A comprehensive review on rheological studies of sludge from various sections of municipal wastewater treatment plants for enhancement of process performance

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A comprehensive review on rheological studies of sludge from various sections of municipal wastewater treatment plants for enhancement of process performance

Eugene Hong[1], Anteneh Mesfin Yeneneh[1], *Tushar Kanti Sen[1], Ha Ming Ang[1], and Ahmet Kayaalp[2]
[1]Chemical Engineering, WASM: Minerals, Energy & Chemical Engineering, Curtin University
GPO Box U1987, Perth, 6845 Western Australia, Australia
[2]Water Corporation of Western Australia, West Leederville, 6007, Australia
*Corresponding author's email: T.Sen@curtin.edu.au

Abstract

Large quantities of sludge is generated from different sections of a wastewater treatment plant operation. Sludge can be a solid, semisolid or liquid muddy residual material. Understanding the flow behaviour and rheological properties of sewage sludge at different sections of a wastewater treatment plant (WWTP) is important for the design of pumping system, mixing, hydrodynamics and mass transfer rates of various sludge treatment units, optimization of conditioning dose and for sustainable sludge management. The current article provides a comprehensive review on up to date literature information on rheological behaviour of raw primary sludge, excess activated sludge, thickened excess activated sludge, mixture of raw primary and thickened excess activated sludge (mixed sludge), digested sludge, and biosolid under the influence of different operating parameters and their impacts on process performance. The influences of various process parameters such as solid concentration, temperature, pH, floc particle size, primary to secondary sludge mixing ratio, ageing and conditioning agent doses on the rheological behaviour of sludge from different treatment units of WWTPs are critically analysed here. Yield stress was reported to increase with increasing solid concentration for all types of sludge whereas viscosity showed a decreasing trend with decreasing total solid concentration and percentage of thickened excess activated sludge in the mixture. Temperature showed an inverse relationship with yield stress and viscosity. Viscosity was reported to be decreased with decrease in pH. The effect of various conditioning agents on the rheological behaviour of sludge are also discussed here. The applicability and practical significance of various rheological models such as Bingham, Power Law (Ostwald), Herschel-Bulkley, Casson, Sisko, Careau, and Cross models to experimental rheological characteristics of various sludges were presented here. The reported results on various rheological parameters such as shear stress, yield stress, flow index, infinite, zero-rate viscosity, and flow consistency index of different sludge types obtained from the best fitted model were also compiled here. Conclusions have been drawn from the literature reviewed and few suggestions for future research direction are proposed.

Key words: Rheology, sludge, biosolid, modelling, conditioning agents

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1. Introduction

Rheology is the study of flow and deformation of materials under applied forces. The rheology of Non-newtonian fluids like, polymers, detergents, pastes and wax, oil and biological materials like sludge is very complex and requires thorough investigation [1-7]. This particular research reviews the rheological flow behaviour of municipal sewage sludge. Published articles in recent years have reported different aspects of the rheological flow behaviour of sludge from different parts of municipal wastewater treatment process. Sustainable sludge and wastewater management is getting increasingly more difficult with the rapid growth of urban population and the demand for environmentally friendly methods for disposal. This in turn demands the development of present technologies and operation for wastewater treatment plants such as improving pumping, hydrodynamics, mass transfer rates, sludge settling, filtration and other related processes. Significant improvement in monitoring, control and performance of wastewater treatment processes can be achieved by investigating flow and rheological behaviour of sludge. A larger number of research work has been conducted in the area of sludge rheology [5-14]. The rheological flow behaviour is highly influenced by wastewater treatment operating parameters such as source of sewage, total solid concentration of sludge, temperature, and sludge treatment methods [5-7, 9, 13, 15]. Studies show that sludge is highly complex in nature and needs detailed investigation to improve the understanding on the impacts of different operating parameters on the rheological and flow properties of different sludge type [5-7, 13]. A typical wastewater treatment plant generally consists of four stages, which are preliminary, primary, secondary, and advanced treatment stages. Different types of sludge are generated from these various treatment sections, such as raw primary sludge, excess activated sludge, and thickened excess activated sludge, mixed sludge, digested sludge and biosolid. Raw primary sludge that comes from the underflow stream of primary sedimentation tanks is transferred to secondary treatment units of aeration and sedimentation where nutrient removal and biomass accumulations takes place [16]. The product of the secondary treatment process, activated sludge, is thickened in the dissolved air flotation thickener (DAFT) to form thickened excess activated sludge. Thickened excess activated sludge is a complicated colloidal material which is composed of organic and inorganic particles. Raw primary sludge and thickened excess activated sludge is then mixed to form mixed sludge which is fed to the anaerobic digesters for further degradation [17].

The product of the anaerobic digestion process, digested sludge, would be fed to the dewatering plant for further solid-liquid separation. Both the anaerobic digestion and sludge dewatering operations account for approximately 70% of the overall wastewater treatment plant operation cost, making it a vital process for rheological investigation [9, 13, 15, 16, 18].

Sludge rheology (viscosity, yield stress and shearing behaviour) is affected by many factors including total solid concentration, temperature, pH, dose of polymer or other agents, chemical composition especially concentration of biopolymers and organics [5-7, 11-14]. According to Einstein law of viscosity, solids existing within a fluid is considered as a key factor that contributes to non-Newtonian flow behaviour [19]. Different sludge types generally behave like a non-Newtonian and shear thinning material, which has been reported in many literature [11, 19-24]. Total solid content is a parameter that influences the rheological and flow behaviour of sludge types. It was found that increasing viscosity of sludge due to the increase of solid content will lead to stronger inter-particle interactions which are caused by the size increase of particles in suspension, resulting in higher apparent viscosity for different sludge types [5-7]. Experimental studies have confirmed that solid content is a key parameter that highly influences the rheological behaviour. It helps to validate the dynamic and complex nature of different sludge types. Baudez [25] also found that shear stress and shear rate increase with the increase of total solid content and are highly dependent on the fractal dimensions of the floc. Utilizing one parameter alone such as total solid content to describe the rheological behaviour is not adequate hence the use of multiple parameters is recommended to improve the understanding [5-8, 26-28]. Temperature is one of those key parameter that has strong effect on the rheological properties by affecting flocculated particle size, shape, and degree of dispersion within the different sludge types [19]. Studies have shown that yield stress increases with increasing total solid content but decreases with increasing temperature, while viscosity shows lower values at higher temperature [5-7, 11, 29-31]. pH is another parameter which highly influences the rheological behaviour of different sludge types. The network strength and surface charge of particles change as the pH is increased or decreased [32, 33]. Studies on the relationship between rheological characteristics of digested sludge and dewatering performance particularly on rheology as an indicator or monitoring tool of dewatering performance are only emerging very recently.

According to Hong, Yeneneh [5], Yeneneh, Hong [6], Hong, Yeneneh [7], Markis, Hii [18], Hong, Yeneneh [27], studies on different sludge types are few, limited, and inconsistent. Furthermore, literature agrees that each type of sludge is unique to the source, hence different sludge types have different rheological properties; therefore, future research should continue to improve overall understanding on the various aspects of sludge rheology [10, 18, 34, 35]. Furthermore, the effect of rheological behaviour of sludge from different parts of wastewater treatment plant on pumping cost, mixing and mass transfer are very scattered and limited. Therefore, this review article first time presented the up to date literature information on rheological behaviour of raw primary sludge, excess activated sludge, thickened excess activated sludge, mixture of raw primary and thickened excess activated sludge (mixed sludge), digested sludge, and biosolid under the influence of different operating parameters and their impacts on process performance of a wastewater treatment plant (WWTP). This review paper intends to show the findings of published literature on the rheological characteristics of sludge coming from different parts of wastewater treatment plant under the influence of key operating parameters. Rheological measurement techniques and standards for sludge systems have also been included in this review. The challenges and the research gaps were addressed accordingly.

2. Rheological modelling of Sludge

According to Björn, Karlsson [36], ideal fluids exhibits rheological behaviour, which is linear and are classified as Newtonian fluids, while non-Newtonian fluids exhibit a non-linear rheological behaviour as the fluid properties are usually complex in structure. Non-Newtonian fluids are characterised as pseudo-plastic, viscoplastic, dilatant and thixotropic fluids. Rheological models are used to determine rheological parameters such as shear stress, yield stress, flow index, infinite, zero-rate viscosities, and flow consistency index, which depict the general flow behaviour of the fluid. Typical plots of rheological models (shear stress versus shear rate) is shown in Figure 1.

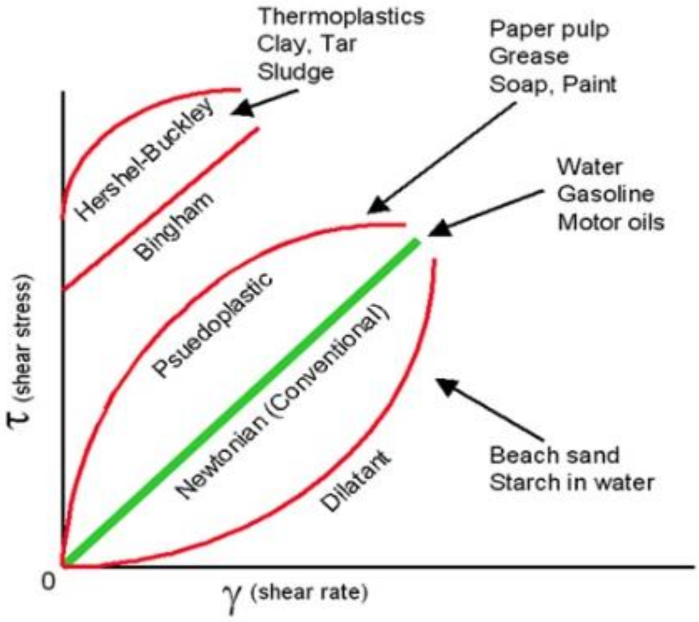

Figure 1 Shape of common rheological models [36].

In the case of sludge, several rheological models are used to determine its relevant rheological parameters [3, 37]. Bingham, Ostwald, Herschel-Bulkley, Sisko, Careau, and Cross models, as shown in Equations (1), (2), (3), (4), (5), and (6) respectively, are different shear stress and viscosity models used for all sludge types to determine and characterize their flow behaviour properties [3, 12, 22]. Studies have shown that applying the six different rheological models to investigate the rheological behaviour of different sludge types are very limited and the applicability of each of the models is subjective and strongly depends on the condition of the sludge [3, 11].

$$\tau = \tau_y + \eta_B \dot{\gamma}^n \tag{1}$$

$$\tau = K\dot{\gamma}^n \tag{2}$$

$$\tau = \tau_y + K\dot{\gamma}^n \tag{3}$$

$$\mu = \mu_\infty + K\dot{\gamma}^{n-1} \tag{4}$$

$$\frac{\mu-\mu_\infty}{\mu_0-\mu_\infty} = (1+(\lambda\dot{\gamma})^2)^{\frac{n-1}{2}} \tag{5}$$

$$\frac{\mu-\mu_\infty}{\mu_0-\mu_\infty} = \frac{1}{1+(\lambda\dot{\gamma})^m} \tag{6}$$

where τ_y is yield stress (Pa), η_B is the high shear-limiting viscosity (Pa.s), $\dot{\Upsilon}$ is the shear rate (s^{-1}), *n* is the flow index, K is the consistency index (Pa.s^n), μ_∞ is the infinite-rate apparent viscosity (Pa.s), μ_0 is the zero-shear apparent viscosity (Pa.s), λ is the time constant (s), and *m* is the Cross rate constant. Equations (2-1) to (2-6) are commonly used to model the shear stress (τ is the shear stress in Pa) profile and viscosity (μ is the viscosity in Pa.s) profile.

The apparent viscosity of Newtonian fluids exhibits a linear and constant relationship between shear stress and shear rate. Yield stress, the force required to be applied to fluid system before it will flow, is not considered in the Newtonian equation. Hence, there is no yield stress to overcome with the increase of shear stress. This is not applicable for sludge system. This is because, yield stress and varying viscosity occurs in sludge systems. For sludge system, the models that are of greatest interest are the non-Newtonian model such as Bingham, Casson, and Herschel-Bulkley models [30]. In all three of these models the system behaves as a solid when the shear stress is less than the yield stress, however when the yield stress is exceeded the system acts as a fluid. The ratio between shear stress and shear rate in each of those models represents the apparent viscosity of the material can be seen as the gradient of the line. The Bingham and Casson models are robust, two parameter models. They are able to characterise non-settling fine particle slurries [38]. The Bingham model represents a linear relationship between shear stress and shear rate once the yield stress of the material has been exceeded. This model is time independent, which is acceptable when using diluted sludge as there are reversible thixotropic events that with stirring and measurement are negligible [3, 11, 39]. In the development of Casson model, Casson theoretically considered the magnitude of inter-particle forces, the model was originally used for the characterisation of printing inks [38]. The Casson model like the Bingham model is also time independent. The total resistance to shear for both the Bingham and Casson models can be shown using the apparent viscosity. The apparent viscosities (μ_{app}) for Bingham and Casson models are shown in Equations (7) and (8) respectively.

$$\mu_{app} = \frac{\mu_p}{1-\frac{\tau_y}{\tau}} \quad (7)$$

$$\mu_{app} = \frac{\mu_\infty}{\left(1-\sqrt{\frac{\tau_C}{\tau}}\right)^2} \quad (8)$$

The Herschel-Bulkley model is a three parameter model which takes into account yield stress and the non-linear relationship between shear stress and shear rate [40]. The K and N values are found experimentally once the collected data is plotted on a curve. From rheological measurement, it is reliably possible to find the yield stress which enables a suitable model to be fitted. The Herschel-Bulkley model can take into account the effects of shear thinning and shear thickening, which makes it a very universally applicable model for the analysis of sludge rheology.

3. Sludge rheometry

There are many different methods of measuring the rheological properties of sludge with the different properties being measured using varying equipment and control techniques. Dapčević, Dokić [41] looked into the methods of testing yield stress for various pseudo-plastic materials, the use of controlled shear rate, controlled shear stress and controlled deformation were discussed. It was found that the method of controlled shear stress was the preferred method due to its simplicity and reproducibility. The vane geometry discussed by Dapčević, Dokić [41], suggested that when the sample size is sufficient it is advantageous to use this method. This is due to the elimination of wall slip and the simple operation of the equipment with minimal sample destruction.

A rheometer is capable of operating at either constant shear stress or constant shear rate, which enables many different measurements to be performed [9, 42-44]. A viscometer can only measure using controlled shear rate which can give flow and viscosity curves, however a rheometer can control the shear stress to be able to measure viscoelastic properties, creep and recovery measurements [9, 42-44]. From measurement of flow properties, the yield stress is able to be found as the point where the shear rate is equal to zero. This yield stress value can then be used in the application of a suitable model.

The geometry of the rheometer can be either parallel plate, cone and plate, concentric cylinder or vane. The nature of the slurry being researched rules out the possibility of using either parallel plate or cone and plate geometries. The remaining two systems of the concentric cylinder and vane could be possibly used as they are both immersed in a vessel while rotating and measuring the rheological properties. The concentric cylinder comes in many design. The double gap design is used to increase surface area for testing with very low viscosity materials, while the other two take into account end effects. Due to the smooth nature of the concentric cylinders slip effects may be present, as well as settling due to the heavy nature of the particles. Furthermore, the double gap geometry can limit settling during rheological measurements while enhancing the sensibility of the shear stress measurement for concentrated sludge system [9, 45-47]. Vane geometry is ideal for sludge system, as it is simple, and eliminates slip effects. This geometry is frequently used to measure rheological properties due to being the simplest technique and the most consistent [4, 13, 25, 47-49].

The complexity of sludge as well as a lack of uniformity associated with sludge rheometric techniques have resulted in the difficulty to optimize processes within wastewater treatment plants [1]. Hence, a viable sludge rheological measurement technique that can ensure reproducibility of results and improve accuracy of measurement should be developed accounting for the challenges cited above.

4. Rheological characteristics of different sludge types from WWTPs

The conventional wastewater treatment process involves four major treatment steps. Preliminary, primary, secondary (biological) and tertiary (advanced) treatment steps. Municipal sewage sludge undergoes significant change in physio-chemical and rheological behaviour from the preliminary to the advanced treatment steps. Different types of sludge are generated from these treatment stages, raw primary sludge, excess activated sludge, and thickened excess activated sludge, mixed sludge, digested sludge and biosolid. Raw primary sludge that comes from the underflow stream of primary sedimentation tanks is transferred to secondary treatment units of aeration and sedimentation where nutrient removal and biomass accumulations takes place [16]. Raw primary sludge shows complex, shear thinning, non-Newtonian rheological flow behaviour with higher yield stress and viscosity compared to the excess activated sludge from secondary sedimentation tanks. The thickening that occurs in the dissolved air floatation thickener increases the total solid concentration of the excess activated sludge and the rheological flow behaviour and the non-Newtonian character significantly increases. Activated sludge, a product of the secondary treatment, is thickened in the dissolved air flotation thickener (DAFT) to form thickened excess activated sludge. Thickened excess activated sludge is a complicated colloidal material which is composed of organic and inorganic particles. Raw primary sludge and thickened excess activated sludge is then mixed to form mixed sludge which is fed to the anaerobic digesters for further degradation [17]. The product of the anaerobic digestion process, digested sludge, would be fed to the dewatering plant for further solid-liquid separation. Both the anaerobic digestion and sludge dewatering operations account for approximately 70% of the overall wastewater treatment plant operation cost, making it a vital process for rheological investigation [1, 9, 13, 15, 16, 18, 50]. The various literature information of different sludge types are presented below.

4.1 Rheological characteristics of raw primary sludge

According to Bhattacharya [34], raw primary sludge, product of the primary treatment, contains both organic and inorganic materials with trapped bubbles within the suspension. The flow behaviour and rheological properties of raw primary sludge is highly influenced by physico-chemical properties such as concentration, composition, temperature, pH and etc.

Few studies have focused on the rheological behaviour of primary sludge. The pioneering work of Bhattacharya [34] and Moeller and Torres [35] are the only two studies to date that address the rheology of primary sludge. Bhattacharya [34], reported that the rheological properties of raw primary sludge behaves like a shear thinning fluid for a total solid concentration range of 3.0% to 8.0%. In contrast, Moeller and Torres [35], reported that no yield stress could be detected for a total solid concentration range of 1% to 3%. It is reported that any inconsistency arising from experimental work could be due to the lack of uniform rheometric methods and techniques which were highlighted by Seyssiecq, Ferrasse [9], Eshtiaghi, Markis [11], Ratkovich, Horn [12]. Thus far, Markis, Baudez [1], Hong, Yeneneh [7], Markis, Baudez [13] are the only few recent rheological research studies that have some focus on raw primary sludge which also included work from our own research group.

4.2 Rheological characteristics of excess activated and thickened excess activated sludge

Current literature mainly focuses on the rheological characteristic of both excess activated and thickened excess activated sludge which is commonly known as activated sludge. Activated sludge is the product of the secondary treatment and contain mainly polysaccharide and protein rich bacteria and micro-organisms that form extracellular polymeric substances. Activated sludge is described as a complex non-Newtonian, viscoelastic and shear thinning fluid [13]. According to Eshtiaghi, Markis [11], Keiding, Wybrandt [51], Sutherland [52], the gel like structure of activated sludge are held by both electrostatic and hydrogen bonds. Markis, Baudez [13], Tixier, Guibaud [20], Tixier, Guibaud [21], Unno and Akehata [53] illustrated that activated sludge is thixotropic and undergoes aging as the solid structure can rebuild under shear. Our research group; Hong, Yeneneh [5], investigated the effect of change in total solid concentration on thickened excess activated sludge rheological flow behaviour for total solid concentrations of 0.9% to 3.7%. It was reported that, viscosity was observed to increase with the increase of total solid concentration due to the increase in solid content within the sludge sample. Furthermore, they used different rheological behaviour models to fit the shear stress-rate curve to determine important rheological model parameters. According to the Bingham pseudo-plastic model, the increase in total solid concentration resulted in the increase of yield stress, Baroutian, Eshtiaghi [30], Farno, Parthasarathy [31] also reported similar trend. This is also due to the change of flow consistency and the flocculated particle size of the thickened excess activated sludge where the energy of cohesion and inter-particle interaction increase with increasing solid concentration [22]. Furthermore, this is due to stronger network of sludge floc structure with the increase of solid concentration where colloidal and hydrodynamic forces between sludge particles change [13, 30].

4.3 Rheological characteristics of raw primary sludge and thickened excess activated sludge mixture

The mixture of both raw primary sludge and secondary sludge forms what is known as mixed sludge. The overall rheological behaviour of mixed sludge is partially similar to those of raw primary and thickened excess activated sludge [7], where the yield stress, viscosity and, shear stress-shear rate profiles falls in between those of raw primary sludge and secondary sludge. It was reported that, the rheological properties of mixed sludge have significant implications on the performance of anaerobic digester. According to research, the yield stress and viscosity of mixed sludge have significant impact on the overall mixing hydrodynamics, mass transfer and the power requirement for anaerobic digester [12, 54-56]. Raw primary sludge exhibits lower yield stress and excess activated sludge directly coming from the activated sludge treatment process has extremely low yield and behaves like a Newtonian fluid as the total solid content is very low. The mixing ratio between raw primary sludge and thickened excess activated sludge is an essential process parameter that affects flow hydrodynamics and the biochemical methane production capacity, digestion kinetics, volatile solid removal, and overall performance of anaerobic digestion process and dewaterability of the digested sludge that comes out of this process which is also studied by our previous work [16, 50]. Hong, Yeneneh [7] investigated the effect of varying mixing ratio for raw primary sludge to thickened excess activated sludge. The test range conducted were 80:20, 70:30, 60:40, 50:50, 40:60, and 20:80 of raw primary to thickened excess activated sludge respectively. Generally, typical mixing ratio ranges between 70:30 to 50:50 of raw primary to thickened excess activated sludge are used within industrial operations [16, 50]. Based on the results of literature, it can be seen that with increasing percentage of secondary sludge, yield stress and viscosity significantly increased and the greater percentage of raw primary sludge in the mixed sludge enhances anaerobic digester performance by reducing the total and volatile solid concentration of sludge. Furthermore, both raw primary and activated sludge behaved as shear thinning, yield stress fluids with primary sludge exhibiting highly thixotropic behaviour. The apparent viscosity, yield stress and fluid consistency of both raw primary and activated sludge increase with increasing total solids concentration and followed the Herschel–Bulkley model [7, 13, 16, 50].

4.4 Rheological characteristics of digested sludge, biosolid and centrate

Studies on the rheological properties of digested sludge have been conducted by many researchers, including our own research work, such as Markis, Baudez [1], Dieudé-Fauvel, Héritier [2], Yeneneh, Hong [6], Baudez, Markis [10], Markis, Baudez [13], Farno, Parthasarathy [31], Moeller and Torres [35], Wang and Dentel [48], Yeneneh, Kayaalp [50], Farno, Baudez [57], Tian, Zhang [58], Noutsopoulos, Mamais [59], Eshtiaghi, Yap [60], Forster [61], Houghton and Stephenson [62], Paul, Camacho [63], Baudez, Slatter [64], Lay, Lee [65], Lau, Ang [66]. On the other hand, limited research work has been undertaken on rheological properties of biosolid and centrate. Hence we conducted detailed research work on the rheological behaviour of biosolid and centrate, Hong, Yeneneh [27], which adds to the limited works of Neyens, Baeyens [33], Carrère, Dumas [67], Hamel, Higgins [68], Higgins, Hamel [69], Ayol, Filibeli [70], Dursun and Dentel [71]. According to these researchers the rheological behaviour of digested sludge, centrate and biosolid were found to fit best to Herschel-Bulkley rheological model, which is mostly used to represent non-Newtonian viscoelastic shear thinning fluid flow behaviour which was supported by our previous study [27]. The zero-rate and infinite rate viscosities determined using this model showed that biosolid was observed to have the highest initial rate viscosity, followed by digested sludge and centrate. The significant deviation in the yield stress, zero-rate and infinite-rate viscosities of biosolid compared to that of digested sludge and centrate is mainly due the increase in total solid concentration and flocculation colloidal effect of the polymer due to bridging effect and increase of the network strength between sludge flocs particles [6, 72]. Baudez, Markis [10] and Farno, Baudez [57] reported similar rheological behaviour of digested sludge but not on biosolid. The shear force requirement and torque of biosolid is also more than 100 times higher than that of digested sludge and centrate and the shear modulus showed a similar trend. The significant deviation in torque requirement and shear modulus of biosolid shows the network strength and strong non-Newtonian viscoelastic behaviour of the biosolid floc particles, which is responsible for higher pumping cost and centrifuge power requirement [9].

According to Baudez, Markis [10] and Monteiro [73], at low temperature digested sludge exhibits a linear viscoelastic behaviour while at high temperature it behaves similar to Bingham fluid. In contrast to temperature, at varying total solid concentration the property of digested sludge tend to maintain its form and quality. Baudez, Markis [10] also mentioned that there are many factors which affects the quality and rheological properties of digested sludge, resulting in difficulties in maintaining consistent results implying that the particle interactions within the digested sludge are dominated by steric effect more than an electrostatic effect. Furthermore, Dentel [4], Dursun and Dentel [71] work on digested sludge concluded that rheological method are for more applicable for characterizing digested sludge dewatering properties when compared to traditional methods such as CST. They also concluded that the rheological method can improved by utilizing an immobilized cell, during the process of sludge concentration by dewatering.

5. Effect of various physico-chemical and other process parameters on rheological characteristics of sludge

5.1 Effect of pH

It is generally known that rheological properties of sludge are affected pH. Rheological parameters such as shear stress and viscosity follow a decreasing trend with increasing pH. This trend has been frequently reported in many research papers including articles previously published by us Hong, Yeneneh [5] and others like Pevere, Guibaud [74] Pevere, Guibaud [23] Tixier, Guibaud [21] Sanin [19] Ruiz-Hernando, Martín-Díaz [75] Sanin [19]. Sanin [19] investigated the effect of change in pH on the rheological properties of activated sludge. He reported that apparent viscosity increased with increasing pH of the activated sludge. It was also reported at slightly acidic pH of 5-6, the surface of the sludge floc is only slightly negatively charged and the floc maintains its most compact structure. When the sludge flocs are more compact, the exposed cross-sectional area of solids is reduced, therefore the obstruction of fluid flow and deformation properties will be less resulting in lower viscosity and shear stress. As the pH of sludge increases beyond pH of 7, the effect of pH on viscosity and shear stress are increasingly intensified. This trend was also reported by Tixier, Guibaud [21] and Tenney and Stumm [76] where the sludge floc became increasingly negatively charged with increasing pH resulting in repulsion and expansion of the floc structure which leads to the increase in exposed cross-sectional area resulting in higher resistance to flow. Hence, higher viscosity and shear stress values are expected at higher pH and vice versa. Pevere, Guibaud [23] also reported the same trend, but added that pH has limited impact on the overall rheology of sludge but instead sludge rheology is highly dependent on the source of the sludge. Wang, Ma [77] reported that in the pH range of 2.6- 6.8 the viscosity and shear stress of sludge was observed to increase with increasing pH in the same way as the reports of previous researchers. It was also reported that sludge floc structure and surface properties are highly dependent on pH. Al-Dawery and Reddy [78] confirmed that sludge particles formed larger floc sizes at higher alkalinity compared to more acidic sludge environment. As pH of sludge increases yield stress was found to increase in the same manner as the viscosity and shear stress. The pH dependence of rheology has been considered by Tombácz and Szekeres [79] on similar colloidal material particularly on kaolinite and montmorillonite. In the same way as the other findings reported above, they observed that the charge on the faces of the particles depended on the pH of the solution, with a high pH resulting in a net negative surface charge and a low pH a net positive surface charge. This surface charge has a bearing on the rheology of the material as it changes the way the particles interact, changing the strength of the interparticle forces. This change in interparticle forces directly affects the way the material reacts to shear rate and shear stress. The pH of the material can have a direct impact on the surface charge of the particles, hence affecting the inter-particle forces and the electrical double layer. The electrical double layer results from the ionic environment surrounding the particle developing to neutralise the net charge between the particle and the bulk medium. Due to the effect of interparticle forces. Table 1 shows the summary of the reports by different researchers on the effect of pH on sludge viscosity and shear stress for varying pH ranges.

Table 1. Impact of pH on rheological properties of different types of wastewater sludge.

Sludge type	**pH range**	**Shear rate (s^{-1})**	**Model**	**Results**	**Reference**
DS	2.6 – 6.8	0 – 1000	Herschel-Bulkley	Shear stress increases with increasing pH. Viscosity value increases with increasing pH value.	Wang, Ma [77]
DS	5.6 – 9.0	0 – 1000	Bingham	Yield stress increases with increasing pH.	Al-Dawery and Reddy [78]
EAS/TEAS	3.6 – 10.0	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Shear stress increases with increasing pH. Viscosity value increases with increasing pH value.	Hong, Yeneneh [5]
EAS/TEAS	6 – 14	-	-	Viscosity value increases with increasing pH value.	Ruiz-Hernando, Simón [80]
EAS/TEAS	6 – 14	0 – 300	-	Viscosity value increases with increasing pH value.	Ruiz-Hernando, Martinez-Elorza [81]

EAS/TEAS	6.8 – 7.2	600	-	Viscosity value increases with increasing pH value.	Pevere, Guibaud [74]
EAS/TEAS	2 – 11	200 – 1000	-	Viscosity value increases with increasing pH value.	Pevere, Guibaud [23]
EAS/TEAS	2 – 12	0 – 800	Bingham, Ostwald	Viscosity value increases with increasing pH value.	Tixier, Guibaud [21]
EAS/TEAS	5.5 – 9.1	1.8 – 73.4	Ostwald	Viscosity value increases with increasing pH value.	Sanin [19]
EAS/TEAS: Excess activated sludge/thickened excess activated sludge; DS: Digested sludge					

5.2 Effect of temperature

Rheological properties as a function of temperature have been investigated by many researchers as shown in Table 2, including our own study, and generally it has been reported that yield stress and viscosity of different sludge types decrease with increasing of temperature [5-7, 11, 15, 29-31, 63, 64, 75, 82-85]. Baroutian, Eshtiaghi [30] have conducted work on the rheological behaviour of mixed primary and thickened excess activated sludge and have reported that yield stress decreases with increasing temperature. This trend was also reported by Khalili Garakani, Mostoufi [3], who also applied seven different models on activated sludge system in order to obtain a deeper understanding of the actual sludge behaviour. While Farno, Baudez [86] studied the effect of temperature on both yield stress and viscosity. It was reported that increasing the temperature decreased the apparent viscosity of the sludge, however at high shear rates, viscosity has been reported to have an increasing trend instead. Bougrier, Delgenès [87] performed a similar study which involved determination of the effect of thermal treatment on the solubilisation, physical properties and anaerobic digestion of several activated sludge samples. In their study, treatment temperature ranged up to 180ºC, which is considered to be unreasonably high as it would lead to the boiling of the sludge solution. They reported that as temperature increases the viscosity decreases. As the temperature of the thermal treatment continues to rise the viscosity change begins to slow and eventually no change will be observed. Hence, this confirms that such high temperatures are both impractical and ineffective in terms of changing the sludge viscosity and shear stress. Furthermore, Hii, Parthasarathy [88] investigated the effects of thermal pre-treatment on sludge. It was found that, the rheology of the sludge changes when allowed to be cooled back to room temperature, suggesting that it is critical that rheological measurement are conducted immediately.

Table 2. Impact of temperature on rheological properties of different types of wastewater sludge.

Sludge type	**Temperature range** (˚C)	**Shear rate (s^{-1})**	**Model**	**Results**	**Reference**
EAS/TEAS	80 – 145	0 – 600	Herschel-Bulkley	Viscosity and yield stress decrease linearly with increasing temperature.	Hii, Parthasarathy [88]
DS	60 – 180	-	-	Viscosity increase with the decrease in temperature.	Zhang, Xue [89]
DS	20 – 45	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Increasing temperature from 20 to 50 °C resulted in decrease in viscosity from 0.0053 to 0.0011Pa. Digester operating temperature range of 35–36 °C enhanced rheological	Yeneneh, Hong [6]

				properties and also dewatering process.	
EAS/TEAS	23 – 45	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress decreased by 2.5 times when the temperature was raised from 23 to 55°C. Viscosity decreased by 4.3times with an increase in temperature from 23 to 55°C.	Hong, Yeneneh [5]
EAS/TEAS	50 – 80	0 – 1000	Herschel-Bulkley	Yield stress and infinite viscosity decreases with increasing of temperature.	Farno, Baudez [57]
DS	20 – 55	0 – 300	Bingham, Ostwald, Herschel-Bulkley	Viscosity decreased by 6 times with an increase in temperature from 20 to 55°C.	Cao, Jiang [85]
MS	25 – 55	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Viscosity decreased by 50% with the increase of temperature from 25 – 55°C. Yield stress decreased by 33%	Hong, Yeneneh [7]

				with the increase of temperature from 25 – 55°C.	
EAS/TEAS	70 – 80	5 – 300	Ostwald	Pre-treatment and post-treatment conditioning (low-temperature thermal) resulted in reduction of viscosity.	Ruiz-Hernando, Martín-Díaz [75]
DS	10 – 60	0 – 1000	Bingham	Increasing temperature resulted in decrease in yield stress and viscosity. Preheating and cooling sludge as a pre-treatment condition resulted in the decrease of initial yield stress.	Baudez, Slatter [64]
MS	25 – 55	0 – 1000	Herschel-Bulkley	Yield stress decreases with increasing temperature.	Baroutian, Eshtiaghi [30]
EAS/TEAS	4 – 35	100	-	Increasing temperature resulted in decrease in yield stress and viscosity.	Dieudé-Fauvel, Van Damme [90]
EAS/TEAS	15 – 30	-	Bingham,	Increasing	Hasar,

			Ostwald	temperature resulted in decrease in yield stress and viscosity.	Kinaci [29]
EAS/TEAS	0 – 25	0 – 1000	Bingham	Temperature greatly affected the rheological properties of sludge at lower total solid content. Increasing temperature resulted in decrease in yield stress and viscosity.	Sozanski, Kempa [82]
RPS EAS/TEAS	10 – 25	-	Bingham	Yield stress has an exponential relationship with temperature. Flow behaviour index were found to be essentially independent of temperature. Temperature changes the overall sludge consistency resulting in significant energy loss	Manoliadis and Bishop [83]

RPS: Raw primary sludge; EAS/TEAS: Excess activated sludge/thickened excess activated sludge; MS: Mixed sludge; DS: Digested sludge

B: Bingham; O: Ostwald; HB: Herschel-Bulkley; S: Sisko; C: Carreau; Cr: Cross; Ca: Casson

5.3 Effect of total and volatile solid concentration

Total suspended solids (TSS) concentration is one of the most important parameters affecting sludge rheology and therefore several studies have been performed on this topic. These studies as shown in Table 3, involve varying the TSS concentration and then observing the effects on various rheological properties, predominately apparent viscosity and/or yield stress, in order to improve the understanding of sewage sludge flow behaviour. Rheological properties under the influence of TSS concentration have been investigated by several researchers such as Yeneneh, Hong [6] Markis, Baudez [1] Hong, Yeneneh [5] Cao, Jiang [85] Hong, Yeneneh [7] Piani, Rizzardini [26] Markis, Baudez [13] Baroutian, Eshtiaghi [30] Khalili Garakani, Mostoufi [3] Yang, Bick [91] Laera, Giordano [92] Wu and Chen [56] Mori, Seyssiecq [22] Pevere, Guibaud [23] Hasar, Kinaci [29] Tixier, Guibaud [20] Spinosa and Lotito [93] Sanin [19] Rosenberger, Kubin [94] Forster [61] Lotito, Spinosa [8]. Several of these studies were discussed focusing on an overview of their relevant findings. The range of TSS concentrations chosen varies in great degree, the investigated range highly depends on the origin of sludge and the expected output conditions of the wastewater treatment plant being investigated. Although, different authors investigated different TSS conditions, this does not necessarily mean that their findings are less accurate.

Baroutian, Eshtiaghi [30] investigated the effect of total solid concentration on sludge rheology and reported that yield stress of digested sludge is directly related to total solid content of the system where yield stress increases with increasing total solid concentration. This is due to the existence of solids particle within the sludge system which resulted in an increase in viscosity within the sludge system. This trend was also reported by Farno, Parthasarathy [31] and Yang, Bick [91]. Yang, Bick [91] reported that the apparent viscosity of sludge reflects the internal and external interactions and forces occurring within sludge flocs resulting in different flow curve behaviour for low and high solid concentration. Baudez and Coussot [95] and Forster

[96] also reported that the rheological properties of sludge is governed by the synthesis of volatile fatty acids. Another similar study was performed by Markis, Baudez [1] in which they looked at the impact of TSS concentration on the rheological properties of primary and secondary sludge (activated sludge). The results from experiments performed by Markis, Baudez [1] show that as solid concentration increases the apparent viscosity of the activated sludge also increases, this agrees with the findings of Tixier, Guibaud [20]. Additionally, it shows that there is a linear relationship between the TSS concentration and apparent viscosity whereas Tixier, Guibaud [20] found more of an exponential relationship and this difference could be due to the TSS concentration range used (i.e. At low concentrations the relationship may start off as exponential but then as it gets higher it becomes linear). The other study discussed is that of Sanin [19] who examined the effect of different operational and other process parameters on the rheology of activated sludge with one of them being solids concentration (TSS). The findings from Sanin [19] agrees with both Tixier, Guibaud [20] and Markis, Baudez [1] that as solids concentration increases so does apparent viscosity additionally it supports the idea that at low TSS concentration the relationship is exponential.

Table 3. Impact of total solid concentration on rheological properties of different types of wastewater sludge.

Sludge type	**Total solid concentration range (g/L)**	**Shear rate (s^{-1})**	**Model**	**Results**	**Reference**
DS	10 – 20	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress increased with the increase of total solid concentration. Viscosity increased with the increase of total solid concentration.	Hong, Yeneneh [27]
DS	10 – 20	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress increased 6 times with the increase of total solid concentration from 10 – 20g/L. Viscosity increased 41 times with the increase of total solid concentration from 10 – 20g/L.	Yeneneh, Hong [6]
RPS EAS/TEAS	28 – 50 28 – 92	0 – 1000	Herschel-Bulkley	Rheological properties of mixed sludge changed dramatically with	Markis, Baudez [1]

				increasing TEAS concentration.	
EAS/TEAS	9 – 37	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress increased 6 times with the increase of total solid concentration from 9 – 37g/L. Viscosity increased 6 times with the increase of total solid concentration from 9 – 37g/L.	Hong, Yeneneh [5]
DS	40 – 100	0 – 300	Bingham, Ostwald, Herschel-Bulkley	Yield stress increased 78 times with the increase of total solid concentration from 40 – 100g/L. Viscosity increased 42 times with the increase of total solid concentration from 40 – 100g/L.	Cao, Jiang [85]
MS	20 – 30	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress decrease by 85% with the decrease of total solid concentration from 30 – 20g/L. Viscosity	Hong, Yeneneh [7]

				decrease by 15% with the decrease of total solid concentration from 30 – 20g/L	
EAS/TEAS	0 – 1	0 – 240	Ostwald	Sludge sample show slightly thixotropic and shear-thinning behaviour with increasing total solid concentration.	Piani, Rizzardini [26]
RPS EAS/TEAS	28 – 82 28 – 50	0 – 1000	Herschel-Bulkley	Both RPS and EAS/TEAS behave as shear thinning, yield stress fluids.	Markis, Baudez [13]
MS	43 – 98	0 – 1000	Herschel-Bulkley	Concentration has a significant impact on the sludge yield stress and the model coefficients.	Baroutian, Eshtiaghi [30]
EAS/TEAS	2.74 – 16	25 – 1000	Bingham, Ostwald, Herschel-Bulkley, Carreau	Both yield stress and viscosity increases as total solid concentration of sludge increases.	Yang, Bick [91]
EAS/TEAS	3.7 – 22.9	3 – 1300	Bingham, Ostwald	Both yield stress and viscosity increase as total	Laera, Giordano [92]

				solid concentration of sludge increases. Model parameters shows strong correlation with total solid concentration.	
EAS/TEAS	4.2 – 25	940	-	Yield stress decrease by 38% with the decrease of total solid concentration from 4.2 – 25g/L. Viscosity decrease by 38% with the decrease of total solid concentration from 4.2 – 25g/L	Wu and Chen [56]
EAS/TEAS	27 – 57	0 – 3000	Bingham, Ostwald, Herschel-Bulkley	Yield stress decrease by 90% with the decrease of total solid concentration from 27 – 57g/L for both dynamic and flow measurements.	Mori, Seyssiecq [22]
EAS/TEAS	8.3 – 22.6	200 – 1000	-	Increase in shear stress was observed with increasing total	Pevere, Guibaud [23]

				solid concentration. Viscosity increased with increasing total solid concentration.	
EAS/TEAS	2.9 – 12.3	-	Bingham, Ostwald	Viscosity showed minimum change (<1%). Yield stress increased 2.5 to 4 times with the increase of total solid concentration from 2.9 – 12.3g/L.	Hasar, Kinaci [29]
EAS/TEAS	3.1 – 6.3	0 – 800	Bingham, Ostwald	Viscosity was greatly affected by total solid concentration. Viscosity of sludge with the same total solid content differ greatly due to source even when the treatment process is exactly the same.	Tixier, Guibaud [20]
-	35.1 – 446.7	0.05 – 4.05	Bingham	Yield stress increase with the	Spinosa and Lotito [93]

				increase of total solid concentration.	
EAS/TEAS	2.0 – 18	1.8 – 73.4	Ostwald	Viscosity of sludge increased by 5 times with increase in total solids concentration for the range.	Sanin [19]
EAS/TEAS	2.7 – 47	0 – 2200	Ostwald	Increase in viscosity of approx. 15% with increasing total solid concentration. Increase in shear stress with increasing total solid concentration.	Rosenberger, Kubin [94]
EAS/TEAS	10.5 – 26.6	0 – 10	-	Increase in shear stress with increasing total solid concentration.	Forster [61]
EAS/TEAS MS DS	3 – 47 11 – 82 12 – 67	0.015 – 4.05	Bingham, Ostwald	Rheological properties of sludge changes above 80-100g/L if total solid concentration.	Lotito, Spinosa [8]

RPS: Raw primary sludge; EAS/TEAS: Excess activated sludge/thickened excess activated sludge; MS: Mixed sludge; DS: Digested sludge

5.4 Effect of conditioning agents

Better understanding of sludge dewatering processes helps to improve biosolid management and results in further economic and environmental benefits. Enhanced dewatering can lead to reduction in liquid volume within biosolid which would reduce the capital, transportation and operational costs [33, 97, 98]. Dewatering is typically achieved by use of filter presses or centrifuges. In order to enhance the dewatering process, condition agents such as polymers are used to flocculate the sewage sludge. These conditioning agents can modify the floc structure of the sludge resulting in the change of fluid properties and can impact the overall efficiency of the dewatering process [99]. Dewatering of waste activated or digested sludge is a costly process in the operation of wastewater treatment plants. Expenses related to the dewatering process, including cost of conditioning agents, typically account for 30-50% of the annual operating cost of municipal treatment plants [100]. Considering the huge cost related to the dewatering process it seems highly relevant to improve our understanding of the relation between suspension structure (rheology) and dewaterability, and in particular how to control suspension structure for optimisation of conditioning and dewatering [5, 7, 27, 101]. Furthermore, there is lack of fundamental knowledge within the dewatering process, particularly on how flocs are structurally organized and how this may relate to their mechanical and dewatering properties [99]. Many researchers have investigated the effectiveness of various conditioners on sludge dewatering and highlighted the importance of particle size and distribution and their impact on dewatering [62, 66, 98, 99, 101-113]. All these published literature show that CST measurement has been used as a common indicator for dewatering performance and rheology was used to determine the flocs mechanical properties. In addition, polymer dose was found to be the main parameter which controls the floc structures, particle size and distribution hence rheology of the sludge system.

Forster [114], Forster [115], Sanin and Vesilind [116] investigated the effects of different doses of conditioning agents on the rheological characteristics of sludge. The results showed that there is viscosity reduction due to floc breakup into smaller floc structure with the increase in polymer extracted. Dieudé-Fauvel and Dentel [99] investigated the effects of particle size and distribution and their impact on dewatering with multiple polymers as the condition agents. The conditioning agents used in this work had varying molecular weight, cationic charges and cross-linkage. Dieudé-Fauvel and Dentel [99] found that the rheological curves had the same trend and shape regardless of the type of conditioning agent used. Hence, the conditioning agent results in shifting of the rheograms only. It was noted that the key factors which resulted in shifting of the curves was the molecular weight and cationic charges of the conditioning agent and the dosage used. It was found that, the flocs size increases with increasing polymer dose which are supported by other researchers such as Houghton and Stephenson [62], Al-Dawery and Reddy [78], Mikkelsen and Keiding [101], Spicer and Pratsinis [102], Qi, Thapa [103], Chu and Lee [117]. Based on rheological results, once optimum polymer dose has been reached, the sludge structures no longer undergo any changes but it does impact the liquid sludge properties. As a result of this, a relationship between rheological properties and polymer dosage can be established. Furthermore, Lee and Liu [118] suggested that using dual polyelectrolytes conditioning method significantly improves the performance of dewatering while decreasing the chance of overdosing. Table 4 compiled several research results on various conditioning agents in relation to sludge dewaterability and rheological properties.

Table 4. Various research work on the impacts of conditioning agents on dewaterability.

Sludge type	**Conditioning agent**	**Results**	**Reference**
EAS/TEAS	Polymeric ferric suphate and cationic polyacrylamide	Improved sludge dewaterability. Increases sludge floc compactness.	[119]
EAS	Polyaluminium, chloride and high performance polyaluminium, chloride	Improved sludge dewaterability. Increases sludge floc size and compactness.	[120]
TEAS	Sulphuric acid and betaine	Improved sludge dewaterability under pH condition of 2.5.	[121]

EAS/TEAS	Seawater and brine	Improved dewaterability.	[122]
EAS/TEAS	Acidithiobacillus thiooxidans and Acidithiobacillus ferrooxidans	Improved dewaterability.	[123]
EAS/TEAS	Microbial flocculant	Improved sludge dewaterability. Increases sludge floc compactness.	[124]
EAS/TEAS	Alum and ferric chloride	Improved sludge dewaterability.	[125]
EAS/TEAS	Talaromyces flavus S1 (filamentous fungus)	Improve sludge dewaterability.	[126]
EAS/TEAS MS	Alkaline hydrolysis	Reduces sludge viscosity. Increases total solid content. Negatively impacted dewaterability.	[81, 127]
DS	Chitosans, organic polyelectrolytes and inorganic metal cations	Improved sludge dewaterability.	[113]
MS	Mixture of hydrogen peroxide and ferrous iron (fenton's reagent)	Improved sludge dewaterability for a pH condition of 7.	[128]
DS	Mixture of hydrogen peroxide and ferrous iron (fenton's reagent)	Improved sludge dewaterability.	[129]
DS	Enviro-Zyme 216 and Percol 757 (Enzyme complex and cationic copolymer)	Improved dewaterability.	[130]
DS	Chitosan	Improved sludge dewaterability.	[131]

DS	Copolymer of starch with cationic vinyl monomer	Improved sludge dewaterability. Improved sludge flocculation ability.	[132]
DS	Cationic polyelectrolytes	Improved sludge dewaterability.	[133]
DS	Alum and cationic polymer	Improved sludge dewaterability.	[134]
DS	Cationic and anionic polyelectrolytes	Improved sludge dewaterability.	[135]
DS	Biomass ash	Improved sludge dewaterability.	[136]
DS	Surface-active monomer (benzyl dimethyl 2-ethyl ammonium chloride)	Improved sludge dewaterability.	[137]

EAS/TEAS: Excess activated sludge/thickened excess activated sludge; MS: Mixed sludge; DS: Digested sludge

5.5 Effect of chemical oxygen demand (COD)

Rheological properties of digested sludge also depend on total organic content or chemical oxygen demand (COD) of the feed to the anaerobic digesters and performance of the anaerobic biodegradation process [57]. It was reported that the rheological behaviour of sludge from anaerobic digesters is governed by the synthesis of volatile fatty acids by extracting the main solid components (proteins, lipids and carbohydrates) [95]. Biosolid produced from digested sludge also showed poor dewaterability with the increase in volatile organic content of the digested sludge coming out of anaerobic digesters. This results in the increase of polymer consumption to compensate for the deterioration in dewaterability, which in turn incurs additional operational cost [70]. Not many work have been conducted to investigate the effect COD on rheology of sludge. Hii, Parthasarathy [88] have attempted to find a correlation between COD, yield stress and viscosity. It was reported that yield stress and viscosity were found to decrease with the increasing COD which could be attributed to cell wall breakdown of microorganism and release of soluble organics and breakdown of insoluble proteins into soluble amino acids. Similar trend was also reported by Farno, Baudez [57], where the results confirmed that rheological parameter have a relationship with COD and a correlation can be developed to aid as monitoring tool. It is reported that the rate of change in COD when exposed to thermal treatment can be used to predict rheological parameters such as viscosity and yield stress. Similarly, Zhang, Xue [89], also observed some correlation between rheological measurement and COD. In this work, rheological measurement such as viscosity was used as a performance indicator to investigate the effects of COD change due to thermal pre-treatment, while the impact of COD on rheological properties were not investigated. Ciaciuch, Gaca [138] also used a similar approach, where COD and rheological measurement were used as performance indicators to monitor the performance of two-stage anaerobic digestion process and no solid link between COD and rheological properties were made. The lack of detailed investigation between the relationship of rheological properties and COD was also highlighted by Oliveira, Reed [139]. It was reported that, rheological measurement coupled with COD should be explored further due to the potential it has to aid in monitoring conditioning requirements during plant operation.

6. Rheology as a tool for monitoring and control of important parameters in WWTPs

Rheological characteristics of sludge vary as a function of many factors such as source, environment and intrinsic properties of the sludge [140]. Hence, Spinosa and Lotito [93] and Markis, Baudez [1] explained that rheology could potentially be used as a tool for monitoring and optimizing various wastewater treatment unit operations. This section investigates the applicability of rheology as a tool to monitor, control and optimize operational parameters.

6.1 Rheological parameter monitoring and control for anaerobic digester performance enhancement

The most common, preferred and cost effective process in the wastewater treatment plant to achieve significant sludge volume reduction is the anaerobic digestion process [10, 16, 141-143]. The digestion process occurs in three stages, namely hydrolysis, acidogesis and methanogenesis. The digestion process starts with hydrolysis of the feed sludge which breaks down the insoluble organics. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and acetic acid. Finally, methanogenesis stage converts the remaining organics products into biogas. The remaining solids would have formed the digested sludge which would have organic matter removed when compared to activated sludge [16, 55, 140, 144]. Within the anaerobic digester, the composition of sludge is constantly changing and creating a scenario where it is difficult to understand and monitor the rheological behaviour of the sludge. Many researchers such as Markis, Baudez [1], Dieudé-Fauvel, Héritier [2], Yeneneh, Hong [6], Baudez, Markis [10], Markis, Baudez [13], Hong, Yeneneh [27], Farno, Parthasarathy [31], Bhattacharya [34], Moeller and Torres [35], Wang and Dentel [48], Farno, Baudez [57], Eshtiaghi, Yap [60], Forster [61], Houghton and Stephenson [62], Paul, Camacho [63], Baudez, Slatter [64], Lay, Lee [65], Lau, Ang [66], Ayol, Filibeli [70], Farno, Baudez [86], Mikkelsen and Keiding [101], Lau, Chong [145], Oliveira, Reed [146] have investigated the change in rheological behaviour of feed (activated sludge) and the product sludge (digested sludge) sludge of the anaerobic digester. Results from Tixier, Guibaud [20] shows that viscosity greatly changes during the digestion process and settlability of the sludge also showed similar trend which indicates that sludge is sensitive to floc structure changes. They recommended that rheology can be used as a tool to determine sludge quality which potentially can be useful information for digester performance optimization. Monteiro [73] reported that there is a relationship with sludge rheological behaviour changes with degree of digestion. Moreover, Monteiro [73] explained that the total solids concentration changes is not sufficient to describe the change of rheological properties within the digester. Monteiro [73] suggested that the rate of change of the rheological parameters follow the evolution of the biological process. For the range of solids concentration Monteiro et al studied it has been verified that the degree of digestion is the main factor affecting the rheological behaviour of the sludge and that sludge rheology is not significantly affected by the solids concentration of the sludge. In contrast, Moeller and Torres [35] showed that there is no viscosity changes for the sludge tested and suggested that using rheological properties as a tool for process control should be investigated carefully.

6.2 Rheology as a tool for monitoring and control of dewatering performance

Rheological characteristics of sludge were found to be efficient tools for monitoring, control and performance improvement of sludge treatment processes. Researches such as Yeneneh, Hong [6], Lotito, Spinosa [8], Hong, Yeneneh [27], Stickland [44], Laera, Giordano [92], Tang and Zhang [140], Örmeci and Abu-Orf [147], Örmeci [148], Yen, Chen [149], Abu-Orf and Dentel [150], Abu-Orf and Örmeci [151], have suggested that sludge rheological characteristic can be used as a tool for the optimization of polymer dose in the dewatering unit. Many of these researches were designed to identify key rheological parameter that can potentially be used as indicator for controlling the amount of conditioning agent used in wastewater treatment plants.

According to Kopp and Dichtl [152], dewaterability of digested sludge is highly dependent on the distribution of sludge-water in the sludge mass. There are four classes of sludge-water, free water, surface water, interstitial water, and intracellular water. Accurately measuring the amount of water within the digested sludge samples can be very difficult due to the complex nature, interaction and origin of these waters. For digested sludge, free water can easily be removed from solids particles using simple gravitational settling. Surface and interstitial waters exhibit some interaction with the solid particles which can be removed by chemical conditioning coupled with mechanical methods. Microbial extracellular polymeric substances (EPS) are major components of the sludge floc matrix. EPSs are regarded as one of the most important factors that influence the dewatering characteristic of sludge. Information regarding EPS is thus relatively favourable for understanding the exact roles of EPS in controlling dewaterability and for revealing the mechanisms enhancing dewatering [33, 153]. According to Neyens, Baeyens [33], Ouyang, Wang [153] dewatering of sludge is more dependent on soluble EPS and not bound EPS. It was known that soluble EPS is responsible for water retention and the strong water binding capability of digested sludge, concluding that the higher the amount of soluble EPS in digested sludge results in poor dewatering performance.

According to Youcai and Guangyin [154], a key rheological parameter that highly impacts the dewatering performance is viscosity. Research work by Yeneneh, Hong [6], Hong, Yeneneh [27], Tang and Zhang [140], Örmeci [148], supports that statement and found that CST value showed a significant correlation with viscosity. In the processes of traditional chemical conditioning and dewatering, capillary suction time (CST) tests are commonly-used indices for quantitative evaluation of the dewatering effect although it has been indicated that CST lacks reliable reproducibility [155]. The result of the work concluded that digested sludge samples with higher viscosity exhibits difficulties in dewatering. Furthermore, there is also a correlation between viscosity and soluble EPS. This is because, higher amount of soluble EPS have higher affinity for water which results in higher sludge viscosity value and ultimately, as mentioned above, resulting in poor dewatering performance. Örmeci and Abu-Orf [147], Örmeci [148], Abu-Orf and Örmeci [151], [156] have used rheological parameters to define the effects of conditioning agents on the physical characteristic of digested sludge. They were able to develop a simple protocol to determine the optimum polymer dosing conditioning using rheological parameter such as viscosity. Furthermore, they concluded that, comparing both traditional method and rheological parameters, rheology is more reliable as a control tool for optimizing conditioning agents for the dewatering process.

7. Conclusion, recommendation and future direction

In this review, the rheological and physico-chemical characteristics of different types of wastewater treatment plant sludge were discussed at the beginning. Up-to-date developments, findings and compilations on rheological properties of sludge and the influence of different operational parameters on sludge rheology and the relationships were presented in fair depth. Based on detailed investigating of significant number of published articles, the impacts of different operational parameters like solid concentration, temperature, pH, floc particle size, mixing ratio, dose of sludge conditioning agents on the rheological behaviour of sludge from different parts of WWTPs were analysed. Raw primary sludge, excess activated sludge, thickened excess activated sludge, mixture of raw primary and thickened excess activated sludge (mixed sludge), digested sludge, and biosolid rheological and flow behaviour under the influence of different operating parameters and the impacts on process performance were investigated and compared. Yield stress was found to increase with increasing solid concentration for all sludge types. Likewise, viscosity showed a decreasing trend with decreasing total solid concentration and percentage of thickened excess activated sludge in the mixture. Temperature showed an inverse relationship with yield stress and viscosity. This comprehensive review analysed and identified the following research gaps.

- Lack of fundamental knowledge within the dewatering process, particularly with the way flocs are structurally organized and how this may relate to their mechanical and dewatering properties.
- Lack of uniform rheometric methods and techniques resulting inconstancy when comparing to other rheological studies.
- Studies on different sludge types are few, limited, and inconsistent. Too much studies have focused on activated sludge or digested sludge and very limited research were undertaken on rheological properties of biosolid and centrate.
- Not many work have been conducted to investigate the effect of COD on rheology of sludge.
- Further studies on the relationship between rheological characteristics of digested sludge and dewatering performance particularly on rheology as an indicator or monitoring tool of dewatering performance are required.

Based on the findings of this review, the following research directions are recommended for further investigations in the future.

- Investigating the microscopic characteristic and composition of sludge and their influence on the rheological behaviour of sludge and identifying the specific constituent which greatly affects sludge rheology.
- Investigating relationship between rheology and conditioning agents at microscopic level and optimizing the conditioner dose based on mechanistic understanding of the flocculation process in relation to rheology and dewatering.
- Investigating the dynamic rheological response of sludge in anaerobic digestion unit and the applicability of rheology in monitoring and controlling the performance of digesters.
- Investigating the applicability of sludge rheology in monitoring and control of the performance of aeration unit and establish the relationship between sludge rheology and aerobic degradation of sludge or the performance of the activated sludge process.

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Highlights

- Rheological behaviour of different sources sludge of a WWTP has been reviewed
- Various physico-chemical factors on sludge rheological behaviour has been analysed
- The impacts of sludge rheology on process performance has been critically discussed
- Identified future research gap on sludge rheology study