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Review of rheological behaviour of sewage sludge and its importance in the management of wastewater treatment plants

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ABSTRACT

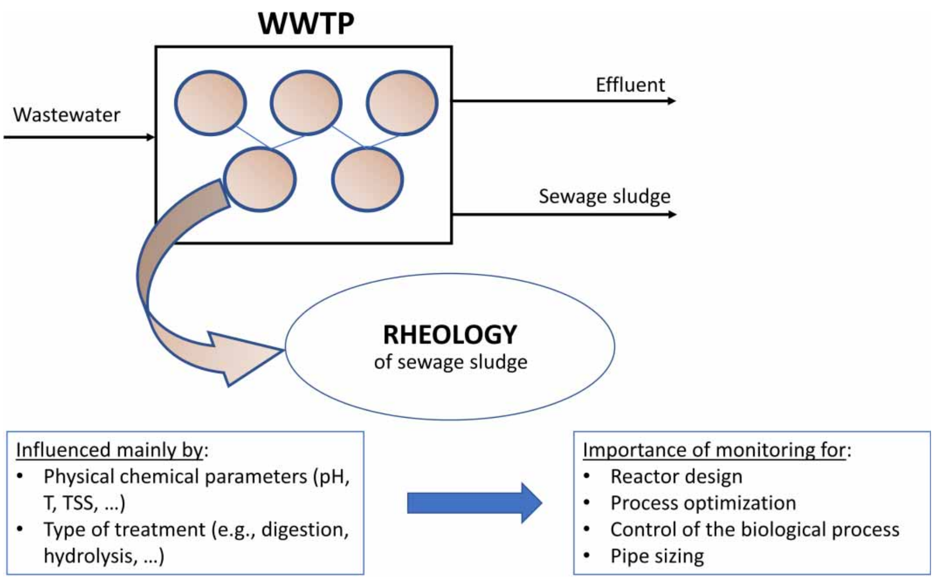
The process operation of wastewater treatment plants (WWTPs) is based on the proper set up of several physical, chemical and biological parameters. Often, issues and problems arising in the process are strictly linked to the rheological behaviour of sewage sludge (SeS). Therefore, rheological measurements, which recently have captured a growing interest, represent an important aspect to consider in the design and operation of WWTPs, especially in the sludge-handling processes. The knowledge of rheological behaviour of SeS represents a crucial step to better understand its flow behaviour and therefore optimize the performance of the processes, minimizing the costs. The SeS are non-Newtonian fluids and, to date, Bingham and Ostwald models are the most applied. This work presents an overview of scientific literature about the rheological properties of SeS and discusses the importance of its knowledge for the management of WWTPs.

Key words: chemical-physical properties, mechanical behaviour, rheology, sewage sludge, viscosity, WWTP management

HIGHLIGHTS

- Sewage sludge behaves like non-Newtonian fluids.
- The rheological properties are strongly influenced by the TSS concentration and type of treatment.
- Knowledge of the rheological properties of sewage sludge is crucial for the management of wastewater treatment plants.
- An incorrect attribution of the rheological behaviour leads to the choice of non-optimal operating conditions.

GRAPHICAL ABSTRACT



INTRODUCTION

Recently the number of urban and industrial wastewater treatment plants (WWTPs) is growing (Spellman 2013) mainly due to (i) the more stringent limits imposed by legislation (EUR-Lex 1998), and (ii) the population growth and consequent urbanization (Kelessidis & Stasinakis 2012; Collivignarelli *et al.* 2019a). Consequently, a significant increase of the amount of sewage sludge (SeS) has occurred. At European level, the SeS production is estimated at over 11 Mt_{DM}/year (Eurostat 2019). It is expected that this value increases over the years due to the introduction of more stringent limits for the effluents of WWTPs. In this case, the implementation of more efficient minimization technologies could represent an opportunity to limit this increase (Bertanza *et al.* 2014; de Oliveira *et al.* 2018; Guneysu & Arayıcı 2019; Corsino *et al.* 2020).

SeS can be produced: (i) in biological reactors, due to the life cycle of bacteria present in the WW as in the conventional activated sludge (CAS) system (Collivignarelli *et al.* 2007; Jafarinejad 2017; Collivignarelli *et al.* 2019b), or (ii) in chemical-physical processes without the use of chemical reagents (e.g., primary sedimentation) or by the addition of chemicals and the subsequent separation of the precipitated phase (e.g., coagulation-flocculation) (Collivignarelli *et al.* 2007, 2019b). The sludge extracted from primary and secondary settlers is characterized by diverse total solids content (2–9%TS and 0.8–3.3%TS), respectively) and by diverse content of putrescible organic material, generally higher in secondary sludge (up to 88%TS with respect to 60–80%TS of primary sludge) (Collivignarelli *et al.* 2019b; Gherghel *et al.* 2019). In fact, it is a complex heterogeneous mixture of microorganisms representing the residue produced during the biological treatment (Collivignarelli *et al.* 2019b).

According to European legislation (EUR-Lex 2018), waste management must follows a precise hierarchy: (i) prevent and minimise the production, (ii) recovery of the matter, (iii) recovery of the energy, and finally (iv) residual disposal. Therefore, the current legislation favours the reuse of matter instead of energy (Kominko *et al.* 2017; Collivignarelli *et al.* 2020a, 2015). To date, SeS must respect stringent limits before possible reuse in agriculture (EUR-Lex 1986) reachable only by treating the SeS. In fact, despite the management of SeS involves high costs (Zhang *et al.* 2017), they represent an interesting resource due to the high energetic value (Oladejo *et al.* 2019; Das *et al.* 2020) and high content of nutrients (Kirchmann *et al.* 2017; Das *et al.* 2020). Before any possible reuse options, thickening and dewatering processes decrease the volume of the SeS, whereas aerobic or anaerobic digestion reduce the microbial contamination, and the residual organic substances stabilizing the SeS (Guo *et al.* 2013; Bertanza *et al.* 2014; Ukwatta *et al.* 2015; Torretta *et al.* 2021).

To optimize the sludge treatment processes, the knowledge of their properties, including rheological ones, is of fundamental importance. However, the rheology of SeS has not been studied intensively in the past years, neglecting a fundamental aspect to be able to fully characterize the SeS and therefore the treatments to which it is subjected, optimize both in terms of performance and in economic terms (Collivignarelli *et al.* 2007).

In this work, firstly the results of scientific literature on the rheological characteristics of diverse type of sludge are presented. Secondly, the effect of the main operating parameters on the rheological behaviour are analysed and the importance of its knowledge in the management of WWTPs is discussed highlighting the main gap of literature data.

Strategy of literature review and structure

The literature was retrieved by querying the Scopus® database and Google Scholar with keywords related with the rheological behavior of SeS (e.g., 'rheology sewage sludge', 'mechanical properties sewage sludge').

Peer-reviewed papers and books published from 2011 to 2021 (last update on 05-29-2021) were included in the present review. Older studies were also included when deemed necessary to complete the technological descriptions. We selected relevant studies by screening titles and abstracts, then analyzing full text.

The present work aims to present an overview of rheological behavior and properties of SeS and importance of knowing these aspects for an effective management of WWTPs. These topics were presented according to this structure:

- Description of the rheological behavior of SeS
- Effect of process parameters on rheological behaviour: (i) influence of chemical-physical properties, and (ii) influence of the type of treatment
- Discussion on the importance of knowing the rheology of sludge

The paper highlights the most important issues for each category and identify future directions of exploitation of rheological analysis in the contest of WWTPs.

Rheological behaviour of sewage sludge

The rheological behaviour of a fluid describes how its deformation rate varies under the action of applied stresses. The relationship between shear stress and shear rate is represented in a rheogram and described by a curve. In case of Newtonian fluids, the curve is a straight line with coefficient μ, and for a fluid with fixed conditions of temperature, pressure, and concentration of suspended solids, the viscosity can be considered constant. Relatively diluted suspensions are treated as Newtonian fluids (Collivignarelli *et al.* 2007).

However, in most cases the relationship between shear stress and shear rate of the SeS is not linear and therefore, this matrix falls into the category of non-Newtonian fluids (Seyssiecq *et al.* 2003). The stress-strain rate relationship can be described with models of increasing complexity of which the most used (Collivignarelli *et al.* 2007) are the following: Ostwald de Vaele, Sisko, Bingham, Herschel-Bulkley, Cross, Casson and Carreau (Seyssiecq *et al.* 2003; Ratkovich *et al.* 2013).

The Ostwald and Sisko equations describe a pseudoplastic behaviour of the SeS, which therefore has a decreasing apparent viscosity as the shear stress increases, but still depends on the shear rate (Collivignarelli *et al.* 2007).

The Bingham, Herschel-Buckley and Casson models consider SeS-like plastic fluids. For the flow to begin, the SeS must be subjected to a stress greater than the yield stress of the solid component. In fact, the solid particles oppose the deformation of the suspension, and the sludge begins to flow only when the yield stress is exceeded; namely, the stress is enough to overcome the Van der Waals cohesion forces (Seyssiecq *et al.* 2003). As reported by Collivignarelli *et al.* (2007), it can be assumed that the value of the yield stress increases, for a given suspension, as the volumetric fraction of solids increases or that, at constant solids concentrations, it decreases when the sludge flocs are destroyed by shearing.

In some cases, SeS can show viscoelastic behaviour (Baudez *et al.* 2013a). By subjecting the SeS to a sudden applied shear stress, the initial value of the shear rate may vary over time. This is partly due to the thixotropic behaviour of SeS and partly to its ability to store a portion of the mechanical energy supplied in the form of elastic energy.

SeS are viscoelastic materials because they can be set in motion (viscous component), but when the stress tends to cancel itself, a partial elastic recovery is observed (elastic component). Thixotropy is defined as a reversible, time-dependent decrease in viscosity of a fluid subjected to constant shear stress or shear rates and it is generally attributed to excess sludge. The thixotropic behaviour of the activated sludge was related to the presence of filamentous bacteria, responsible for the bulking phenomenon (Tixier *et al.* 2003). The analysis of the amplitude of the hysteresis described by the rheogram of the activated sludge can therefore constitute a useful tool for identifying the presence of bulking. The thixotropy of these fluids makes their rheological characterization more difficult. However, it is often cited as the cause of possible errors in rheological measurements, but it remains rarely investigated (Seyssiecq *et al.* 2003).

Effect of process parameters on rheological behaviour

Influence of physical chemical parameters

A link between the rheological and physico-chemical properties of SeS has been studied for several years (Collivignarelli *et al.* 2007). Forster (1981) hypothesized that the non-Newtonian behaviour of these suspensions was related to the surface charges of the flocs. Forster (1983) also subjected diverse types of SeS to various enzymatic treatments demonstrating that the surface radicals that most strongly influence the rheological properties are proteins and polysaccharides for activated sludge but proteins and lipopolysaccharides for digested sludge. Forster (1983) also verified that even the water content of the SS strongly influences its rheological behaviour and that this influence could be modified by the action of metal ions.

Dick & Ewing (1967) focused their studies on the relation between total suspend solids concentration (TSS) and rheological properties, highlighting an exponential growth of the threshold shear stress with the concentration of TSS. Christensen *et al.* (1993) and Dentel (1997) confirmed previous results and identified that the existence of a critical value of TSS above which the SeS exhibit an initial threshold value. Füreder *et al.* (2017) showed that the TSS content is one of the main parameters that influence the rheology of raw mixed (primary and secondary) sludge rheology finding that an increase of TSS from 6% to 8% at least doubles the shear stress according to an exponential behaviour affecting the design of pipes and pumps. Moreover, testing a pilot plant simulating real conditions, they also found that the impact of TSS in raw mixed sludge is combined with the influence of the secondary sludge/primary sludge ratio. In particular, the shear stress increases by increasing this ratio (Füreder *et al.* 2017).

Dollet & Baudu (2000) tested the combined effect of the TSS and pH variation on parameters of Bingham rheological equation. Testing a secondary sludge, they found that both the threshold stress and the plastic viscosity were positive correlated with pH increases up to 7, highlighting that the best cohesion of the flocs and occurred in acidic conditions with pH between 6 and 7 (Dollet & Baudu 2000).

Abbà *et al.* (2017) and Collivignarelli *et al.* (2019c) studied the effect of TSS content on rheological behaviour showing that the sludge derived from a Thermophilic Aerobic Membrane Reactor (TAMR), with 150 g_{TSS}/L exhibited shear-thickening (dilatant) behaviour. When TSS increase up to 190 g/L, the interactions between the sludge particles were expected to be even more intense and therefore a non-zero yield stress was observed.

Hong *et al.* (2018) reported that secondary sludge floc structure and surface properties are highly dependent on pH. The sludge particles formed larger floc sizes at higher alkalinity compared to more acidic sludge environment. So, as pH of SeS increases, yield stress was found to increase in the same manner as the viscosity and shear stress (Hong *et al.* 2018).

Mikkelsen (2001) studied a secondary sludge from a CAS system. They hypothesized the development of a network of intraparticle bonds responsible for a limitation of the flow and therefore an increase in surface erosion of the primary particles to demonstrate a correlation between the concentration of fine particles, the resistance to filtration and the rheological properties of the SeS. These proved that the increase of fine particles within the medium results in a bad tendency of the SeS to dewatering (Mikkelsen 2001; Collivignarelli *et al.* 2007).

Also, the content and the nature of the compounds occurring in the SeS affect the rheological behaviour. Vachoud *et al.* (2019) showed that the addition of a high-molecular weight biopolymer (xanthan) in a secondary sludge from a CAS system affected the liquid compartment (viscosifying effect) as well as the solid compartment (flocculation state, reinforcement of the linkages between and within the flocs). Numkam & Akbari (2019) showed that nonionic surfactants impact on the rheological properties of fluids. This confirms that the study of rheological behaviour is key to prevent foaming events in biological reactors, as suggested by Nishiguchi & Winkler (2020).

Many researchers have also investigated the effectiveness of various conditioners on SeS dewaterability and on rheological behaviour. A relationship between rheological properties and polymer dosage has been reported by Zhang *et al.* (2014). They highlighted that the flocs size and compactness increase with increasing polyaluminium chloride and high performance polyaluminium chloride dose testing a concentration up to 25% g/g dry substance (Zhang *et al.* 2014; Hong *et al.* 2018).

The temperature also plays a key role in rheological behaviour. Baroutian *et al.* (2013) carried out several experimental tests and showed that the yield stress is in linear relationship with solid concentration and exponential with the inverse of temperature. Also, Baudez *et al.* (2013b) showed that the anaerobic digested sludge, when the temperature increased, became progressively more fluid and both Bingham viscosity and yield stress decreased with increasing temperature. However, the fluidisation of sludge is affected by other parameters such as the the previous changes in temperature to which it was subject. In fact, if the sludge was preheated and cooled before test, dissolution of some of the solids may cause a decrease of the yield stress and an increase of the Bingham viscosity (Baudez *et al.* 2013b).

The main results of the influence of physical-chemical parameters on rheological properties are summarized in Table 1.

Influence of the type of treatment

The rheological parameters of the SeS can significantly affect, as reported before, the treatment processes, as well as the transport and storage operations and the final use of the material (Collivignarelli *et al.* 2007).

Activated sludge is extracted from a CAS system and can be described as a complex non-Newtonian, viscoelastic and shear thinning fluid (Hong *et al.* 2018). In the hypothesis of Bingham model, the apparent viscosity is better correlated to the concentration of TSS than the threshold stress while for the Ostwald model the coefficient K is better correlated to the TSS concentration with respect to exponent n (Collivignarelli *et al.* 2007).

Several studies have tried to highlight a correlation also between the type of treatment to which SeS is subjected and the change in rheological properties. For instance, Wichmann & Riehl (1997) studied the influence of the water content on the SeS dewatering and on the value of their threshold stress. In fact, as demonstrated

Table 1 | Main results about the relationships between rheological properties and the physical-chemical parameters

Parameters	Main results	References
pH	Threshold stress and plastic viscosity increase with pH	Hong *et al.* (2018); Dollet & Baudu (2000)
T	Digested sludge became progressively more fluid with increasing temperature	Baroutian *et al.* (2013); Baudez *et al.* (2013b)
TSS	Only above a critical TSS concentration, the SeS exhibits an initial threshold value	Christensen *et al.* (1993); Dentel (1997)
	TSS and shear stress are positive correlated. Increasing TSS from 6% to 8% at least doubles the shear stress	Füreder *et al.* (2017)
	An exponential growth of the threshold shear stress with the increasing of the TSS concentration was observed	Dick & Ewing (1967)
	The presence of metal ions can alter the effect of TSS concentration on rheological properties	Forster (1983)
	TSS higher than 190 g/L is related to a non-zero yield stress	Abbà *et al.* (2017); Collivignarelli *et al.* (2019c)
	High-molecular weight biopolymers affect liquid and solid compartment (high viscosity)	Vachoud *et al.* (2019)
	A network of intraparticle bonds can limit the flow and therefore increase the surface erosion of the primary particles, determining a bad tendency of the SeS to dewatering	Mikkelsen (2001)

by Lotito *et al.* (1997) and Abu-Orf & Dentel (1997), the rheological characteristics of the SeS in diverse treatment stages are mainly influenced not only by the concentration of TSS, but also by the addition of chemicals (e.g., polymers), the type of treatment whom SeS is subjected.

According to Collivignarelli *et al.* (2007), the mixed untreated SeS generally shows a lower viscosity than the digested sludge while activated sludge presents the higher viscosity for both rheological models. They also indicated that above a certain TSS concentration (80–100 kg/m^3), the rheological behaviour tends to change rapidly probably due to the achievement of the limit zone between liquid and plastic state (Collivignarelli *et al.* 2007).

The digested sludge shows a different rheological behaviour according to the digestion time. Monteiro (1997) demonstrated that significant changes on the SeS rheological properties occurred during anaerobic digestion and that the viscosity was inversely proportional to the sludge residence time. Baudez *et al.* (2011) focused on the influence of TSS in the digester and highlighted that the rheological properties of digested sludge are qualitatively the same at different TSS concentrations depending only on the yield stress and Bingham viscosity. Di Capua *et al.* (2020) observed that digested sludge (with a 6–8% TSS content) with a sludge retention time (SRT) of 20 days had a higher shear stress and friction loss compared to sludge with a 25-day SRT.

Moreover, the thermally treated sludge exhibited gel-like, viscoelastic characteristics similar to untreated sludge (Hii *et al.* 2017). Abbà *et al.* (2017) studied the rheological properties of the sludge derived from a Thermophilic Aerobic Treatment Reactor (TAMR), that is an innovative membrane bioreactor (MBR) treatment that works around 50 °C. Also in this case, the most important parameter that affect the rheological behaviour is the TSS concentrations (in this case up to 200 g/L). In this case, the sludge exhibited shear-thickening (dilatant) behaviour. Moreover, the effects of aeration were sometimes not univocal and reveal an opposing behaviour depending on the values of the other parameters.

The main results of the influence of type of treatments on rheological properties are summarized in Table 2.

Discussion about the importance of knowledge of SeS rheological behaviour

Rheological parameters have a fundamental importance in SeS characterization, as they strongly affect almost all treatment, utilization, and disposal operations, such as storage, pumping, transport and drying. As reported in the present work, the rheological behavior of the SeS represents an aspect that is still little considered in the management of the WWTPs, but it is essential for adopting an adequate sludge treatment strategy. In the opinion of the authors, many aspects still remain unclear regarding the rheological behavior of SeS. First of all, although the influence of some parameters such as TSS, pH and temperature is clear, the effect on the rheology of the

Table 2 | Main results about the relationships between rheological properties and the type of treatment

Type of SeS	Main results	References
Non-digested mesophilic sludge	Non-Newtonian behaviour	Hong *et al.* (2018); Wichmann & Riehl (1997)
	Strong influence of TSS	Lotito *et al.* (1997)
	Strong effect of polymers dosage	Abu-Orf & Dentel (1997)
Digested mesophilic sludge	Increase in viscosity as sludge retention time increase	Monteiro (1997)
	Digested sludge (with a 6–8% TSS content) with an SRT of 20 days had a higher shear stress and friction loss compared to sludge with a 25-day SRT	Di Capua *et al.* (2020)
	Dewatered SeS after anaerobic digestion showed less viscosity and less influence by solids concentration[a] and temperature, when comparing to dewatered but not digested SeS	Cao *et al.* (2016)
Thermal hydrolysed sludge	Thermophilic sludge shows a gel-like characteristic	Hii *et al.* (2017)
Thermophilic sludge	Sludge with shear-thickening behaviour	Abbà *et al.* (2017)

[a]Results are referred to total solids (TS) concentration.

sludge of substances naturally present in the sludge (e.g., heavy metals, extracellular polymeric substances (EPS), etc.) remains poorly defined. To date, the data on these aspects are very few (in some cases completely absent) but if available they would be very useful for delineating the rheological behaviour in a complex system such as the SeS. Therefore, future research on this topic is suggested.

The knowledge of the rheological properties of the sludge allows optimization of the WWTPs in relation to the aeration conditions in the oxidation tank and in the sludge settleability. As reported by Collivignarelli *et al.* (2007), the apparent viscosity of SeS represents an important parameter to evaluate the oxygen transfer in the sludge and therefore the performance of the process. In fact, Durán *et al.* (2016) proved that rheological properties highly influence the oxygen solubility, in particular its propagation inside the reactors and the reactions between oxygen and substrate. In their experimental set-up, they exploited a bubble column with a capillary rheometer continuously fed with activated sludge. With this setting they analysed data coming from two different WWTPs (with a CAS system and a membrane bioreactor, respectively) obtaining an empirical correlation between the superficial gas velocity and the sludge apparent viscosity (Durán *et al.* 2016).

The knowledge of the rheological behaviour of sludge is particularly important also in MBRs, where the high energy demand of the membrane systems is closely related to the viscosity of the sludge. For instance, Pollice *et al.* (2006) evaluated the rheology of sludge in a complete retention MBR pointing out that an increase of TSS from 3 to 30 g/L determined an increase in energy requirement of 25–30%, although in real systems the increase of energy requirements could be less visible.

Also in the sludge treatment line, the study of the rheological properties can improve the operating conditions of the digesters, pumping stations, as well as installations for the transport and storage of SeS (Slatter 1997; Collivignarelli *et al.* 2007). For instance, Lotito & Lotito (2014) tried to optimize the pumping system of diverse types of SeS finding that the mixed sludge was the easiest to be pumped while the activated sludge was the worst one. In their opinion, considering the correct apparent viscosity can help to design the piping system and accurately predict the pressure drop in pipes to optimize the system (Lotito & Lotito 2014).

Several authors pointed out the influence of rheological properties of SeS on possible forms of reuse/disposal (Dentel 1997; Lotito *et al.* 1997; Collivignarelli *et al.* 2007). Lotito *et al.* (1997) highlighted that recovery in agriculture is strictly influenced by the rheology, as the preparatory conditioning process is influenced by these aspects and influences at the same time the rheology of the SeS due to the addiction of high molecular weight polymers that increase the volume and size of the flocs (Dentel 1997).

Finally, deepening our understanding of the rheological behaviour of SeS is a crucial aspect also in the design of new WWTPs and when searching potential hydrodynamic anomalies in the existing ones. In fact, recently, the optimization of the WWTPs is gaining interest to enhance the performance of pollutant removal and reduce the chemical and energy consumption (El-Sheikh 2011; Drewnowski 2019; Borzooei *et al.* 2020; Collivignarelli *et al.* 2020b). However, as suggested by Ratkovich *et al.* (2013), the hydraulic mathematical modelling of the dynamic flow of SeS inside the reactors is highly improved by a proper evaluation of the shear stress that can be assessed studying the apparent viscosity.

CONCLUSIONS

From a rheological point of view, the SeS behaves like non-Newtonian fluids. The rheological properties of the SeS are strongly influenced by physical-chemical parameters (e.g., TSS concentration), but also by the type of treatment. In particular, the paper explored the relationships between rheological behaviour, physical-chemical parameters, and the type of treatment. In particular, the rheology of the sludge can be strongly influenced by temperature, pH and the concentration of total solids, and by eventual digestion or hydrolysis of the sludge. As results of the analysis, the authors stress the importance of the knowledge of rheological behavior of SeS in WWTPs since an incorrect attribution of this parameter can lead to the choice of non-optimal operating conditions, low efficiencies, and consequent cost increase. Only by knowing in depth the rheological behavior of SeS is it possible to best size the reactors, pipes and pumps that make up the treatment line, the oxygen supply, and also consider any hydrodynamic anomalies due to the hydraulic behavior of the matrix.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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