Rheology Serving the Environment to Characterize Sludge from Wastewater Treatment Plants (WWTPs); New Model for New Concentration Range

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ABSTRACT

Rheological parameters were a fundamental importance in sludge characterization, as they strongly affected almost all treatment, utilization and disposal operations, such as storage, pumping, transport and drying. This paper will present different sludge rheological parameters from wastewater treatment systems. These parameters were obtained by fitting the experimental data of various shear rates $\dot{\gamma}$ from 0 to 100 s^{-1}, under a series of Total Suspended Solids (TSS) content. The temperature was maintained constant at 20 ± 2 °C. The apparatus used was a rheostress RS600. The results obtained showed that viscosity of sludge of concentrations 25% and 30% (Total Solids TS), underwent an increase of 1.71 to 2.06 mPa.s and of 1.56 to 2.12 mPa.s successively. In the same way for the other concentrations studied. The rheological results showed that the sludge study belonged to a non-Newtonian family. The most fitting model to describe this rheological behavior was the Ostwald one. This research confirmed that rheological characterization was considered as a relevant tool to understand the wastewater sludge suspension behavior in order to improve wastewater treatment process operation.

I. Introduction

Primary and secondary sludge produced in wastewater treatment plants is composed of a complex mixture of organic and mineral, dead and alive matter that is further treated using specific processes of treatment of this excess sewage sludge. Such processes aim at providing a material usable in the classical fields of conversion of biological wastes such as agricultural reuse, dumping, incineration or thermo -chemical conversion. The main goal of the treatments applied to rough sewage sludge is the reduction of both volumes and injuries. At the exit of wastewater treatment processes, sewage sludge is composed of 99% of water and occupies considerable volumes. Sewage sludge is also a highly fermentescible matter releasing strong odours. As a consequence, in order reduce sludge volumes and injuries; they have to be submitted to various treatments (concentration, aerobic stabilisation or anaerobic digestion, conditioning, dewatering, storage, etc. During these operations rheological properties of sludge suspensions will strongly influence working conditions and scaling-up calculations of tanks, settlers, pumping stations or installations for sludge transport and storage. For all these reasons, some articles have been devoted to the rheological study of more or less concentrated sludge, in order to optimize such processes of treatment of sewage sludge [1]. In Algeria, the National office of Cleansing (ONA) manages 154 WWTPs [2]. Table 1presents the majority of key figures from ONA for the month of January 2020. It was of major to importance to be able to measure some wastewater sludge rheological parameters that can be used as tools to investigate the treatment proper functioning. Rheology described the body deformation under shear stress influence. More specifically, the shear stress (τ) determination as a function of the shear rate ($\dot{\gamma}$) was called "rheogram" and this allowed the matter rheological behavior characterization. The rheological parameters recorded from bacterial suspensions in pure culture or sludge depended on the rheological equipment used and the measurement procedure applied [3] and [4]. Sludge produced in wastewater systems (i.e. from primary, secondary or tertiary treatment) characteristics varied greatly, due to the tremendous difference in wastewater composition, and in wastewater treatment plants design and operation. Sludge rheological properties depended on sludge parameters such as shape (size of particles), dispersion degree, solid components content, chemical constitution, temperature and physical features. Activated sludge was a suspension showing non-Newtonian fluid behavior [5]. This meant that the shear stress (τ) was not linearly related to the shear rate $(\dot{\gamma})$.

Table 1. Figures from ONA for the month of January 2020 [2]

Number of municipals managed by ONA	**1147** Municipalities
Total length of networks managed by the ONA	**55281** Km
Number of sanitation centers	**268** centers
Volume of wastewater discharged	**105** Million m^3
Number of interventions carried out	**32832** interventions
Linear network of priests	**621081** mL of pipes
Number of connection made	**71** connections
Linear of renewed pipes	**971** mL
Number of manholes performed	**80** manholes
Volume of solid waste evacuated	**30904 m^3**
Number of lifting stations managed by the ONA	**499** lifting and drainage station
Number of WWTPs in operation by ONA	**154** WWTPs
Installed capacity of WWTPs	**10.390.779 Million** inhabitant equivalent
Monthly volume of purified water	**21 Million** m^3
Average daily flow of treated wastewater	**668.386 million** m^3/day

I.1. Fluids viscosity

For biological sludge, viscosity was strongly influenced by sludge particle-particle interaction. Different factors such as the Total Solids (TS) [6], the surface chargen [7], the bulk solution ionic strength, the extra cellular polymeric substances (EPS) content, the sludge particles size [8] and the temperature can affect the sludge viscosity evolution.

The Eq.(1); presented Einstein's relationship giving the suspension viscosity according to the solvent viscosity :

$$\frac{\mu}{\mu_0} = 1 + 2,5\varphi \qquad (1)$$

Where μ and μ_0 was the suspension and solvent viscosities and φ the suspension volume fraction occupied by particles [1]. For a non-Newtonian fluid, only an apparent viscosity can be calculated. These fluids were characterized by the relationship variation between the shear stress and the gradient speed for the same temperature and under the same pressure.

The viscosity variability was the structure changes proceeding result in the sludge during the flow. Sludge thickening increased its viscosity and caused more difficulties in the pump and hydraulic transport according to the results reported [9]. The equation of state was given according to apparent viscosity like continuation:

$$\tau = \mu_a . \dot{\gamma} \qquad (2)$$

With μ_a : apparent viscosity was dependent on time and varies with the shear rate. In the majority of the cases, four following flow typologies can describe the fluids with the non-Newtonian behaviors.

I.2. Rheology behaviour models

The sludge rheological behavior can be described by Bingham model (Eq.(3)), the Ostwald model (Eq.(4)), the Herschel-Bulkley model (Eq.(5)), and the Sisko model (Eq.(6)) [10]

$$\tau = \tau_0 + k\frac{dv}{dx} \qquad (3)$$

$$\tau = k\left(\frac{dv}{dx}\right)^n \quad (4)$$

$$\tau = \tau_0 + k\left(\frac{dv}{dx}\right)^n \quad (5)$$

$$\tau = \mu_B\frac{dv}{dx} + k\left(\frac{dv}{dx}\right)^n \quad (6)$$

Where $\tau(Pa)$ the shear stress and $\frac{dv}{dx}$ (s^{-1}) the shear rate. The consistency index k represented the fluid cohesiveness, and the flow behavior index n far from one meant high deviation from Newtonian behavior (n = 1 for Newtonian fluids) and the yield stress τ_0 indicated the sludge resistance to the deformation until sufficient stress was applied to exceed the solid phase yield strength. The parameter μ_B was the high shear limiting viscosity where the shear rate imposed on the fluid tended to an infinite value [11].

II. Material and Methods

II.1. Source and preparation of samples

Sludge used in the present study came from Sidi Belabbes (Algeria) wastewater purification plant. The sludge dried in a laboratory drying oven under a temperature of 40°C during 24H. Due to the rheological measurement cell size gap, the sludge was crushed then sieved with an 80 μm mesh sieve. Five samples were prepared and tested into the L.R.T.T.F.C (Rheology, Treatment and Transport of Complex Fluid Laboratory) at Universty of Oran (USTO), for different solid matter concentration content 25, 30, 35, 40, and 45g.L^{-1}

II.2. Rheological measurements and protocols

The apparatus used was a rotational rheometer "Rheostress RS600"**.** The sludge sample volume (v) used for each measurement was 17 mL. The protocol used was to increasing linearly shear rate to study sludge in laminar flow and not turbulence one, from 0 to 100 s^{-1} in 210 second. Note that the treatment method was chosen as the most appropriate model for the behaviour of sludge of WWTPs from the decontation basin to the drying bed. The temperature was maintained constant at 20±2°C. Every sample was tested 6 times; therefore 30 tests were carried out out in the present research. The RS600 device is controlled by a computer using the Projob Manager software and the results are processed with the Rheowin Data software allowing instant visualization of Rheograms (recording of the shear stress (τ) as a function of shear rate $(\dot{\gamma})$ and the calculation of the various rheological parameters according to the modelling chosen for the flow). The Excel software is then used for tracing the rheograms, Figure 1 showed different steps followed from rheometer to rheograms plotting.

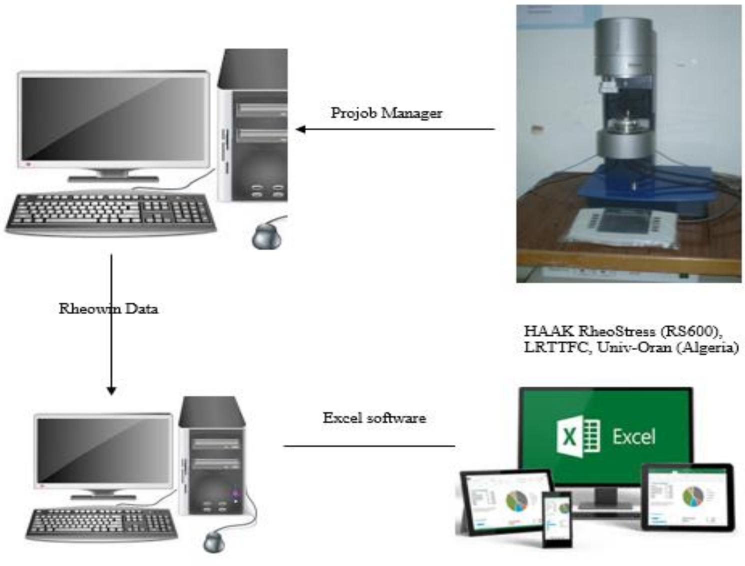


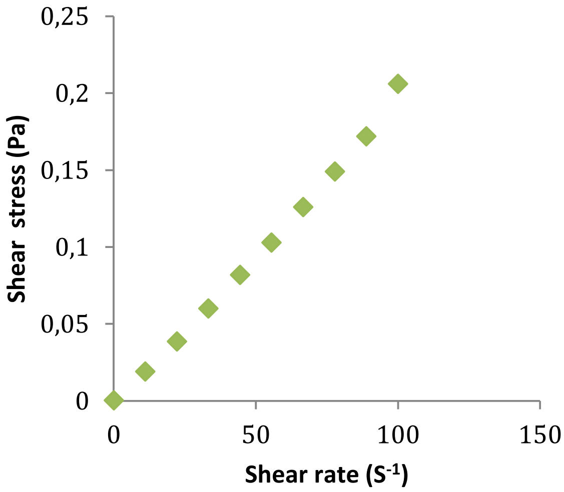
Figure 1. Process followed from rheometer to rheograms plotting (L.R.T.T.F.C Univ-Oran)

III. Results and Discussion

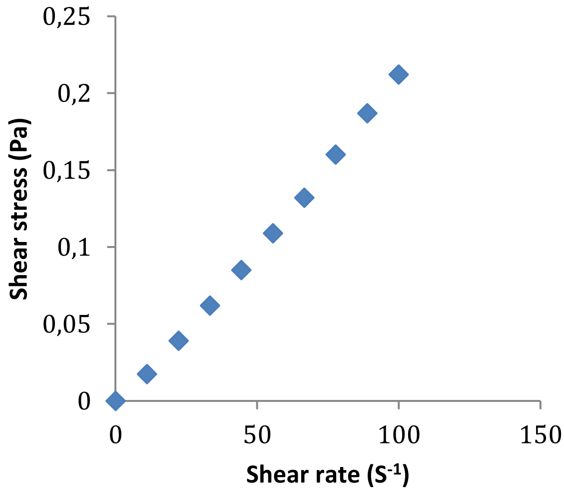
Figure 2 showed rheograms obtained for sludge wastewater sample at different TS content. It was clear that curves obtained for the application of an increasing shear rate were basically the same. The results proved that sludge belongs to a non-Newtonian family. The most fitting rheological model describing this rheological behavior was the **Ostwald model**. Different Ostwald's model parameters (consistency index k, and the flow behavior index n) were mentioned in table 2.

Table 2. Rheological parameters of studied sludge

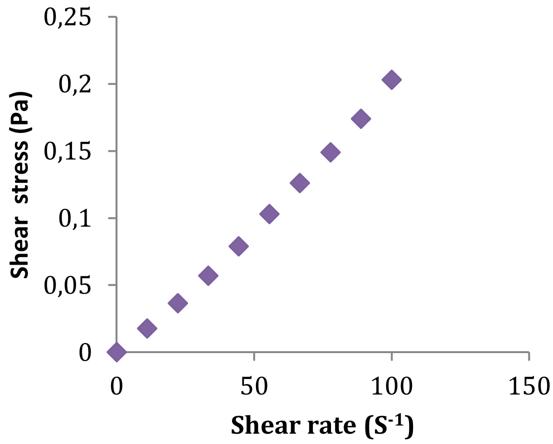
TSS ($g.l^{-1}$)	Ostwald de waele parameters		
	K($mPa.S^{-1}$)	n	r
25	1,161	1,119	0,9993
30	1,149	1,113	1
35	1,017	1,148	0,9999
40	1,223	1,118	0,9996
45	0,933	1,172	0,9999



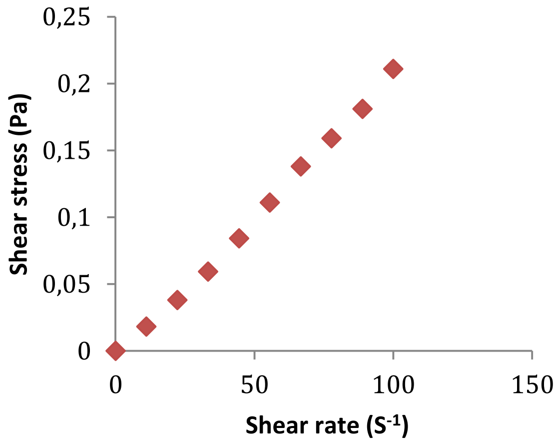
(a): Rheogram of shear stress vs shear rate of sludge of **25%TTS**



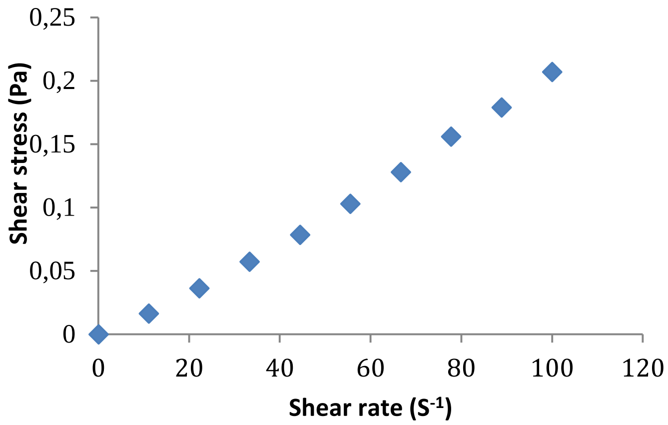
(b): Rheogram of shear stress vs shear rate of sludge of **30%TTS**



(c): Rheogram of shear stress vs shear rate of sludge of **35%TTS**



(d): Rheogram of shear stress vs shear rate of sludge of **40%TTS**



(e): Rheogram of shear stress vs shear rate of sludge of **45%TTS**

Figure 2. Rheograms of shear stress vs shear rate of sludge through different concentrations (a, b, c, d, e)

Figure.2. illustrated a remarkable increase in the apparent sludge viscosity for different Total Solids (TS) content during the shearing imposed history. This increase in apparent viscosity translated the Bernoulien effect and the Waaliennes forces caused particles adhesion. An apparent viscosity summer maximum value reached equal to 2.12 mPa.s for a shearing speed of 100 s^{-1} and for a Total Solids (TS) of 30 g/L. Table 1 presented Ostwald's model different parameters (consistency index k, flow behavior index n, and the correlation coefficients r). The table 3 locates our original research which gave the suitable model to describe behavior of actived sludge of the concentration range (25- 45) $g.L^{-1}$. It's noted that the range chosen shows the actuel concentration range of sludge leaving the decontation basin towards the drying beds.

Table 3. Psitioning of the results obtained in the art literature of rheology

Autors	Nature of sludge study	Range of TS ($g.L^{-1}$) tested	Type of Rheometer used	Rheological model
Battistoni P, .(1997) [12]	Anaerobic digestion sludge	40 - 330	rotationnel Viscosimeter	Bingham and Ostwald

Lolitto V, et al. (1997) [13]	Activated and digeted sludge	12 - 75	Co-cylinder rotary rheometer	Ostwald
Dollet P, (2000) [14]	Activated sludge	0 - 20	Co-cylinder rotary rheometer, double air gap	Bingham
Djafari D, (2020)	**Activated sludge**	**25 - 45**	**Haak RheoStress RS600**	**Ostwald**

IV. Conclusion

The rheological characterization and thermal analysis were used to draw the following conclusions: For rheological characterization, sludge studied had shown a non-Newtonian behavior. The rheological model as adopted to describe this behavior was that of Ostwald de Vaele. On one hand, this characterization helped to understand sludge's response to deformation, knowledge essential in developing crystal specifications for handling, transportation, applications, and in determining the optimum conditions for the processing equipment's efficient operations. On the other hand, thermal analysis was one of the key tools to know the transformation different phases.

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