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Pumping of dewatered sludge: Slipping or flowing behavior?

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HIGHLIGHTS

- Measured rheological behaviors of dewatered sludge are device-dependent.
- A shear localization appears during rheological measurements.
- Usual rheological models no longer works with dewatered sludge.
- Pipe flow of dewatered sludge has to be modeled considering a slipping behavior.

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ABSTRACT

The current design of dewatered sludge pumping devices is based on material flowing properties assuming it is a non-Newtonian highly viscous fluid. From rheological analysis, we first clearly established that current rheological models are no longer valid for this purpose. By using parallel-plates geometry, it was shown that the apparent behavior is dependent on the gap between the plates: results are less representative of sludge intrinsic properties that of the interface interactions between sludge and rotating surfaces. By reproducing dewatered sludge pipe flow at lab-scale, it was highlighted that sludge does not flow but slips along the wall of the pipe. The existence of a thin lubrication layer is suspected and the behavior law to be considered is a slippery law, similar to a Norton–Hoff model.

1. Introduction

Sewage sludge management is a growing challenge for municipalities around the world. For many years, sludge was considered as a basic waste to be landfilled but with the growth of sustainable management, it is now seen as a 'second-hand raw material' from which the organic matter can be reused to produce energy or fertilizers. To increase the calorific value of sludge or to decrease volumes which have to be spread on agricultural fields, sludge is dewatered to concentrate organic matter. However, between the dewatering step and the furnaces or the storage area, dewatered sludge is often pipelined and the design of pumping facilities is of major importance to avoid pipe clogging or pump oversizing.

In order to design pumping facilities, head losses and power consumption are prerequisite parameters which are related to apparent and local viscosities of sludge and to the yield stress as well. As stated by Slatter [8], at high concentration, pipe flows become inevitably laminar. In some cases, laminar flow presents major problems [4], as settling may occur, leading to pipeline blockage. In the case of mechanical dewatered sludge, solid concentration is far above the settling limit and the material can be considered as monophasic. Thus, laminar rheological properties usually determined with conventional rheometer can *a priori* be considered to model sludge pumping behavior.

In laminar conditions, the rheological constitutive model of any fluid can be written in the form:

$$\tau = f(\dot{\gamma}) = f\left(-\frac{\partial v_r}{\partial r}\right) \quad (1)$$

where τ, $\dot{\gamma}$, v_r, r are respectively the shear stress, the shear rate, the radial velocity of the flow within the pipe and the distance from the pipe axis.

For cylindrical pipe, the shear stress varies linearly over the pipe cross-section:

$$\tau(r) = \tau_0 \cdot \frac{r}{R} \quad (2)$$

where τ_0 is the wall shear stress and R the radius of the pipe.

Thus, the velocity profile through the pipe cross-section is obtained by integrating the constitutive equation and the

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volumetric flow rate Q_v is obtained by integrating the velocity profile on the whole cross-section:

$$Q_v = 2\pi \int_0^R v_r(x)dx = 2\pi \int \int_0^R f^{-1}(\tau)d\tau dr \tag{3}$$

The determination of the constitutive rheological model is then requested to model the pumping behavior of sludge.

The rheological behavior of pasty dewatered sludge, ranging from 10% to 15% dry matter, is well modeled by a Herschel–Bulkley model [1] of the form:

$$\tau = \tau_c + K \cdot \dot{\gamma}^n \tag{4}$$

where τ_c is the yield stress, K the consistency and n the power-law index.

At higher concentrations, [2] showed that cracks take place within the material during shear, indicating that frictional interactions intervene between solid compounds, similarly to what happened with concretes [11]. These frictional effects induce dilatancy of the materials [9] to flow. In a confined volume such as in pipe, dilatancy is not allowed and solids cannot move freely as expected in laminar homogeneous flow.

Thus, because of the high solid content of dewatered sludge, ranging from averagely 15% to 30%, the constitutive rheological model could be more complex than the ones which are classically used, such as the Bingham plastic or the Herschel–Bulkley models. In this paper, we demonstrate that the pipe flow of sludge higher than 15% solids is not dominated by viscous forces but mainly by slippage along the wall. Dewatered sludge does not behave like usual non-Newtonian fluids and it has to be considered as soft solids which mainly slip in the pipeline. The rheological model appears to be frictional and to obey to a slipping behavior.

2. Material and methods

Dewatered sludge from various origins (Table 1) was picked-up after the centrifuge dewatering step. Samples are representative of what it is usually found in wastewater treatment, with biological sludge and sludge from biofilter. Their solid concentration is ranging from approximately 16% to 25%.

A model material composed of kaolin in water (dry solid: 60%) was also used to control extrusion tests.

Prior to rheological measurements, sludge was deflocculated to simulate the impact of pumping on sludge structure. This deflocculation was simulated by stirring sludge with a blade-impeller at 300 rpm during 5 min.

Rheological measurements were performed with a MCR301 rheometer equipped with parallel-plates geometry (radius: 10 mm; gap ranging from 0.25 to 1.5 mm). Tool surfaces were roughened to avoid wall slip [13]. Because pipe flow of dewatered sludge is usually slow, a decreasing shear rate ramp was applied from 10 s^{-1} to 0.01 s^{-1}. Measurements were done in triplicate to evaluate the reproducibility.

Pipe flow was also mimicked by using a sensor-equipped piston-driven extruder (Fig. 1) consisting of a chamber with a piston at the top and an extrusion die at the bottom. The sludge contained in the chamber is pushed into the extrusion die by applying a sufficient pressure on the piston. Instantaneous applied pressure and piston position are online recorded as well as experimental time. The extrusion die is connected to capillary tubes of different length/diameter ratios ($L/D = 6.1$; 10; 12.2 and 18.75). For each applied constant pressure, the piston velocity was recorded until the steady state was reached (i.e. when the piston velocity was considered constant). For each couple (pressure, piston velocity), the velocity within the pipe was calculated by applying the mass conservation principle:

$$v_{\text{pipe}} = \left(\frac{R_{\text{piston}}}{R_{\text{pipe}}}\right)^2 \times v_{\text{piston}} \tag{5}$$

where v_{pipe} and v_{piston} refer respectively to the fluid velocity within the pipe and to the piston velocity; R_{piston} and R_{pipe} refer respectively to the piston radius and to the pipe radius.

Shear rate and shear stress were calculated by first drawing the Bagley diagram to evaluate the die entry head loss and then by using the Rabinovich–Mooney correction to take into account the non-Newtonian character of the materials [10]. Details are given in Appendix A.

Table 1
Sludge origin and characteristics.

Sludge origin	Solid content (%)	Volatile fraction (%)
A (biofilter)	23.56	73.0
B (biological)	16.06	79.84
C (biological)	17.66	79.38

3. Results and discussion

3.1. Rheological analysis from a rheometer

The rheological procedure gave extremely reproducible results (Fig. 2) when the gap is imposed and kept constant. However, the rheological behavior appeared to be strongly dependent on the gap between the parallel plates (Fig. 3): the smaller the gap, the thicker the apparent behavior.

Because the rheological characteristics are material intrinsic properties, they should not be dependent on the measuring tools. In our case, these characteristics are dependent on the geometry used to determine them. Thus, this measured rheological behavior cannot be considered representative of the material.

The shear rate/stress calculation assumes the whole volume is sheared between the plates. In our case, the radius and the rotational velocity are imposed values and thus cannot be erroneous.

With parallel-plates geometry, shear rate and shear stress are defined as follow:

$$\dot{\gamma} = \frac{R}{e} \cdot \omega \tag{6}$$

$$\tau = \frac{3C}{2\pi \cdot R^3} \tag{7}$$

where R represents the radius of the plates, e the gap, ω the angular velocity and C the torque.

Knowing that R and ω are imposed, the observed evolution of the rheological measurements must only come from the gap which is partially sheared.

By reducing both shear rate and shear stress [1], a master curve of the form $\tau/a = f(\dot{\gamma}/a)$ is obtained (Fig. 4). It was found that the dimensionless parameter a is proportional to the gap e, (Fig. 5). [1] defined a similar master curve by dividing both shear rate and shear stress with the yield stress. Thus, assuming the dimensionless parameter a is related to the yield stress, its proportionality with the gap indicates that shear localization effectively occurred [2]. Only a thin layer of sludge was effectively sheared (Fig. 6), explaining why the apparent rheological behavior (given by the rheometer according to the tool dimensions) appears all the more fluid that the gap is large.

As a consequence, two conclusions can be made at this stage:

1. Conventional rheological tests and procedures give inadequate data to model the rheological behavior of dewatered sludge.