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Shear and solid-liquid separation behaviour of anaerobic digested sludge across a broad range of solids concentrations

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ABSTRACT

Due to the non-homogeneous and multiphase nature of anaerobic lagoon constituents, CFD modelling for process optimisation requires continuous functions for shear and solid-liquid separation properties across a large range of solids concentrations. Unfortunately, measurement of existing material properties of anaerobic sludges is limited to only shear or solid-liquid separation, or to a limited solids concentration. In this work, the shear properties of an anaerobic sludge were measured from 0.4 to 12.5 vol%, which corresponds to the solids concentrations seen in lagoons. The sludge showed Newtonian behaviour at 0.4 vol% and Herschel-Bulkley yield stress fluid behaviour for higher concentrations ranging from 0.5 to 12 vol%. We compared multiple approaches to determine relationships between the model fitting parameters of consistency, k, flow index, n, and shear yield stress, τ_y with solids volume fraction ϕ.The solid-liquid separation properties were measured from sedimentation and filtration experiments to obtain compressibility and permeability properties across all the above-mentioned concentrations, enabling development of hindered velocity sedimentation curves. Comparison to full-scale anaerobic digestate identified that the pilot lagoon sludge had faster sedimentation at a given solids concentration in comparison to the digestate. This is the first study on simultaneous rheological characterisation and solid-liquid separation behaviour of an anaerobic sludge across a wide range of concentrations, thus enabling CFD modelling of the hydrodynamics and performance of anaerobic lagoons.

1. Introduction

Anaerobic lagoons are in-ground structures used for treatment of raw wastewater through sedimentation of suspended solids, and anaerobic digestion of sediment and soluble organics to generate methane. They offer several advantages over conventional mesophilic anaerobic or aerobic sludge treatment processes. They do not require additional energy because the lagoon contents are not heated, mixed or aerated. As a result, they are less expensive to construct and operate. However, due to the lack of mechanical mixing and temperature control, they experience significant variation in operating conditions and performance (Papadopoulos et al., 2003).

Solids behaviour in lagoons is a critical aspect of lagoon performance and long-term operational costs (Ho et al., 2017). They not only disrupt and adversely impact on hydrodynamic flows but also result in long-term desludging costs. Current models describing solids accumulation are generally simple accumulation models (Vega et al., 2003).

Computational fluid dynamics (CFD) modelling is used as a tool to investigate and optimize the performance of existing anaerobic digestion processes under normal operation as well as extreme wash out conditions, and to ensure effective and energy efficient designs for new processes (Wu, 2013). Due to the limited mixing and the variation in hydrodynamics across the different zones in lagoons, the lagoon constituents are non-homogeneous in nature (Papadopoulos et al., 2003) and subject to large gradients in solids concentration with depth, ranging from as low as 1 mg/L to thickened sludge of greater than 100 g/L). While CFD has been used to simulate the impact of sludge on hydrodynamics, generally this has considered sludge structures as static, with the fluid as Newtonian (Vega et al., 2003). The ability to simulate non-Newtonian rheology across a broad range of concentrations is

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critical to the development of an effective model, and the requisite data is currently unavailable.

Understanding the shear and solid-liquid separation behaviour of the settled sludge layers plays an important role in predicting lagoon performance. The aim is to maximise the sedimentation rate of suspended solids and the digestion rate of the organic fraction of the settled sludge, and to reduce the cost of sludge handling and disposal.

The shear behaviour of sludge across the broad, layered range of concentrations is described by the properties of shear yield stress and viscosity, whereas the solid-liquid separation behaviour is described by the properties of compressibility and permeability. These properties are mostly dependant on the solids concentration of the sludge samples, and are also influenced by the extent of digestion and temperature (Baroutian et al., 2013; Cao et al., 2016; Dentel, 1997; Eshtiaghi et al., 2013; Jiang and Zhou, 2020; Markis et al., 2014, 2016; Miryahyaei et al., 2019; Skinner et al., 2015; Ye et al., 2014).

The shear rheology of sewage sludge at very low solids concentrations is Newtonian, where the viscosity is constant with shear rate. At low solids concentrations, the Newtonian viscosity increases with concentration. Sewage sludges demonstrate non-Newtonian, shear thinning flow behaviour at higher concentrations due to structural changes caused by the flow. At suspended solids concentrations above the gel point (Stickland, 2015), sludges have a measurable shear yield stress due to a continuous particulate network.

Several rheological models have been used to describe the non-Newtonian fluid behaviour of suspensions. The power-law model incorporates shear thinning behaviour and has been used for modelling sewage sludge rheology at lower solids concentrations (Cao et al., 2016; Yeneneh et al., 2016). However, for concentrated sewage sludge, the Herschel-Bulkley model is the most applicable model to describe the shear rheology (Markis et al., 2014, 2016; Stickland et al., 2013). This model has three fitting parameters, which can be obtained from the best fit of the experimental shear stress and shear rate data.

To model the shear rheological behaviour of the sludge, optimisation algorithms are used to find a set of model parameters that best describe a set of experimental rheograms. In general, the model fitting parameters are considered to be functions of solids concentration (Ratkovich et al., 2013). It is very important to ensure the quality of the model parameters as they might suffer from limitations such as identifiability problems especially in an over-parameterized model (Ratkovich et al., 2013). The quality of parameter estimation can be judged from the confidence intervals of the respective parameter estimates. When acceptably small confidence intervals are obtained, the extracted parameters are more trustworthy, and the resulting model will have higher predictive power. Parameter correlation should also be considered, with flow index (n) often correlated to consistency (k) and shear yield stress (τ_y) in the Herschel-Bulkley model (Petersen et al., 2008; Rosenberger et al., 2002).

In this study, the shear rheological properties of anaerobically digested sludge were measured from 0.4 to 12.5 vol%, which corresponds to the solids concentrations observed in lagoons. Multiple approaches were tried to predict reliable relationships between the power-law and Herschel-Bulkley model fitting parameters (consistency, k, flow index, n, and shear yield stress, τ_y) together with the solids volume fraction, ϕ.

Sludge dewatering is important to minimise sludge volume, facilitate transportation, increase the efficiency of energy utilization and reduce leachate production in sludge landfill sites (Hong et al., 2018). Gravity batch settling tests are used to characterise dewaterability at low solids concentrations and slightly beyond the gel point (Lester et al., 2005), whereas single pressure filtration tests are conducted for characterisation at high solids concentration to obtain the compressibility and permeability of sludge (Stickland, 2015; Stickland et al., 2008).

The solid-liquid separation parameters, compressive yield stress, $P_y(\phi)$, and hindered settling function, $R(\phi)$, can be used to predict the compressive settling behaviour of the sludge at different solids concentrations. The settling velocity of the sludge can also be predicted as a function of solids volume fractions using $R(\phi)$ and the solid and liquid densities, which can then be an input for CFD modelling.

Studies conducted so far have characterised either the shear rheological or solid-liquid separation behaviour of a sludge sample. Shear rheology and solid-liquid separation behaviour has not been simultaneously studied. This is the first study that presents the correlations for shear rheology and solid-liquid separation properties as continuous functions across a wide range of solids volume fractions for an anaerobic sludge, to be used as input for the CFD modelling of anaerobic lagoons. These material properties enable CFD to predict the solids consolidation and flow profile within the anaerobic lagoon and their use for optimising process performance.

2. Theory

2.1. Shear rheology of sewage sludge

Several rheological models have been used to describe the non-Newtonian fluid behaviour of suspensions. The power-law model (Eq. (1)) incorporates shear thinning behaviour and has been used for modelling sewage sludge rheology at lower solids concentrations (Cao et al., 2016; Yeneneh et al., 2016).

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

where τ = shear stress (Pa), k = consistency (Pa.s^n), Υ = shear rate (s^{-1}), n = flow index.

The Herschel-Bulkley model (Eq. (2)) is the most applicable model to describe the shear rheology of concentrated sewage sludge since it takes into account the shear yield stress τ_y (Pa) as well as the non-linear relationship between the shear stress and shear rate (Markis et al., 2014, 2016; Stickland et al., 2013). This model has three fitting parameters, which can be obtained from the best fit of the experimental shear stress and shear rate data.

$$\tau = \tau_y + k\dot{\gamma}^n \tag{2}$$

where τ_y = shear yield stress (Pa).

The shear yield stress can be used as a fitting parameter, or alternatively it can be measured using the peak stress value during slow constant rate deformation (Nguyen and Boger, 1992). The measured yield stress is typically higher than the extrapolated value since the former represents initial yielding of the particulate network and the later the cessation of flow (Nguyen and Boger, 1983).

2.2. Dewatering behaviour of sewage sludge

Due to the presence of extracellular polymeric substances (EPS), which are responsible for water retention and strong water binding capability, wastewater sludges have poor dewaterability compared to other materials. EPS generally consists of mostly proteins and polysaccharides. Compared with primary sludge, digested sludge contains relatively higher amount of EPS, which results in poor dewaterability performance (Christensen et al., 2015; Hong et al., 2018; Skinner et al., 2015). The data indicate that higher volatile solids content (in the range of 60–80%) is an indicator of poor dewatering behaviour of sewage sludge (Hong et al., 2018; Skinner et al., 2015)

Gravity batch settling tests are used to characterise dewaterability at low solids concentrations and slightly beyond the gel point (Lester et al., 2005), whereas single pressure filtration tests are conducted for characterisation at high solids concentration to obtain the compressibility and permeability of sludge (Stickland, 2015; Stickland et al., 2008). The compressive yield stress, $P_y(\phi)$, where ϕ is the solids volume fraction, provides a measure of the network resistance to deformation or the solids pressure required to consolidate to a given equilibrium volume fraction. The gel point, denoted by ϕ_g, is defined as the solids concentration at which the solids form a sludge network to resist the applied pressure such that $P_y(\phi)=0$. The hindered settling function, $R(\phi)$, which is inversely related to the settling rate or the permeability, is a measure of the hydrodynamic resistance (Stickland, 2015; Stickland et al., 2008; Usher et al., 2013).

The solids diffusivity $D(\phi)$ defines the rate at which a concentration gradient propagates through the suspension and is related to the compressive yield stress and hindered settling function by Eq. (3) (Stickland et al., 2008).

$$D(\phi) = \frac{dP_y(\phi)}{d\phi} \frac{(1-\phi)^2}{R(\phi)} \tag{3}$$

The solids diffusivity increases monotonically with solids concentration for inorganic materials, leading to traditional quadratic filtration behaviour. For wastewater sludges, however, the solids diffusivity initially increases but then decreases after a peak at low solids concentrations, leading to non-quadratic time versus filtrate volume behaviour where there is a very short linear cake formation period followed by a longer cake compression (Stickland et al., 2005).

The solid-liquid separation parameters, compressive yield stress, $P_y(\phi)$, and hindered settling function, $R(\phi)$, can be used to predict the compressive settling behaviour of the sludge at different solids concentrations. The settling velocity profile of the sludge can also be predicted as a function of solids volume fractions from Eq. (4) using $R(\phi)$ and the solid and liquid densities, and then be used as an input for CFD modelling.

$$u(\phi) = \frac{(\rho_{solids} - \rho_{liquid})\, g\, (1-\phi)^2}{R(\phi)} \tag{4}$$

where $u(\phi)$ = settling velocity (m/s), ρ_{solids} = solids density (kg/m^3), ρ_{liquid} = liquid density (kg/m^3), g = 9.8 m/s^2 and ϕ = solids volume fraction (-).

3. Materials and methods

3.1. Samples

Anaerobic digested sludge samples were collected from a lagoon pilot plant located at the Western Treatment Plant (WTP) and a mesophilic anaerobic digester at the Eastern Treatment Plant (ETP). The pilot plant is operated to replicate a full-scale anaerobic lagoon. Both treatment plants are in regional suburbs of Melbourne, Australia and are operated by Melbourne Water Corporation. The sludge samples were stored in the refrigerator at 4 °C until tested.

The total solids contents of the samples were determined by APHA method 2540B from the loss of weight on drying to constant weight over at least 24 h at 105 °C (APHA, 2005). Volatile solids contents of the samples were measured by APHA method 2540E from loss of weight on drying over 2 h at 550 °C (APHA, 2005). The total suspended solids contents were calculated from the total dried solids and total dissolved solids content (Eq. (5)). The solids densities of the samples were calculated using Eq. (6) from the measured values of suspension density and solids concentration of the slurry, and the density and total dissolved solids of the filtered (through 0.22 μm filter paper) centrate collected from the centrifugation of the samples at 3500 rpm for 2 h in a Beckman Coulter Allegra X-12 centrifuge. Slurry densities were measured using a calibrated density cup, whereas the centrate densities were measured using a calibrated pycnometer. The suspended solids volume fractions were calculated from the total suspended solids content and the solids and liquid densities (Eq. (7)). Note that all solids volume fractions mentioned in this work are suspended solids volume fraction.

$$x_{TSS} = \frac{x_{TS} - x_{TDS}}{1 - x_{TDS}} \tag{5}$$

$$\rho_{solids} = \frac{x_{TSS}}{\frac{1}{\rho_{slurry}} - \frac{1-x_{TSS}}{\rho_{centrate}}} \tag{6}$$

$$\phi = \frac{\frac{x_{TSS}}{\rho_{solids}}}{\frac{x_{TSS}}{\rho_{solids}} + \frac{1-x_{TSS}}{\rho_{centrate}}} \tag{7}$$

where x_{TS} = total solids fraction, x_{TSS} = total suspended solids fraction, x_{TDS} = total dissolved solids fraction, ρ_{slurry} = density of the slurry (kg/m^3), $\rho_{centrate}$ = density of the centrate (kg/m^3), and ϕ = suspended solids volume fraction (-).

The physicochemical properties of the lagoon pilot plant sludge and the mesophilic anaerobic sludge samples are presented in Table 1.

For the measurement of shear rheology, the samples were concentrated in a Beckman Coulter Allegra X-12 centrifuge to a maximum solids concentration of 12 vol% after centrifugation for 2 h at 3500 rpm. The samples were then progressively diluted with the centrate to a minimum of 0.4 vol%.

3.2. Measurement of shear rheology

3.2.1. Shear yield stress measurement

The shear yield stresses of the anaerobic sludge samples were measured with a Haake VT 550 rheometer using the vane-in-large-cup method (Nguyen and Boger, 1992). The sample was placed in a container (diameter 40 mm and length 80 mm) and an appropriate vane (diameter 15 mm and length 40 mm) attached to the rheometer was immersed in the sample. The vane was then rotated at a rate of 0.2 rpm and the shear yield stress was calculated from the maximum torque response and the vane geometry. The samples were hand mixed prior to loading and kept at equilibrium for 5 min prior to commencement of measurement at 20 °C.

3.2.2. Flow curve measurement

Flow curve measurements were conducted using a vane-in-cup (wide gap) or cylindrical bob-in-cup (narrow gap) geometry depending on its solid concentrations using a TA Instruments' AR-G2 rheometer. The vane-in-cup (wide gap) geometry was used for samples with solids concentrations above 4 vol% whereas the bob-in-cup (narrow gap) geometry was used for samples with lower solids concentrations. The detailed geometries of the cup-and-vane and cup-and-bob arrangements are provided in Table 2. The samples were hand-mixed and loaded in the cup, the vane or bob was immersed in the sample, and kept at equilibrium for 5 min. Then a logarithmic distribution of angular velocity from 100 rad/s to 0.01 rad/s was applied, and torque values were recorded at 30 s intervals. This technique was applied instead of increasing the angular velocity in ascending order because in the latter technique longer time is needed to reach steady state torque at a single angular velocity.

For the narrow gap geometry using the bob-in-cup, the shear stress and shear rate values were calculated from the angular velocity, torque, and bob and cup geometry from Eqs. (8) and (9).

Table 1
Physicochemical properties of lagoon pilot plant sludge and mesophilic anaerobic sludge.

Properties	Lagoon pilot plant sludge	Mesophilic digested sludge
Total solids (TS), wt%	5.7	2.2
Volatile solids (VS), wt%	3.48	1.56
VS/TS	0.61	0.71
Total dissolved solids (TDS), wt%	0.14	0.13
Solids density, kg/m^3	1708	1356
Solids volume fraction (ϕ), (v/v)	0.0333	0.0165

Table 2
Geometries of the cup-and-vane and cup-and-bob used for flow curve measurements.

Geometry		Diameter$D$(mm)	Length L(mm)
Cup-and-vane	Cup	30	80
	Vane	10	40
Cup-and-bob	Cup	30	80
	Bob	28	50

$$\tau = \frac{T}{2\pi L_b R_b^2} \quad (8)$$

$$\dot{\gamma} = 2\Omega \frac{R_c^2}{R_c^2 - R_b^2} \quad (9)$$

where T = torque (N.m), L_b = length of bob (m), R_b = radius of bob (m), Ω = angular velocity (rad/s), and R_c = radius of cup (m).

For the vane-in-cup (wide gap) geometry, corrected shear stress and shear rate values were calculated from the measured angular velocity and torque data. The corrected shear stress was calculated from the torque data and vane geometry using Eq. (10) (Nguyen and Boger, 1992).

$$\tau = \frac{T}{K_v} \quad (10)$$

where K_v = the vane constant given by Eq. (11) (Nguyen and Boger, 1992).

$$K_v = \pi D_v^2 \left(\frac{L_v}{2} + \frac{D_v}{6}\right) \quad (11)$$

where L_v is the length of the vane (m) and D_v is the diameter of the vane (m).

The corrected shear rate was calculated from the angular velocity and local gradient of the logarithmic curve of shear stress versus angular velocity using Eq. (12) (Krieger and Maron, 1952; Nguyen and Boger, 1992). A cubic fit for the logarithmic curve of shear stress versus angular velocity was used to calculate the local gradient.

$$\dot{\gamma} = \frac{2\Omega}{n} \quad (12)$$

where n = local gradient of the logarithmic plot of shear stress versus angular velocity.

3.3. Measurement of dewaterability

Gravitational batch settling tests were used to extract dewaterability data at low solids concentrations whereas several single pressure filtration tests were used to determine dewaterability data at high solids concentrations. In a gravity settling test, the decrease of the solid-liquid interface over time was recorded whereas time versus filtrate volume data was generated from the single pressure filtration tests.

3.3.1. Batch settling tests

The settling tests were conducted at lower concentrations than as-received sludge by diluting the samples with their own liquor down to 0.8–0.9 vol% (solids volume fraction 0.008–0.009) so that a clearly defined solid-liquid interface was observable. The samples were poured into a 500 ml measuring cylinder and the solid-liquid interfacial height was recorded over time.

The analytical method for determining hindered settling function, $R(\phi)$ as a function of solids concentration, the gel point ϕ_g, and compressibility $P_y(\phi)$ data near the gel point from the batch settling data is reported in Lester et al. (2005).

3.3.2. Single pressure filtration tests

At least two single pressure filtration tests between 50 kPa and 300 kPa were conducted for each sample in a constant pressure filtration device (de Kretser et al. 2001) to have reliable dewatering data. A known amount of sludge (100 mL) was added to the filtration device and the filtration was continued until the filtrate volume reached equilibrium.

The extraction of the dewatering parameters from the pressure filtration data was conducted using the method described in Stickland et al. (2008).

3.3.3. Combining solid-liquid separation data into curve fits

The methods for combining the analysed data from the gravity batch settling and the pressure filtration tests into curve fits are presented in Usher et al. (2013) and Mercer et al. (2021). The detailed explanations of the analytical methods and curve fits are also provided in Supplementary 1.

3.4. Parameter estimation

The three parameters used in the Herschel-Bulkley model were fitted to individual rheology curves simultaneously using the secant method (lsqcurvefit) in Matlab R2018b with uncertainty (95% CI) and correlation determined from the parameter-residual Jacobian (linear approximation). Non-log residuals were used as objective functions, with $\log_{10}$ residuals also tested, and found not to result in substantive differences in parameters. True parameter confidence region was also evaluated by an F-test (non-linear ANOVA, Batstone et al. (2009) to identify that the linear approximation was appropriate.

From the aggregate parameter variation in solids concentration, models were proposed and optimised for fitting parameters using all data in that range with non-log residuals as optimum. An F-test as above was used to determine confidence in parameters.

All data is stored in Figshare (Das et al., 2022).

4. Results

4.1. Shear rheological behaviour

As noted above, all flow curves were fit using a Herschel Bulkley model, and parameters analysed for variation across all ranges. At solids concentration of 0.4% (solids volume fraction, ϕ = 0.004) and presumably below, the flow behaviour is Newtonian. The measured viscosity at 0.4 vol% (*ϕ = 0.004*) is 0.00169 Pa.s, which is almost twice the viscosity of water of 0.001 Pa.s. At solids concentrations above 0.4 vol% (*ϕ = 0.004)*, the fluid flow behaviour changes from Newtonian to shear thinning (i.e., $n < 1$) and above 0.7 vol% (*ϕ = 0.007)*, there was a measurable (i.e., significant) yield stress.

The flow curves for the sludge samples with solids volume fraction from 0.5% to 12.0 vol% (*ϕ = 0.005–0.12)* with optimal HB fits are provided in Fig. 1(a) and 1(b). The flow curves were generally comparable across different concentrations, except the 2.1 vol% (*ϕ = 0.021)*, which had high levels of variability at low shear rates, and the 12 vol% (*ϕ = 0.12)*, which had an apparent high n (compared to other samples), likely due to development of secondary flows at high shear rates.

The shear yield stress (τ_y) variation with solid concentration is shown in Fig. 1(c). As noted above, there was a significant shear yield stress at solid concentrations higher than 0.74 vol% (*ϕ=0.0074)*, with the function generally following a power law model with the exception for the two lowest concentrations of 0.53 and 0.74 vol% (*ϕ = 0.0053 and 0.0074)* for there was a large variation between the HB individual fit and predicted shear yield stress values from the power law curve fit.

The consistency, k, values varied by orders of magnitude between concentration ranges, and was modelled as a power law function across the entire range of solids concentrations (Fig. 1d).

The flow behaviour index, n, decreased from close to 1 at 0.5 vol%

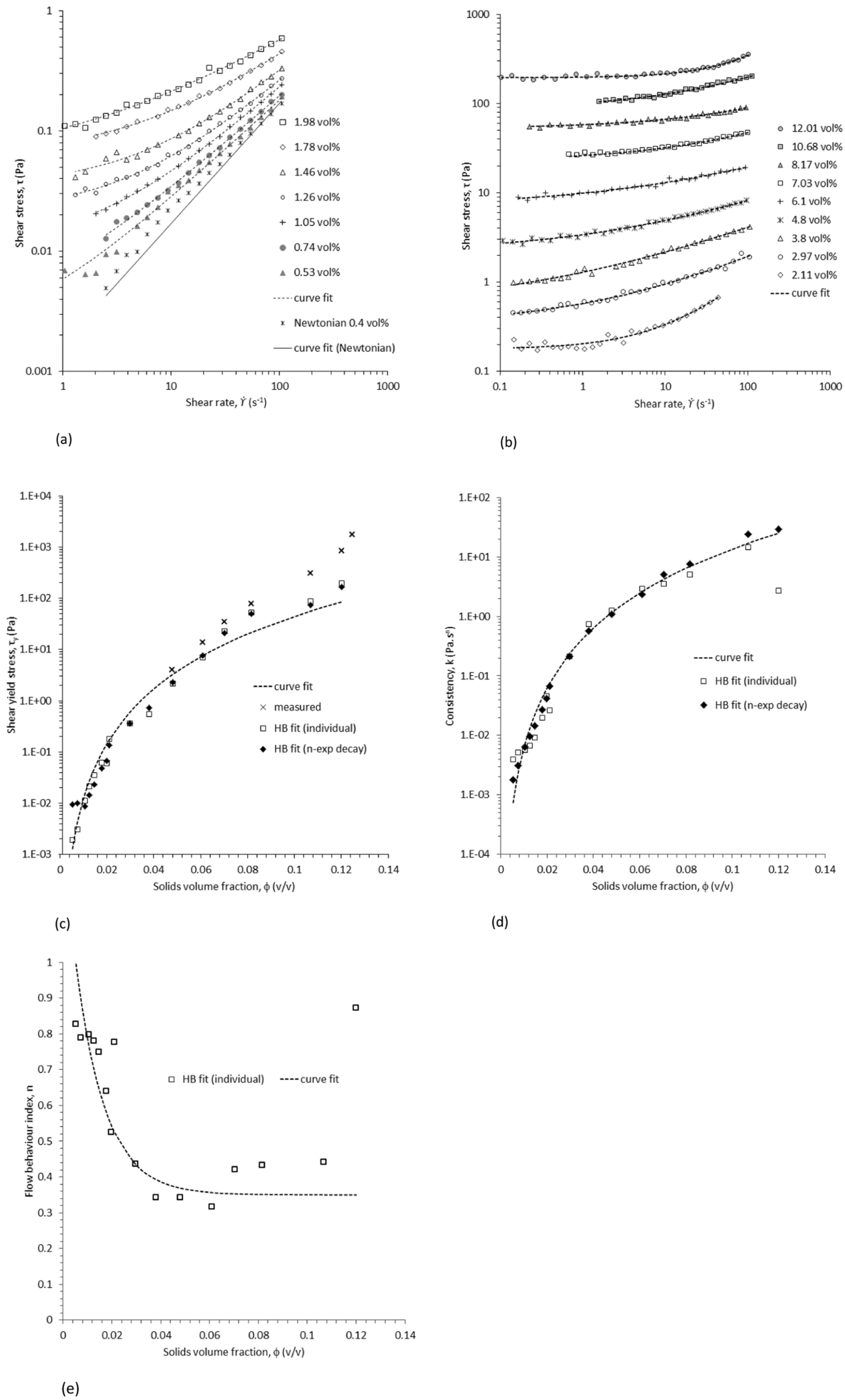

Fig. 1. Flow curves for lagoon pilot plant sludge and their Herschel-Bulkley (HB) model fits at (a) lower concentrations, and (b) higher concentrations. (c) Shear yield stress, τ_y, from HB fitting (rectangles) and directly measured by vane (cross); HB τ_y fitted using a power law function (diamonds). (d) HB consistency, k, from individual fits (rectangles) and using exponential decay for flow index (diamonds), fitted with a power law. (e) Flow behaviour index, n, fitted with an exponential decay.

(*ϕ=0.005)* to a relatively constant value of ~0.35 above 4 vol% (ϕ = *0.04*) (Fig. 1e). An exponential decay model was used to predict *n* across the entire range.

The optimised models and model fit details are provided in Table 3.

4.2. Characterisation of solid-liquid separation behaviour

The solid-liquid separation behaviour of the sludge is described by the compressive yield stress, hindered settling function and solids diffusivity. These material parameters were measured using batch sedimentation and pressure filtration, and were predicted as continuous functions of solids volume fraction from curve fitting to both experimental results of the sedimentation and pressure filtration. The settling velocity as a continuous function of the solids volume fraction is required as an input into the CFD modelling of the lagoon, which was calculated from the hindered settling function, solids volume fraction, and the solids and liquid density values.

The experimental and predicted solid-liquid separation parameters for the digested sludges from the pilot plant (non-homogenised lagoon system) and the mesophilic anaerobic digester (homogenised digester system) are provided in Figs. 2–4. The compressive yield stress values for both the sludges vary by five orders of magnitude over the solids concentration range from 2 vol% to 40 vol% (ϕ = *0.02 to 0.4)* Fig. 2). The constitutive equations for the prediction of compressive yield stress of the digested sludges from pilot plant are provided in Eqs. (13) and ((14) and the mesophilic anaerobic digester are provided in Eqs. (15) and (16).

$$P_y(\phi) = \left\{ P_{y,1}(\phi) = \left(\frac{0.113(0.63-\phi)(0.01+\phi-0.027)}{(\phi-0.027)} \right)^{-3.371} : 0.027 \le \phi < 0.067 \right. \tag{13}$$

$$P_y(\phi) = \left\{ P_{y,2}(\phi) = \left(\frac{0.253(0.63-\phi)(0.01+\phi-0.014)}{(\phi-0.027)} \right)^{-4.797} : 0.066 \le \phi < 0.63 \right. \tag{14}$$

$$P_y(\phi) = \left\{ P_{y,1}(\phi) = \left(\frac{0.371(0.63-\phi)(0.01+\phi-0.032)}{(\phi-0.032)} \right)^{-5.779} : 0.032 \le \phi < 0.096 \right. \tag{15}$$

Table 3
Optimised Newtonian and Herschel-Bulkley model fitting parameters for the solids volume fraction ranges between 0.4 and 12 vol%.

Herschel-Bulkley sfitting parameters	Solids volume fraction <0.4 vol% (Newtonian)	Solids volume fraction0.53–12 vol% (Herschel-Bulkley)
τ_y (yield stress, Pa)	0	$\tau_y=(10^{\tau 1})\ \phi^{\tau 2}$ τ_1 = 5.201±0.753 τ_2 = 3.555±0.469
k (consistency, Pa.s^n)	0.001693 ± 0.000055	$k=(10^{k1})\ \phi^{k2}$ k_1 = 4.475±0.33 k_2 = 3.341±0.206
n (flow index, -)	1	$n = e^{-n1\phi}+n_2$ n_1=82.739 n_2=0.35

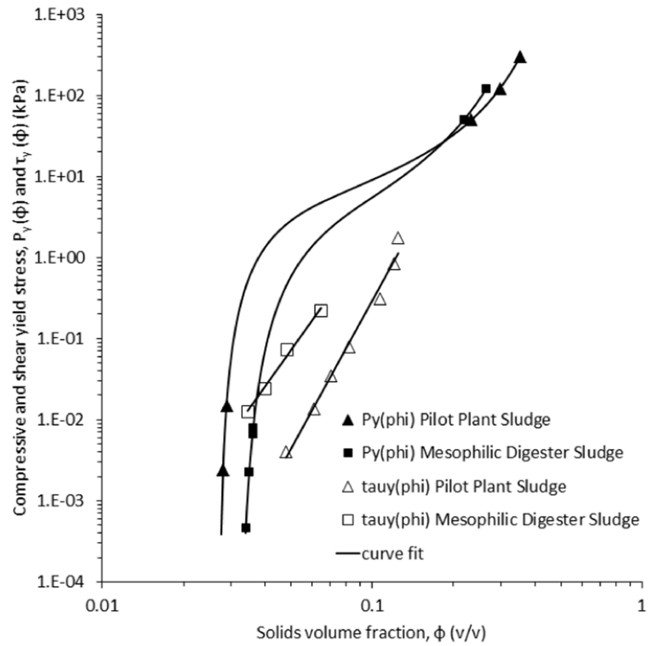

Fig. 2. Compressive and shear yield stress profile at 2–40 vol% solids concentrations for pilot plant sludge (non-homogenised lagoon system) in comparison to mesophilic digester sludge (homogenised digester system).

$$P_y(\phi) = \left\{ P_{y,2}(\phi) = \left(\frac{0.483(0.63-\phi)(0.01+\phi-0.018)}{(\phi-0.032)} \right)^{-6.910} : 0.096 \le \phi < 0.63 \right. \tag{16}$$

For the solids volume fraction range of 2 vol% to 40 vol% (ϕ = *0.02 to 0.4)*, the hindered settling function varies nine orders of magnitude from 10^8 to 10^{17} kg s^{-1}m^{-3}. The hindered settling function for both types of sludges were predicted as power law functions of solid volume fraction, ϕ as provided in Eq. (17) (for pilot plant sludge) and Eq. (18) (for mesophilic anaerobic digester sludge).

$$R(\phi) = 2.294 \times 10^{18}\phi^{5.265} \tag{17}$$

$$R(\phi) = 1.294 \times 10^{20}\phi^{5.672} \tag{18}$$

The predicted solids diffusivity, *D(ϕ)*, profile across the entire range of solids concentration of 2 to 40 vol% (*ϕ=0.02 to 0.4)* and the experimental *D(ϕ)* values obtained from pressure filtration tests are presented in Fig. 5. The experimental values were calculate from the fitting parameters of filtration curve as described in Stickland et al. (2008). The *D (ϕ)* profile was obtained by combining the predicted compressive yield stress, *$P_y(\phi)$* and hindered settling function, *R(ϕ)* using Eq. (3). This non-monotonic *D(ϕ)* behaviour is typical for wastewater sludges, as described in Section 2.2, due to the extended compression zone which has been attributed to the extracellular polymeric network (Mercer et al., 2021; Skinner et al., 2015; Stickland et al., 2008).

In general, materials with a compressibility curve at higher solids for a given pressure and with a lower hindered settling or drag at the same pressure will dewater faster and further (Skinner et al., 2015). From the hindered settling profile (Fig. 3), it appears that the digested sludge from the pilot plant dewaters faster than that from the full-scale mesophilic anaerobic digester. Similar observation can be made based on the settling velocity profile for the two sludges provided in Fig. 5. The pilot plant sludge settled faster compared to the digested sludge from the full-scale digester (homogeneous) across the entire range of solids volume fraction, which indicates the need for specific characterisation of samples rather than generic sedimentation curves. This can be attributed

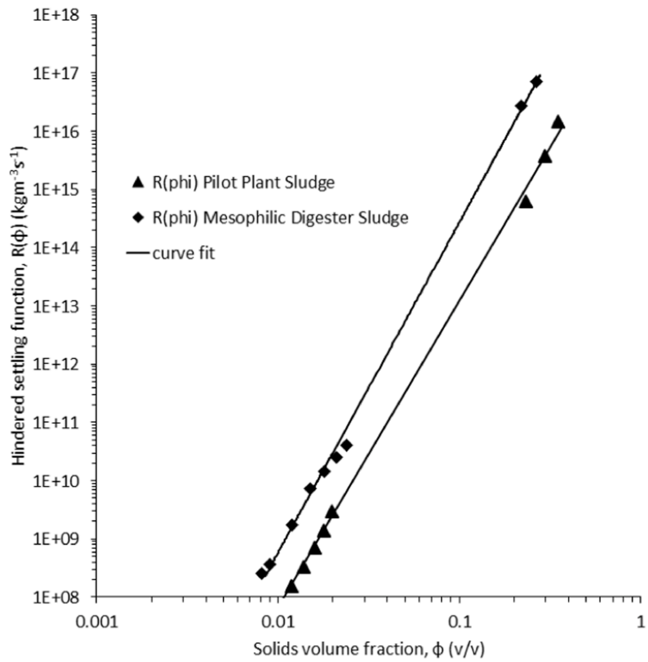

Fig. 3. Hindered settling function profile at 2–40 vol% solids concentrations for pilot plant sludge (non-homogenised lagoon system) in comparison to mesophilic digester sludge (homogenised digester system).

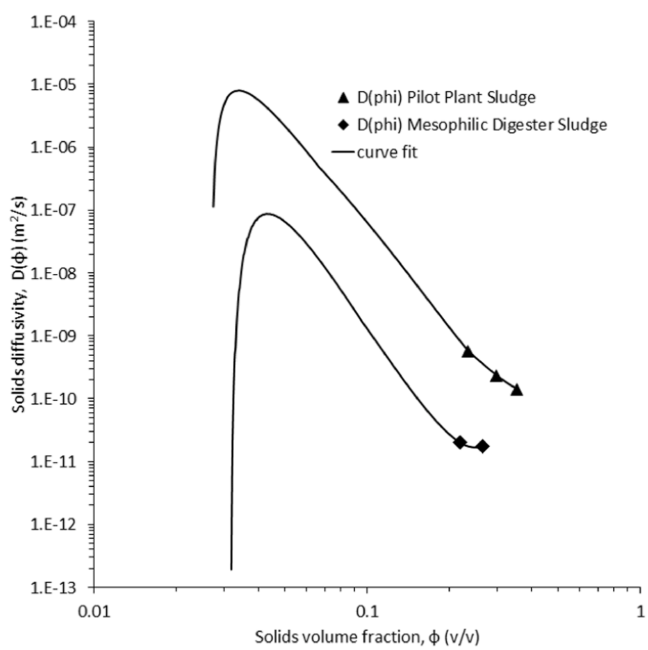

Fig. 4. Solids diffusivity profile at 2–40 vol% solids concentrations for pilot plant sludge (non-homogenised lagoon system) in comparison to mesophilic digester sludge (homogenised digester system).

to higher volatile solids, generation of fines during anaerobic digestion and consequently higher EPS content for the full-scale digester sludge. In addition, at the same solids volume fraction, the shear yield stress values for the digested sludge from the mesophilic full-scale homogenised digester are significantly higher than that for the pilot plant sludge which is a non-homogenised system (Fig. 2).

All of these observations can be attributed to the relatively higher VS content (71% of TS) of the sludge from the full-scale digester compared to the lower VS content (61% of TS) of the pilot plant sample. The

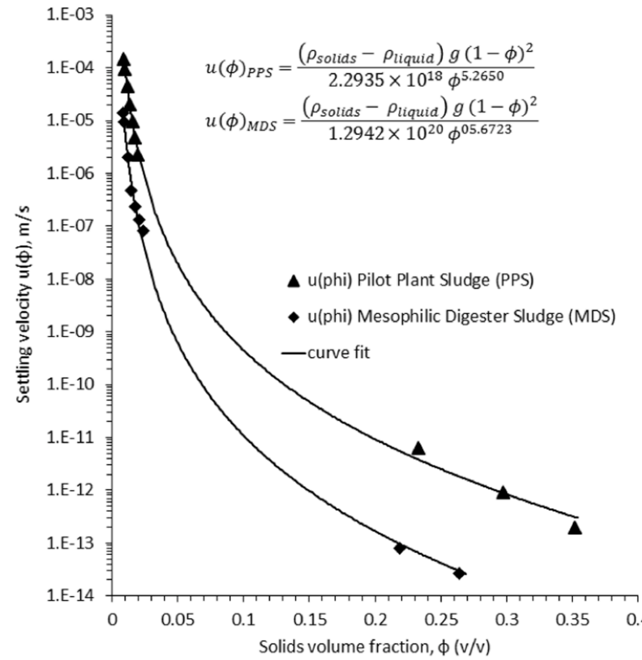

Fig. 5. Settling velocity versus solids volume fractions curves for pilot plant sludge (non- homogenised lagoon system) in comparison to mesophilic digester sludge (homogenised digester system).

volatile solids content of the sludge is considered a surrogate for EPS, which is believed to be responsible for difficulty in dewatering of wastewater sludges (Skinner et al., 2015).

The settling velocity of the lagoon sludge as a continuous function of solids volume fractions can be used as an input for the CFD modelling of anaerobic lagoon process.

5. Conclusions

This study develops continuous constitutive relationships for rheology and solid-liquid separation for large solids gradient materials CFD modelling. This has been primarily focused on lagoon sludges, but has applicability to anaerobic digestate and primary solids.

The results showed Newtonian behaviour to occur at 0.4 vol.%. In the range of 0.5–12 vol.%, the sludge behaved as a Herschel-Bulkley fluid with shear yield stress (τ_y) and consistency (k) as power law functions and flow index (n) as an exponential decay function of the solids volume fraction (ϕ).

The dewaterability data indicated substantial differences in pilot lagoon sludge from a full-scale mesophilic anaerobic digester. Most importantly, the latter had higher values of hindered settling function at a given solids content as the pilot plant, indicating poorer dewaterability and slower sedimentation.

Overall, this work provides for the first time a complete set of rheological properties of an anaerobic lagoon sludge, including the rates and extent to which the sludge will settle and consolidate, as well as its viscous response

Declaration of Competing Interest

The authors declare that they have no competing interest.

Data availability

All data is available in Figshare at 10.6084/m9.figshare.19074614. v1 .

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2022.118903.

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