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# Rheological measurements on different types of sewage sludge for pumping design

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ABSTRACT

Sewage sludge pumping could represent an optimal solution to assure adequate treatment of sludge in centralized plants, with a consequent reduction of the environmental impact of sludge disposal (volume, odour, putrescence), because small wastewater treatment plants usually do not provide an adequate treatment due to high costs. An accurate knowledge of rheological parameters is required to compute head loss for pipeline design, but only few data are available. In order to circumvent the problem of the scarcity of sludge rheological data, we have performed tests on different types of sludge, with solids concentration and temperature in the typical range of a conventional wastewater treatment plant. Bingham rheological parameters and sludge thixotropy values have been processed by regression analysis to identify their dependence on solids concentration or temperature. The results of this study allow the definition of guidelines and optimal strategies for designers in order to reduce pumping costs.


## 1. Introduction

Sludge treatment is a key part of wastewater treatment plants but is highly costly: together with disposal, it represents up to 50–60% of total treatment costs (Novak, 2006). Sludge stabilization is usually performed only in plants of middle or large size, because it is economically unaffordable for small ones. However, stabilization and dewatering are fundamental for a sustainable management of sewage sludge and for the reduction of the environmental impact deriving from sludge disposal (in terms of odours, volumes and putrescence). A solution for small plants could consist in pumping the produced sludge to bigger plants for adequate treatment. Moreover, pumping can be also a convenient solution to transfer the anaerobically digested sludge from larger plants to centralized plants for further treatments, such as incineration.

In spite of the attractiveness of pumping, the design of a piping system for the transport of sludge, a non-Newtonian fluid, is very difficult, due to its complex and variable behaviour. In fact, for such fluids, viscosity is not constant and needs to be determined on the grounds of the fluid-dynamic conditions in the pipe.

Several models have been proposed to describe rheological properties of a non-Newtonian fluid. According to the Herschel-Bulkley model, the shear stress $\tau$ [Pa] is given by the equation:

$$\tau = \tau_y + k\left(\frac{dv}{dr}\right)^n \quad (1)$$

where $\tau_y$ is the yield stress [Pa], $n$ is the fluid behaviour index [dimensionless], $k$ is the fluid consistency coefficient [Pa s$^n$] and $dv/dr$ is the shear rate [s$^{-1}$] (Herschel and Bulkley, 1926). Simpler models can be derived from equation (1) with $n = 1$ (Bingham model) or with $\tau_y = 0$ (Ostwald model). Adopting the latter model, shear thinning or pseudoplastic fluids and shear thickening or dilatant fluids can be modelled with $n < 1$ and $n > 1$ respectively, while Newtonian fluids correspond to $n = 1$.

An apparent viscosity can be defined for all fluids as:

$$\mu_a = \tau\left(\frac{dv}{dr}\right)^{-1} = \tau_y\left(\frac{dv}{dr}\right)^{-1} + k\left(\frac{dv}{dr}\right)^{n-1} \quad (2)$$

As can be seen, the apparent viscosity is non-linear and varies with shear rate, with the exception of Newtonian fluids. In Bingham fluids equation (2) reduces to:

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$$\mu_a = \tau_y \left(\frac{dv}{dr}\right)^{-1} + k \quad (3)$$

which further collapses to the identity $\mu_a \equiv k \equiv \mu$ in the case of Newtonian fluids.

The evaluation of head loss in sludge pumping has been theoretically and empirically studied for both laminar and turbulent flow, giving rise to different formulations (Chilton and Stainsby, 1998; Clapp, 1961; Dodge and Metzner, 1959; Stainsby et al., 1994; Thomas and Wilson, 1987; Tomita, 1959). The drawback of the practical application of such studies lies in the fact that they often require the experimental determination of several rheological parameters for the sludge to be pumped, e.g. the apparent viscosity, necessary for the calculation of the pressure drop in a pipeline. Unfortunately, such experimental data are not yet available when designing a new plant. Moreover, rheological properties are strongly affected by sludge type, i.e. they change as a function of several characteristics specific to each type of sludge, such as density, solids content, particle size and size distribution, settling rates, abrasiveness, particle friability, surface charge, liquid phase conductivity, pH, etc. (Forster, 1982; Mori et al., 2008; Sanin, 2002). Hence, specific information on each type of sludge is necessary.

In some previous studies, the rheological properties of different types of sludge from conventional treatment plants were analysed, using the different models available for the evaluation of sludge viscosity (Civelekoglu and Kalkan, 2010; Moeller and Torres, 1997; Seyssiecq et al., 2008). Over the last years attention has been mainly devoted to the rheology of sludge from innovative treatments, like activated sludge in membrane bioreactors (Hasar et al., 2004; Laera et al., 2007; Rosenberger et al., 2002; Yang et al., 2009) and in rotating biological contactors (Abu-Jdayil et al., 2010), granular sludge in an upflow anaerobic reactor and in an expanded granular sludge bed reactor (Mu and Yu, 2006; Pevere et al., 2009) or waste activated sludge treated by a flat sheet membrane for simultaneous sludge thickening and digestion (Xia et al., 2009).

However, the information provided by all the mentioned studies is very specific to the investigated sludge, usually in a narrow range of solids concentration; hence, a comprehensive data-set of rheological measurements for sludge from the different treatment steps of a conventional wastewater treatment plant in a wide range of concentration is missing. In order to provide reliable data and useful information to design a sludge pumping system for a new plant, we performed rheological measurements on the most common types of sludge from a conventional wastewater treatment plant (return activated, raw mixed and anaerobically digested sludge) at different concentrations and temperatures. Sludge categories, concentrations and temperatures were chosen to encompass all the possible combinations likely to occur in a conventional wastewater treatment plant. In particular, the temperature effect was thoroughly scrutinized as very few studies have investigated this topic (Abu-Jdayil et al., 2010; Baudez et al., 2013; Hasar et al., 2004; Manoliadis and Bishop, 1984), in spite of the well-known dependence of the viscosity on temperature.

Results have been processed by regression analysis to find correlations between rheological parameters and solids concentration or temperature. Moreover, as very few studies have tried to model the thixotropic character of sewage sludge, the effect of both solids concentration and temperature on thixotropy has been studied.

The achieved results provide useful guidelines for sludge pumping design: in fact, they can be used for the choice of the type of sludge that can be more easily pumped and can be precious for a rough estimation of the cost of different pumping solutions in the case of the design of a new plant for which sludge rheological properties are not known.

## 2. Materials and methods

### 2.1. Sample preparation

Rheological tests have been carried out on three different types of sewage sludge at various solids concentrations and temperatures. Samples have been collected from the return activated sludge line of the activated sludge tank (return activated sludge), from the thickener (raw mixed sludge) and from the anaerobic digester (anaerobically digested sludge) of the conventional wastewater treatment plant of Bari-Ovest (Italy). In order to avoid clogging or instable and invalid measurements, all samples have been sieved by a 1000 μm sieve so as to eliminate the impurities normally present in sewage sludge that cannot be considered natural components of the sludge matrix. Every sample has been concentrated by sedimentation and/or centrifugation. A set of samples with different concentrations has been then prepared by diluting the concentrated sludge with different portions of the centrate or supernatant. The samples have been stored at 4 °C before the tests and processed within a week in order to limit possible sludge modifications. Total and volatile suspended solids concentrations (TSS and VSS) for all the samples, determined according to standard methods (APHA et al., 1998), are reported in Table 1 (average of three measures).

### 2.2. Rheological tests

In order to get flux curves, all sludge samples have been tested using a conventional rotating viscometer AR500 of TA Instruments with plate geometry. The following conditions have been adopted:

- gap: 1 mm for samples with solids concentration lower than 3.0%, 1.5 mm for the other ones;
- plate diameter: 40 mm;
- shear rate range: 0–500 $s^{-1}$ for samples with solids concentration lower than 4.5%, 0–200 $s^{-1}$ for those with higher concentrations;
- temperature: controlled at 10, 15, 20, 25, 30 °C (plate with Peltier effect).

The measuring cycle consisted of four steps: first, a conditioning step of 60 s at a shear rate of 5 $s^{-1}$; second, an equilibrium phase of 30 s; then, the flow step until the maximum shear rate was reached; afterwards, the shear rate reduction back to zero in the final phase.

Great attention has been paid to ascertain that the sludge sample does not exceed the plate diameter, because the relevant error is proportional to the fourth power of the ratio between the extra sludge radius and the plate radius. Three tests for each condition have been performed and the average values have been considered.

### 2.3. Data analysis and processing

The Rheology Advantage Software, specifically designed for AR Rheometers, has been used for instrument control, data collection and data analysis. For each tested solids concentration and for each temperature, the values of $\tau_y$ and $k$ have been computed using the Bingham equation. Bingham model has been chosen because it gives non-zero values of viscosity also at high shear rates (differently from the Ostwald model): in fact, as theoretically demonstrated, all fluids exhibit a finite value of apparent viscosity at infinite shear stress (Kozicki and Kuang, 1993). Nonetheless, good correlation coefficients have been also obtained with the Ostwald model. Thixotropy [Pa $s^{-1}$] has been evaluated as the area included