition: $16 l/s$ and pressure head $16 m$ water. Water-meas1 and ref-4.9% are associated the others refers to water-meas2

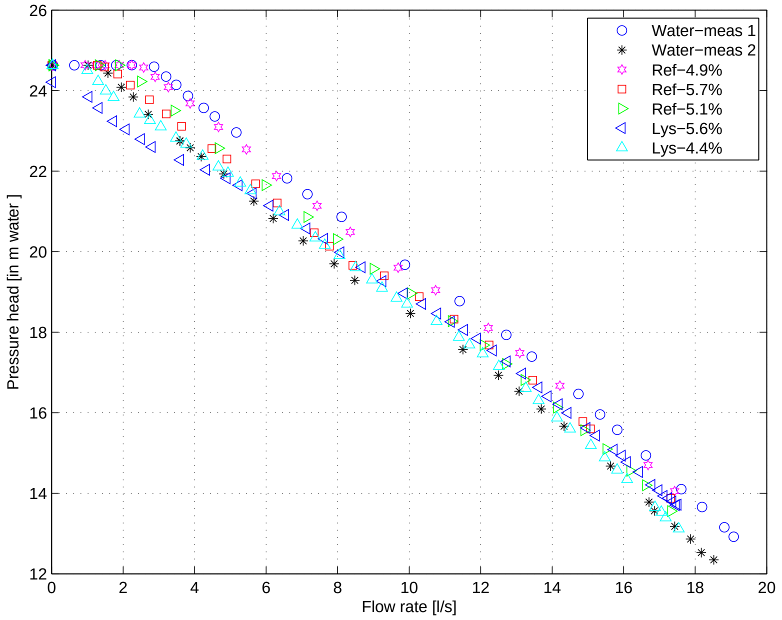

Figure 15: The pressure head vs flow rate for the Flygt N-3102 pump in the flow loop, pipe diameter 53 mm.

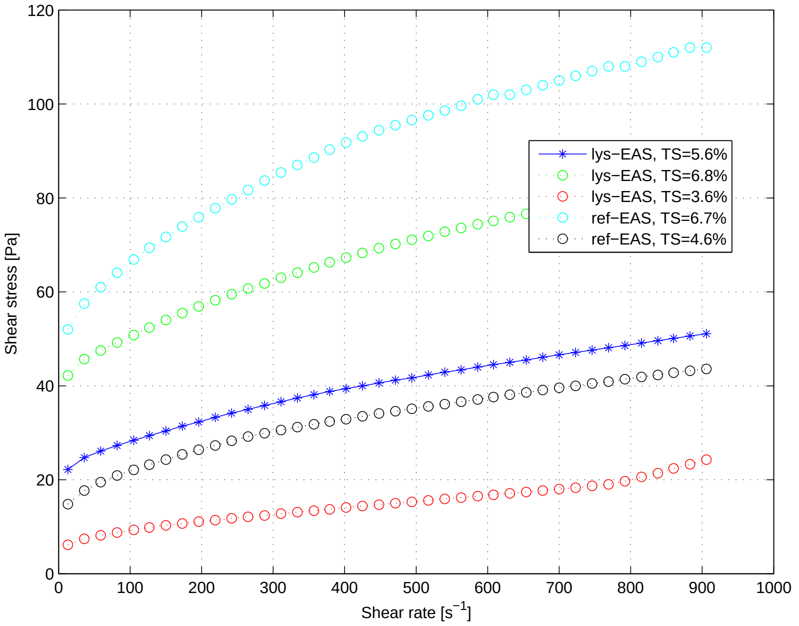

Figure 16: The flow curve obtained from the rheometer, bob-cup configuration for reference and macerated EAS of different TS-content value.

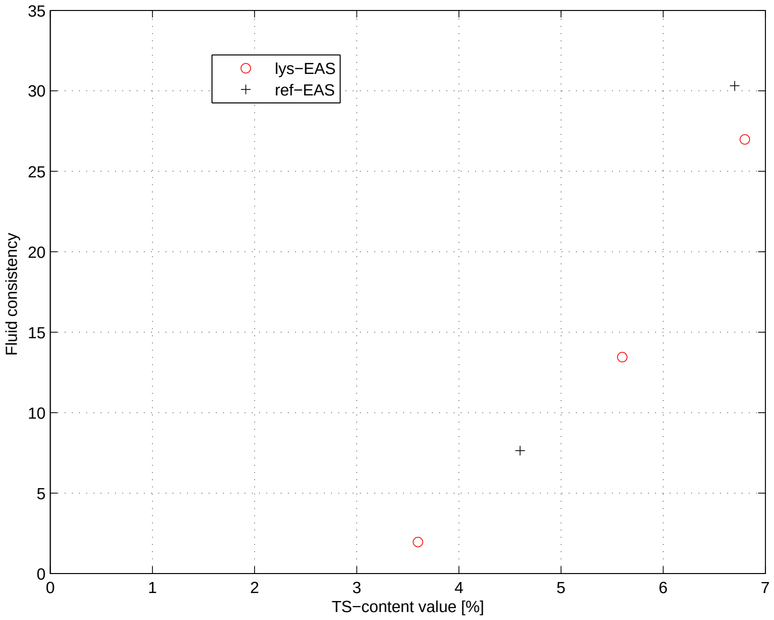

Figure 17: The fluid consistency based on rheometer test for the two types of EAS.

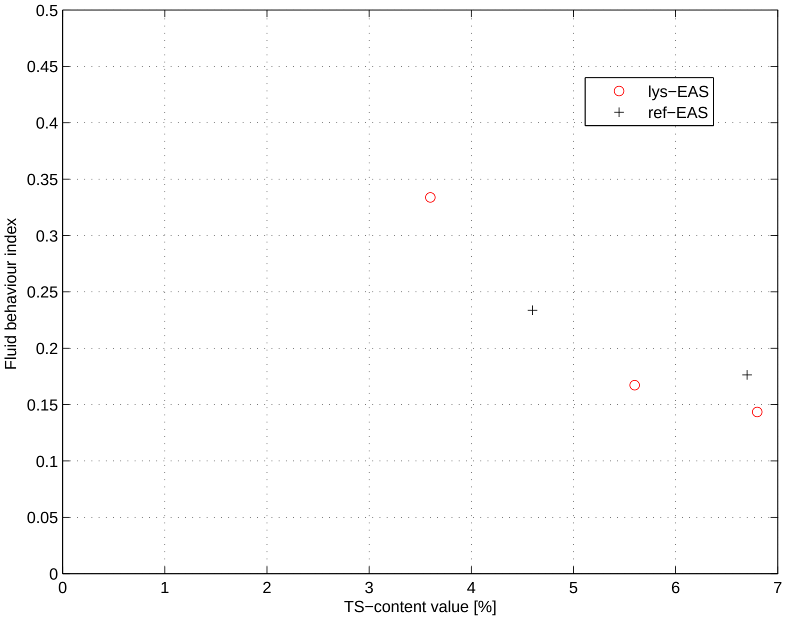

Figure 18: The index rheometer test for EAS vs TS-content.

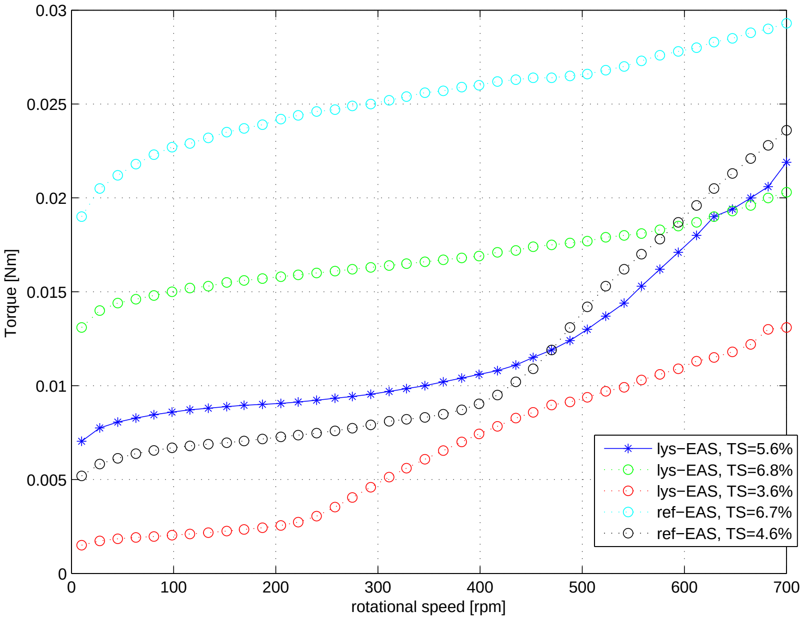

Figure 19: The rheometer data for the paddle-jar configuration.

5 Discussion and conclusions

The results from the rheological study of centrifuge thickened waste excess activated sludge (EAS), called "reference EAS" and a macerated/disintergrated/"lysed" centrifuge thickened EAS show that the flow regime may differ for the two sludge at the same TS-content.

If handling flow in the turbulent regime, the difference in results as well as the evaluation method are limited. The conclusion is that the studied data collapse and show similar behaviour. This was further compared with turbulent water flow. Though not within the scope of this study, this could be further evaluated by Bowen's method. The focus is upon the laminar flow case.

5.1 Power estimation based on-site design.

A simplified system in order to exemplify the influence of the rheology on the design is given here:

Based on the flow rate of $Q = 42 m^3/h$ and pipe diameter $D = 0.15 m$ and the fluid density $\rho = 1000 kg/m^3$, the estimating the apparent viscosity gives,

$$U = \frac{4Q}{\pi D^2} = 0.66 \Rightarrow \dot{\gamma} = 8\frac{U}{D} = 35 \Rightarrow Fig.7. \tag{6}$$

The definition of Reynolds number using the apparent viscosity μ_{app} for a specific $TS = 5.6\%$ gives that

$$\mu_{app} = \left\{ \begin{array}{ll} 0.35 & \text{lyse-EAS} \\ 0.70 & \text{ref-EAS} \end{array} \right. \Rightarrow Re_{MR} = \frac{\rho U D}{\mu_{app}} = \left\{ \begin{array}{l} 280 \\ 140 \end{array} \right. \Rightarrow Fig.13. \tag{7}$$

Thus, conclude that in both cases are within the laminar region, and by using the friction coefficient, (Eqn.4) in estimating the pressure loss per length unit,

$$f = \left\{ \begin{array}{l} 0.1 \\ 0.25 \end{array} \right. \Rightarrow \frac{\Delta p}{L} = \left\{ \begin{array}{ll} 580 & \rightarrow 1000(\text{lyse-EAS}) \\ 1450 & \rightarrow 2200(\text{ref-EAS}) \end{array} \right. \tag{8}$$

A comparison to the measured pressure loss in Fig.6, gives a modified pressure loss, approximately twice the estimated value. Finally a estimation of a required power due to the rheology, use $L = 20m$ pipe result in

$$P_{rheo} = QL\frac{\Delta p}{L} \Rightarrow \left\{ \begin{array}{ll} 230W & (\text{lyse-EAS}) \\ 510W & (\text{ref-EAS}) \end{array} \right. \tag{9}$$

The total required power is a summation of the presented one and the static pressure head contribution. Thus, in $H = 2.2m$ gives a contribution of same order of magnitude.

$$P_{static} = Q\rho g H = [260W] \Rightarrow \left\{ \begin{array}{ll} P_{tot} = 490W & (\text{lyse-EAS}) \\ P_{tot} = 770W & (\text{ref-EAS}) \end{array} \right. \tag{10}$$

5.2 Remarks based on the results

In the laminar regime, the different cases show an interesting result. They are summarized as followed:

- The rheological behaviour index n shows no systematic variation of the type of sludge (reference vs macerated) for different TS-content value. This result renders no significant changes in the micro-structure, known as cell rupture or lysing effect of the EAS, [1].
- The consistency number for macerated EAS shows a lesser dependency on TS-content than reference EAS. For $TS > 5\%$ there is a reduction by half in the consistency number for macerated EAS, although further test data in this range is needed to corroborate this observation.
- The rheometer data shows a similar result and gives an indication that the macerated EAS structure has changed.
- The obtained shear stress or, in this case measured pipe pressure loss, for the same TS-content is reduced for macerated EAS compared to reference EAS. Depending on the flow rate, but within the laminar flow regime, the reduction in pressure loss is order of $30 - 40\%$. As expressed in the apparent viscosity this result in a 10 times reduction, similar result reported in [4]. Consequently, the power reduction and energy saving is proportional to pressure loss reduction *i.e.* $30 - 40\%$ for the studied sludge pumping system of macerated EAS compared to reference EAS.
- In designing a system, based on the sludge rheology and other aspect such as sludge degradation, TS-content value is one design parameter. The obtained result indicate that a macerated EAS TS-content value may be chosen $1 - 2\%$ higher than the reference sludge with remaining pumpability and laminar flow condition.
- The centrifugal pump performance change, de-rating, is within the range of previous studies conducted by ITT W&WW, for similar sludge type and TS-content values. For example, an increase of 5% in power of reference EAS of TS-content of 5% and almost preserved pump pressure head, concluded based on the data. However outside the scope of this study but of interest when designing sludge handling systems. The effect of decrease in apparent viscosity of macerated EAS is observed to be same order of magnitude as the de-rating thus gives a direct power saving.

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