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Electrical and rheological properties of sewage sludge – Impact of the solid content

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ABSTRACT

Sludge treatment is a multistep process during which sludge is mixed, pumped, thickened and dewatered. The total solid content (TSC) increases from a few grams to more than a hundred grams per liter and as underlined by the existing literature, rheological characteristics are key criteria for sludge management. However, these characteristics remain difficult to be determined in-situ and professionals are looking for alternative techniques to evaluate them. In that context, the potential of electrical measurements has been highlighted (Dieudé-Fauvel et al., 2009, 2014). This paper investigates the additional benefits of correlating both rheological and electrical properties for sludge characterization within the range of 1–23%TSC. On a rheological point of view, results are consistent with previous literature. In parallel, electrical impedance spectroscopy allowed us to define an equivalent electrical circuit to model the sludge electrical signature. Results highlight that the circuit parameters follow two regimes according to the range of solid content, similarly to rheological properties. This work opens new insights about sludge characterization and treatment monitoring.

1. Introduction

Due to the increasing efficiency of wastewater treatment plants and the development of international water treatment policies, sludge management is becoming a major concern. The pioneering work of Dick and Ewing (1967) and O'Neil (1985) had highlighted that rheological measurements are key criteria to manage sludge treatment. The rheological behavior of sludge is affected, among other parameters (Baudez and Coussot, 2001; Dieudé-Fauvel et al., 2009), by the solid concentration and has been well described in the literature, though different models are used (Seyssiecq et al., 2003; Chaari et al., 2003; Ratkovich et al., 2013; Eshtiaghi et al., 2013). It was found that sludge rheological parameters (infinite viscosity, yield stress, model parameters of the flow curve) increase with the concentration following either an exponential law (Dick and Ewing, 1967; Forster, 2002; Guibaud et al., 2004; Mori et al., 2006; Pevere, 2009) or a power law (Forster, 2002; Baudez, 2008; Markis et al., 2014). Baudez et al. (2011) merged these results by showing that liquid-like characteristics follow an exponential law while solid-like characteristics follow a power-law model which can only be defined above a critical concentration (Lolito et al., 1997; Forster, 2002; Baudez, 2008), when a solid network can be noticed.

However, because sludge remains the residue of wastewater treatment with unpredictable composition and fluctuating concentration, its rheology cannot be summarized as a basic relationship with total solid content (Spinosa and Wichmann, 2004): a single parameter does not capture the

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changes in the overall sludge characteristics and cannot be used to monitor and predict sludge behavior. Therefore, there is a need for descriptors that encompass the physical, chemical and biological parameters, reflect the changes in sludge characteristics, and predict sludge structural parameters.

In that purpose, Dieudé-Fauvel et al. (2009, 2014) explored an innovative approach based on the coupling of rheology and electrical impedance spectroscopy (EIS), which is a powerful tool to characterize structural properties of materials (Bonanos et al., 1987). Focusing on sludge, electrical and rheological properties are driven by common parameters: water, salts, and temperature (Forster, 1982, 2002; Seyssiecq et al., 2003; Dieudé-Fauvel et al., 2009; Baudez et al., 2013). Dieudé-Fauvel et al. (2009) demonstrated that the same molecular movements and interactions are probably involved in both viscous flow and charges mobility. With a simple electrolytic solution, the relationship between resistivity and viscosity is linear and straightforward. Only free ions contribute to the solution conductivity and the only source of energy dissipation is through viscous friction in the solvent. Thus, the resistivity is described by the following equation:

$$\rho \approx 6\pi\eta_0 \left(\frac{1}{Fe}\right)\left(\sum_i \frac{z_i c_i}{r_i}\right)^{-1}$$

Where ρ and η_0 are the solution resistivity and viscosity, respectively. z_i, c_i and r_i are the ionic charge, concentration and radius, respectively, for ionic species i. F and e are the Faraday and unit electronic charge, respectively.

This equation is basically the Stokes–Einstein equation for the viscous friction coefficient of spherical species in a uniform medium. It can easily be modified in order to take into account the presence of an electrically insulating phase of a given volume fraction. For instance, in the high dilution limit, using the Maxwell mixture model for conductivity and the Einstein model for the viscosity of dilute suspensions, resistivity ρ and viscosity η are related to the solid content ϕ by the following simple relationships:

$$\rho = \rho_0/(1-\phi)$$

$$\eta = \eta_0(1+2.5\phi)$$

In that case, resistivity and viscosity are still expected to be approximately linearly related to each other. The relationship between resistivity and viscosity is much less obvious in complex fluids where the interactions between non-solvent species, that are "solid matter" (neutral or charged macromolecules, colloidal particles, micellar assemblies, lipids, etc.), leads to non-Newtonian behavior and strong departure from Einstein's law, even at very low volume fraction of non-solvent species. In spite of this, as will be shown in the following, rather simple and reliable empirical relationships between resistivity and viscosity can be obtained. It must be specified that we do not claim that the use of electrical measurements would allow the determination of quantitative rheological parameters but we assert that the evolution of a rheological parameter can be effectively followed by the evolution of an electric characteristic related to the structure. Indeed, EIS is also commonly used to characterize structure evolution phenomena (Keddam et al., 1997; Song, 2000; Assifaoui, 2002). In this way, Dieudé-Fauvel et al. (2014) showed that apparent viscosity and electrical resistivity of sludge sample during anaerobic digestion can be represented as vectors of the original sludge and the inoculum with exactly the same coordinates:

$$\eta_{digestate} = \alpha.\eta_{sludge} + \beta.\eta_{inoculum}$$

$$\rho_{digestate} = \alpha.\rho_{sludge} + \beta.\rho_{inoculum}$$

Where $\eta_{digestate}$ is the viscosity of the sludge during anaerobic digestion, η_{sludge} the viscosity of raw sludge, $\eta_{inoculum}$ the viscosity of the inoculum, $\rho_{digestate}$ the resistivity of the sludge during anaerobic digestion, ρ_{sludge} the resistivity of raw sludge and $\rho_{inoculum}$ the resistivity of the inoculum.

Thus, used in accurate conditions, this technique appears to provide good indicators of the evolution of sludge rheological properties. More recently, Ségalen et al. (2015) delved this approach by analyzing the impact of temperature on sludge at a single concentration. It was evidenced that pasty sludge can be summarized by an idealized electrical circuit made of insulators and capacitors, each element being closely linked with solid-like and liquid-like rheological characteristics.

However, these results were only defined through the temperature dependence of a single sludge with a given solid concentration: they may not be directly extrapolated to a wide range of concentrations because solid content clearly impacts sludge rheological properties (Baudez, 2008).

The aim of this paper was to go deeper in that coupling by analyzing the electrical signature of sludge at different solid contents regarding the concentration dependence of their rheological characteristics. A new electrical model was built, including both liquid-like and solid-like characteristics. This model was discussed regarding the brand new publications devoted to sludge electrical signature (Ségalen et al., 2015).

2. Materials and methods

2.1. Materials

Sludge was sampled at the outlet of the dewatering stage at Vichy wastewater treatment plant (Allier, Centre of France) which is an activated sludge plant equipped with a draining table and centrifuge. Its initial solid content was 17.6%. First, the initial sludge was deflocculated and homogenized with a mechanical stirrer (VMI Rayneri) at 300 rpm during 2 h. Then samples at different solid contents were prepared by diluting sludge with demineralized water. Specific attention was previously paid to the choice of the diluting substrate. The use of demineralized water or supernatant did affect neither rheology nor electrical measurement (data not shown). Then, demineralized water was chosen in order not to add external charges and only focus on the initial sludge content impact.

Samples were stored at 4 °C for 30 days before experiments, to ensure no temporal variability, allowing us to use the same material over several days. This technique was successfully used by Curvers et al. (2009).

The final exact total solid content (TSC) was determined by drying at 105 °C during 24 h (ASAE standard, 1999). The