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The rheological behavior of industrial and domestic wastewater sludge

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Abstract The aim of this work was to characterize the rheological behavior of the sludge proceeding from the treatment of mixed industrial and domestic wastewater, with a view to its subsequent processing: mixing, filtration, dewatering. Rheometric tests were performed with coaxial cylinders rheoviscometer, RHEOTEST 2. After the determination of flow curves $\tau = f(\dot{\gamma})$ for mass fraction of suspended solids in the range: 0.227-0.340, it was found that the rheological behavior of this specific sludge is better described by the Bingham model, with moderate shear stress values, even at high shear rates. This indicates that processing this type of sludge will involve moderate energy consumption. The rheological parameters determined in this study can serve to the design of the equipment in different stage of the treatment process.

Keywords: Bingham model, non-Newtonian fluids, sludge rheology, thixotropy

1. Introduction

During the last decades, the question of water pollution has taken worrying proportion whereas, at the same time, water consumption increased mainly due to the demographic explosion. Industrialized countries now aim at reducing the pollution of water to preserve their water supply.

This latter point particularly implies to optimize the treatment processes of both industrial and domestic wastewater [1]. Since wastewater treatment has been a subject of interest, it has been established that, to optimize the process parameters of wastewater treatment plants, the understanding of the hydrodynamic behavior of sludge flows is of prime importance [2]. It is also well known that suspensions of sludge are non-Newtonian fluids [3].

In order to control and scale up sludge's processes, such as aeration tanks in wastewater treatment plants, it is important to get precise rheological measurements of sludge flows in a sufficiently large range of solid concentration [2].

Such a heterogeneous mixture as sludge is, it implies unusual behavior among which thixotropic effects are often cited [4-6]. According to rheologists, thixotropy generally refers to the reversible breakdown of particulate structure under shear [7;8].

The sludge studied in this work from the rheological point of view has a particular composition because it proceeds from two kinds of wastewater: industrial and municipal; these have very different composition: the industrial sludge proceeding form an oil refinery has a high content of hydrocarbons and heavy metals [9] since the municipal sludge has a high content of grease, nitrogen compounds and tensioactive agents [10]; their mixture can lead to a sludge with a particular rheological behavior since interfacial phenomena can appear at the particles interface with water. Things become even more complicated when adding polyelectrolyte to the sludge for easing the water-solid separation, as done in this case. This is why, a rheological study for this sludge is necessary when taking into account the further processing of it:

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mixing, filtration, dewatering. The practical aim of the work was to have a detailed characterization of the mixture of sludge at different dilutions as they appear in the processing of this sludge.

2. Rheological models

The rheological characterization of wastewater sludge presented in the different studies are not always easy to compare, partly due to the non-uniformity of operating conditions, but also to the fact that sludge is a complex material with important variations in structure from one suspensions to another. One of the major consequences of these variations is that an empirical correlation, obtained to characterize a given sludge operated in a given set-up, will not apply universally, at least on a quantitative point of view [2]. The rheological models mostly encountered to characterize the wastewater treatment sludge are viscoplastic ones such as the Bingham model (Eq. 1) [11; 12], the Herschel-Buckley model (Eq. 2) [13; 14], the Casson model (Eq. 3) [15; 1], or purely shear thinning models such as the Ostwald de Waele (power law) model (Eq. 4) [16], depending whether the flow model is considered to start from zero stress or not.

$$\tau = \tau_0 + k \cdot \dot{\gamma} \quad (1)$$

$$\tau = \tau_0 + k \cdot \dot{\gamma}^n \quad (2)$$

$$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{k \cdot \dot{\gamma}} \quad (3)$$

$$\tau = k \cdot \dot{\gamma}^n \quad (4)$$

In Eqs. (1-4), τ is the shear stress, $\dot{\gamma}$ is the shear rate, and k, n and τ_0 are the model parameters. The parameter k in the Bingham equation represents the slope of the linear shear stress versus shear rate, and corresponds to the apparent viscosity of the fluid η_a. In general, the "consistency index" k provides an indication of the cohesiveness of the fluid: higher values reflect higher viscosities. Values of "flow behavior index" n far from one indicated high deviation from Newtonian behavior (n = 1 for Newtonian fluids). The yield stress τ_0 represent the resistance of the sludge to the deformation until sufficient stress is applied to exceed the yield strength of the solid phase [17]. Increasing trends of k and τ_0 and decreasing of n were reported when increasing of sludge solid suspended concentration (SSC) [2; 15]. Numerous studies [18-20] reported exponentials equations types to characterize the variation of sludge viscosity with SSC. Some authors [21] found that there is a linear correlation between sludge viscosity and SSC. For the variation of sludge viscosity versus SSC, some papers [22] report a power function, which characterizes this variation.

3. Experimental

3.1. Origin and nature of sludge

The concentrated sludge samples used in this study were collected from wastewater treatment of a Petrochemical Complex, after the final dewatering stage. Before the treatment processes, the wastewater are mixed with a municipal wastewater.

First, SSC was determined in the original sludge (S0%) by gravimetry. This sludge was collected from the end of the process, after filtration by centrifugation. It contained polyelectrolite for breaking water-oil emulsion. Then, sludge samples were prepared by diluting the concentrated sludge sample, in order to obtain different values for SSC. These dilutions were made, taking into account that during the sludge processing, the moisture content decreases continually. For simplification, the sludge samples are named after the percent of dilution water added to the concentrated sludge sample: S0%, S25%, S40% and S50% respectively, where S0% is the concentrated sludge sample. The values of sludge samples density are shown in **Table 1.**

Table 1. The density of sludge samples

Sludge	Density [kg/m^3]	SSC (weight fraction)
S0%	1035.2	0.340
S25%	1026.4	0.272
S40%	1021.1	0.243
S50%	1017.6	0.227

The method used for the determination of the sludge sample density was ASTM D 1480 – 02.

3.2. Equipment

For the sludge samples rheological behavior determination was used a rheoviscometer, RHEOTHEST 2 with coaxial cylinders, consisting in two units: the viscometer and the block with the measuring apparatus. The schematic representation of this rheoviscosimeter is presented in **Fig. 1** [23].

The viscometer is equipped with a drive with twelve speed steps, one transducer and five measuring devices with different cylinder dimension (S1, S_2, S_3, N and H) depending on the viscosity range being measured.

The apparatus block contains an Ampere-meter, frequency meter, switch for the motor, and switch for the transducer, mechanical correction and electrical correction for the measuring device zero point.

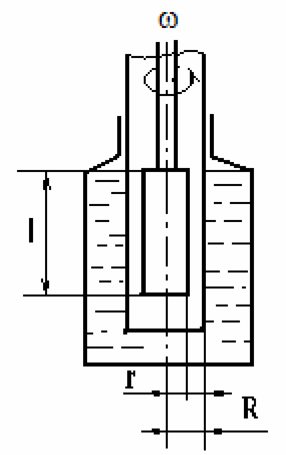

Fig.1. Schematic representation of rheoviscometer with coaxial cylinders

The experimental determination is based on shearing of the fluid between the two cylinders, one being steady and the other one in rotation. The cylinder, which rotates, has an angular speed ω and a moment of torsion M_t that depends on the resistance opposed by the fluid during flow. The torsion, velocity and angular frequency are measured so that real shearing tension can be calculated at the inner cylinder wall, function of radius r and height l.

The calculus relations for the shear stress, shear rate and viscosity are presented in **Table 2.**

Table 2. Equations used for shear stress, shear rate and viscosity

Parameter	Coaxial cylinders
Shear stress, τ	$\frac{M_t}{2\pi l r^2}$
Shear rate, $\dot{\gamma}$	$2\omega \frac{R^2}{R^2 - r^2}$
Viscosity, η	$\frac{\tau}{\dot{\gamma}}$

4. Results and Discussions

4.1. Sludge rheology

The rheological behavior was determined at 25°C, the usual processing temperature for sludge. Four sludge samples with different SSC S0%, S25%, S40%, and S50% were prepared. For these sludge samples it was determined the rheological behavior, meaning the determination of variation curves of shear stress τ [Pa] versus shear rate $\dot{\gamma}$ [1/s]. The variation curves are shown in **Figs. 2-5.**

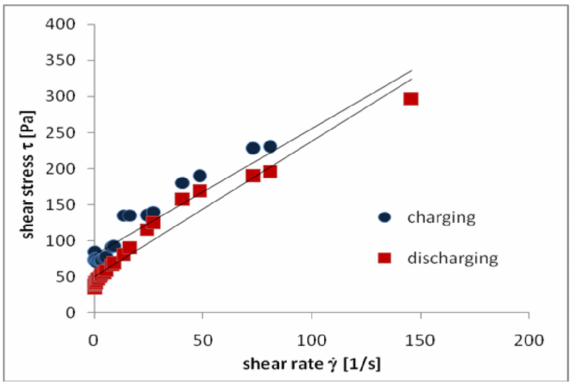

Fig. 2. Rheogram $\tau = f(\dot{\gamma})$ for S0% at 25°C

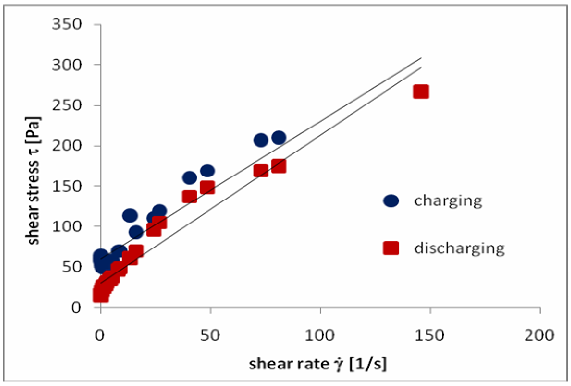

Fig. 3. Rheogram $\tau = f(\dot{\gamma})$ for S25% at 25°C

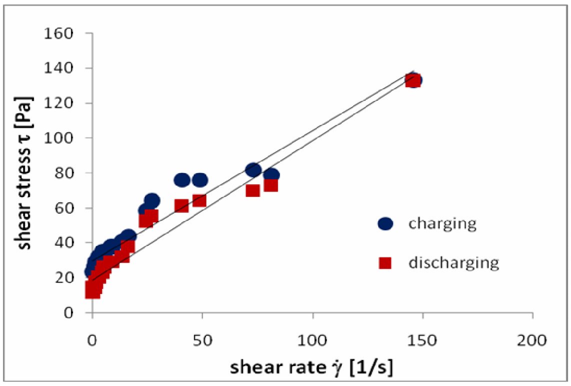

Fig. 4. Rheogram $\tau = f(\dot{\gamma})$ for S40% at 25°C

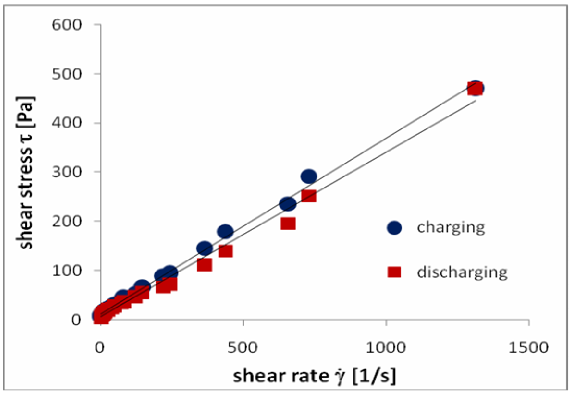

Fig. 5. Rheogram $\tau = f(\dot{\gamma})$ for S50% at 25°C

Figure 6 presents the apparent viscosity evolution as a function of the shear rate of sludge samples at different SSC.

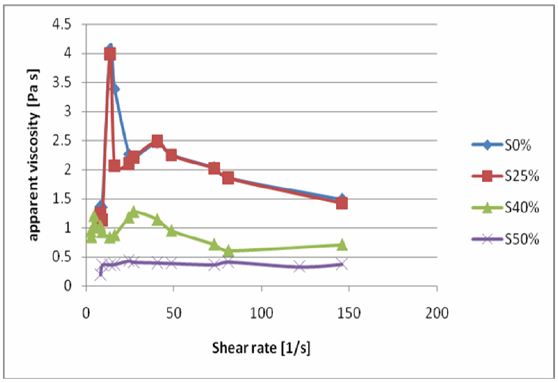

Fig. 6. The sludge apparent viscosity *vs*. shear rate at different SSC.

As seen in the rheograms (Figs. 2-5), the application of the increasing (charging) and decreasing (discharging) shear rates on the same sludge sample may results in different curves, which means the sludge present thixotropy. The area enclosed between the two curves (hysteresis area) provides an indication of time depending rheological behavior. This thixotropic behavior of the sludge suspensions is supposed to be due to the alignment in the flow direction of particles segregated by shear. The thixotropy is dependent on the SSC. The thixotropic effect (hysteresis loop area) increases with increasing SSC, as seen progressively from Fig. 5 towards Fig. 2.

The shear stress increasing with the SSC at the same shear rate is obvious: e.g. at 150 s^{-1}, the sample with SSC=0.227 had a shear stress of 60 Pa since at SSC=0.34, the stress was 300 Pa. It was expected for more concentrated suspensions to be more viscous. Also, the yield stress of the rheograms increases from practically no yield stress at SSC= 0.227 to approx. 80 Pa at SSC= 0.34. In conclusion, on a relatively narrow range of SSC (from 0.227 to 0.34), one can observe consistent differences among the rheological curves in term of parameters values since the shape of the curves indicates the same type of pseudoplastic fluid.

Figure 6 shows that the apparent viscosity of S0%, S25% and S40% increased with a peak (at 20 s^{-1} for S0% and S25% and at about 30 s^{-1} for S40%) and then decreased with the increasing of shear rate. At S50%, the apparent viscosity was observed nearly constant, indicating a different rheological behavior, close to a Newtonian fluid. This conclusion is sustained by the very small hysteresis of the rheogram (Fig. 5).

4.2. Determination of the rheological parameters

After the general observations on the rheological behavior of sludge suspensions in Section 4.1, it would be of practical interest to quantify the rheological parameters and correlate them with the SSC. In the **Table 3**, different rheological models are presented with the values of k, n and τ_0 parameters and the corresponding correlation coefficients R^2, applied to the sludge samples S0%, S25%, S40% and S50% (at different SSC). The models presented in Table 3 were applied only to the charging curve (at increasing shear rates).

Table 3. The rheological models, the values of parameters k, n and τ_0 and the correlation coefficients R^2

Sludge / Model	S0%	S25%	S40%	S50%
Bingham model				
η_P (Pa·s)	1.757	1.706	0.748	0.357
τ_0 (Pa)	80.051	59.945	29.572	12.450
R^2	0.928	0.926	0.934	0.997
Herschel-Buckley model				
k (Pa·s^n)	7.688	5.194	0.963	0.333
τ_0 (Pa)	80.051	59.945	29.572	12.453
n	0.637	0.728	0.971	1.018
R^2	0.848	0.913	0.930	0.990
Casson				
k (Pa·s$^{0.5}$)	0.681	0.758	0.312	0.285
τ_0 (Pa)	59.267	41.420	21.189	4.088
R^2	0.916	0.916	0.928	0.996
Ostwald de Waele (power law) model				
k (Pa·s^n)	75.449	56.295	27.035	3.957
n	0.206	0.237	0.242	0.601
R^2	0.776	0.749	0.912	0.968

Studying the values of correlation coefficient R^2 from the Table 3 is obviously that the sludge samples analyzed in this work have a non-Newtonian behavior which respects the Bingham model, meaning that the variation of shear stress versus shear rate is linear with flow thresholds. The Casson model could also be taken into account, according to the good R^2 values, but Bingham model should be preferred because the Casson model, by its square roots of parameters tends to decrease artificially the errors of the model. So, the equation which describes the rheological behavior of the sludge samples is Eq. (1). An important feature of the Bingham model materials is the presence of a yield stress. Below the yield stress the sludge exhibit solid–like characteristics, i.e., it stores energy at small strains and does not level out under the influence of gravity to form a flat surface. This feature is very important in process design and quality assessment for the sludge. As shown in Table 3, τ_0 and η_P increased from 12.453 to 80.051 Pa and from 0.357 to 1.757 Pa s, respectively, with an increase in sludge SSC from 0.227 to 0.340.

5. Conclusions

The results obtained in this work confirm the supposition that the sludge proceeding from petrochemical wastewater treatment mixed with municipal sewage has a yield threshold rheological behavior with respect to the Bingham model and is also a thixotropic fluid. The relationship between shear stress and shear rate shows a non-Newtonian behavior for all three sludges (S0%, S25% and S40%), except the case of sludge S50%, in which the non-Newtonian behavior was less pronounced.

The interaction between different components of the two sorts of wastewater and phenomena at the interface of particles with the liquid could explain the pseudoplasticity. The hysteresis loop area increases with the increase of the SSC, indicating a thixotropic property. The thixotropy of the sludge is mainly due to the alignment in the flow direction of particles segregated by shear.

The practical goal of the study was to find the parameters of the rheological equations and to correlate them with the sludge SSC. It was found that both yield stress and sludge viscosity increases with SSC. The apparent viscosity of all four sludges decreased with increasing shear rate, although at S50% it looks nearly constant.

The preferred Bingham plastic behavior of the sludge suggested that higher shear stress will be required to overcome the heterogeneity of fermentation medium as reflected in higher agitation rates required for sludge mixing and flow.

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