Rheological Characterisation of Faecal Sludge in Lavender Hill Treatment Plant, Ghana

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Abstract: *Rheological properties of faecal sludge have emerged as effective indicators for fluid characterisation, driven by growing needs in wastewater and faecal sludge treatment plants worldwide. This study analysed the rheological properties of faecal sludge received at the Lavender Hill Treatment Plant in Ghana. Samples were collected from the outlets of key treatment units at the Lavender Hill faecal treatment plant, a 3,500 m3/day facility. The sludge samples were taken from primary sludge, dewatered sludge, dewatered leachates, anaerobically digested sludge, and activated sludge. The analysis revealed that although faecal sludge characteristics varied widely across regions, the choice of treatment technology and shear-induced orientations were critically relevant to its rheological behaviour. The rheological properties of faecal sludge were influenced by the type, test protocols, and inherent properties. Despite these factors, faecal sludge remained a non-Newtonian fluid. However, variations in solids concentration, sludge type, and the treatment method or process unit employed resulted in pseudoplastic, dilatant, thixotropic, or rheopectic behaviour. This study has demonstrated that in-depth knowledge of faecal sludge rheology is essential for the design, management, optimisation, and operation of faecal sludge treatment plants.*

Keywords: *Faecal Sludge, Non-Newtonian Fluid, Plant Operations, Rheological Studies, Wastewater Treatment.*

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Introduction

Generally, fluids are categorised into two types, namely Newtonian and non-Newtonian fluids, based on their rheological properties (Sun et al., 2024; Wajihah & Sankar, 2023). The rheological characteristics of fluid have been proved to be dependent on factors such as viscosity, shear stress, shear rate, temperature and physico-chemical properties (Porwal et al., 2021; Rana & Thakur, 2023). Mostly, rheological characterisation of fluids depends on their ratio of the applied shear stress to the resulting shear rate, which is termed as viscosity. Fluids with a straight rheogram of slope (viscosity) going through the origin are characterised as Newtonian fluids. Thus, they have a simple flow profile with constant viscosity, independent of the applied shear stress and the resulting shear rate, under constant temperature and pressure.

Many researchers have found that fluid with a complex flow profile and irregular slope is non-Newtonian in nature (Bouchendouka et al., 2022; Ding et al., 2022; Narayanan et al., 2024). The flow curve of such fluid does not pass through the origin and is dependent on shear rate, shear stress, flow geometry, and other flow characteristics at constant temperature and pressure. The complexity of non-Newtonian fluid has received significant attention from researchers due to its complicated flow profile and its important industrial applications (Garg et al., 2025; Hu et al., 2024). In the application related to wastewater treatment plants, a lot of research has been done on sludge, which, from evidence, exhibits non-Newtonian behaviour (Collivignarelli et al., 2022; Xiong et al., 2026).

Rheological properties of sewage sludge have been extensively studied in recent years (Santos et al., 2022; Wei et al., 2021). Accordingly, sewage sludge are produce by and not limited to these two processes: sludge are formed in biological reactors, by the activities of the bacteria present in the raw sewage (wastewater) as in the conventional activated sludge system; and in the process of chemical-physical reactions where chemical reagents are not utilized (e.g., primary sedimentation) or by the process of coagulation-flocculation, where addition of chemicals are employed (Di Giacomo & Romano, 2022; Yu et al., 2021; Zhao et al., 2023). In the rheology literature, sewage sludge has been found to behave primarily as a non-Newtonian fluid, although it can sometimes exhibit Newtonian behaviour, depending on the sludge's total solids concentration (Infusino & Caloiero, 2021).

Usually, diluted sludge acts as a Newtonian fluid at a constant temperature and pressure, but changes to a non-Newtonian fluid after the solid concentration of the sludge is increased (Jankowska et al., 2023). According to Gao et al (2024), the effect of solid concentration on the fluid's rheological characteristics may be attributed to the polysaccharide starch and protein content present in the sludge. Similarly, Cao et al (2021) examined the rheological properties of sludge from two different wastewater treatment plants and concluded that temperature and solid concentration are the most significant factors affecting sludge rheology. At room temperature, sludge viscosity raised from 9.82 mPs to 412.69 mPs with variation of the solid concentration from 4% to 10% was recorded in their study (Ma et al., 2024). The Ostwald de Vaele model, Herschel-Buckley model, and Bingham model were utilised to investigate sludge rheology and concluded that sewage sludge samples are pseudo-plastic, with the Ostwald de Vaele model being the best fitting model for the sewage sludge samples (Collivignarelli et al., 2022). However, Ruiz-Hernando et al (2022) went on to show that solid concentration is the main parameter influencing sludge rheology.

According to Liu et al (2024), the sludge yield stress is linearly correlated with sludge solids concentration and varies exponentially with the inverse of temperature. In some studies, temperature was reported to be inversely related to Bingham viscosity and yield stress (Chamran et al., 2026; Dey et al., 2021; Joshi & Malkin, 2025), indicating that digested sludge becomes more fluid as temperature increases. In the study by Markis (2024), the rheological characteristics of primary and secondary sludge were examined in detail. She observed that both sludges, at low shear stress below the yield stress, exhibited viscoelastic (Bingham) characteristics, and that their apparent viscosity and yield stress were positively correlated with the total sludge solids concentration. However, secondary sludge flows smoothly to a steady state, whilst primary sludge behaves exactly the opposite, yielding suddenly (Roychoudhury & Das, 2022). Another work has also indicated that various raw sludges in a pipe viscometer are Bingham fluids (Jankowska et al., 2023).

Therefore, this work studied the rheology of faecal sludge received at the Lavender Hill Treatment Plant, a large-scale facility in Ghana, to inform the requisite operational guidelines for transporting and handling the sludge throughout the treatment processes. Large-scale faecal sludge treatment plants are being constructed and operationalised in Ghana, with the Lavender Hill faecal sludge treatment plant currently the largest of the five in the country. Faecal sludge brought to these treatment plants is aged, ranging from two weeks to twenty-four months, from various sources (Ahmed et al., 2023; Ofori-Amanfo et al., 2025). Sustainability has been a weak area over the years in the management of large-scale wastewater treatment plants in Ghana (Arthur et al., 2023; Tanoh et al., 2022; Twi-Yeboah et al., 2024). Therefore, it is crucial to understand the rheological behaviour of aged faecal sludge during large-scale management to ensure sustainability.

Raw sewage and faecal sludge properties in the African region vary immensely from those in other regions (Odirile et al., 2024). The fundamental physicochemical characteristics of a fluid (such as sewage and faecal sludge) significantly affect its rheology. Total solids and density, for example, contribute immensely to the flow of fluids in pipes and drains. Lack of such information can be attributed to the breakdown and poor maintenance of most of the redundant old treatment plants that are not operational across the country (Koloane et al., 2022; Muhammad & Mahmood, 2025). Nonetheless, comprehensive rheological studies of faecal sludge in a typical large-scale faecal sludge treatment plant have not been conducted.

Knowing the rheological properties of the raw material to be treated gives more insight into the selection of appropriate technology (Aslam et al., 2022). Additionally, it provides the necessary information for selecting design criteria and equipment for each operation and maintenance activity. Rheological knowledge of sludge in a typical treatment plant has high potential for reducing operational costs by allowing the plants to be well-optimised to function effectively (Rossano-Becerril et al., 2024). Thus, this study contributes to the literature on comprehensive rheological characteristics of faecal sludge in a typical large-scale treatment plant in Africa and the operational optimisation of large-scale wastewater treatment plants.

Methods

2.1 The Lavender Hill Treatment Plant and Sample Collection

The Lavender Hill Treatment Plant (LHTP) was a two-thousand-cubic-meters (2,000m3/day) per day treatment plant and has been expanded to a three-thousand-five-hundred (3,500m3/day) cubic meters per day capacity. The treatment plant has a reservoir where screened faecal sludge is stored, and a screw press dewaters the raw sludge, producing both leachate and dewatered sludge. A cationic polyelectrolyte aids sludge dewatering with a screw press. It has an Upflow Anaerobic Sludge Blanket (UASB) reactor that generates biogas and anaerobically digested sludge. The plant also has an activated sludge system in place, where activated sludge is also generated. Secondary digested sludge is generated along the treatment process in the secondary sedimentation tank (see Figure 1). In light of the treatment processes at the plant, the sampling matrix was done as indicated in Table 1, and physicochemical parameters were measured according to the standard methods.

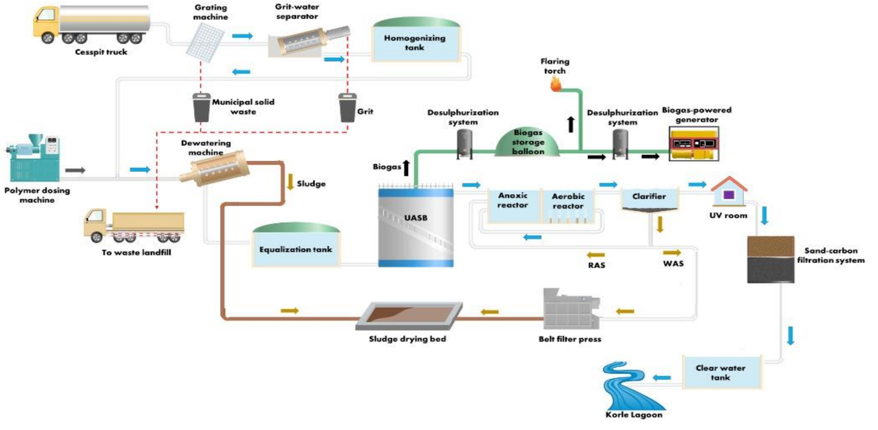

Figure 1: Process Flow diagram of the Lavender Hill Faecal Treatment Plant (LHFTP)

Table 1: Sample Matrix

Sample Source	Description	Type of data
Raw Mixed Primary Sludge	Sludge from the equalisation tank after screening of debris	1. Physical parameters: total dissolved solids (TSS) and temperature. 2. Rheological properties: shear stress, shear rate, viscosity, apparent viscosity.
Dewatered Primary Sludge	Sludge after dewatering with a screw press	
Anaerobic Digested Sludge (UASB)	Sludge obtained from the UASB reactor	
Aerobic Digested Sludge (Activated Sludge)	Sludge obtained from the activated sludge process unit	

Samples were collected from the outlets of the various key treatment units of the LHFTP, which receives between 1,500 and 2,500 cubic meters of faecal sludge per day, equivalent to about 150–250 trucks of faecal sludge per day (Issahaku et al., 2023). Sludge samples from these units are primary sludge (Influent), Dewatered Sludge, Dewatered Leachates, UASB sludge and Activated Sludge. The samples were stored at 4 °C before testing and processed within a week to limit potential sludge modification. The samples were sieved through a 1000 µm sieve to remove impurities that are not natural components of the sludge matrix. A set of samples with different concentrations was prepared by diluting the original sludge samples with distilled water. Another set of samples with different solid concentrations was prepared by concentrating the respective sludge samples with solids obtained from the same sample matrix.

2.2 Rheological Measurement

Rheological properties of the Faecal sludge samples were measured using an Anton Paar MCR 72 Rheometer. The MCR 72 is equipped with a ball-bearing motor and provides rotational measurements, as well as measurements in oscillatory mode for special applications. Reproducible settings are essential for reliable results, and MCR 72 features a motor-driven elevation mechanism and Safe Gap (Austrian Patent AT 517074) technology, which ensures the measuring gap is set identically for every measurement and is consistently reproducible. Furthermore, the slow and precise setting minimises any influence on the sample's structure. When switching between measuring systems, the MCR 72 has a quick-connect feature, which provides great ease of use. This quick-fitting coupling allows one-handed connection of the measuring systems and ensures fast, convenient system changes without the use of a screwing mechanism. Temperature has the biggest influence on rheological measurements (Rothammer et al., 2021). MCR 72 has several air-cooled Peltier temperature units to counteract this. Flow curves and yield stress were measured using the proposed methods reported in the literature (Wei et al., 2021).

After reaching a stabilised set temperature (±0.05 °C), the samples were pre-sheared (15 s^{-1}) for 90s, to get a homogeneous concentration distribution; this was subsequently followed by an equilibrium phase of 60s. In a logarithmical ramp mode, flow properties (curves and yield stress) were measured with an applied shear rate ranging from 1 to 200 s^{-1} at 0.2% tolerance. To study the impact of temperature on the sample's rheology, six temperatures (32, 35, 45, 55, 65, and 75 °C) were applied to the samples to cover a wider range of operational conditions, such as transport, heat exchange, and digestion. The effect of solid concentration on rheology was also observed by varying the concentration of the primary samples by adding 0.5 g of solids from the same sample. The primary samples considered include the Raw Mixed Sludge (RMS), the plant influent, and the anaerobic-digested sludge from the UASB. Six different concentrations were considered (0.0, 0.5, 1.0, 1.5, 2.0, and 2.5g), with 0g representing the original primary samples. All the tests were repeated three times for each condition, and the average values were recorded for this study.

2.3 Quality Control of the Samples

Samples were manually collected by first selecting a well-mixed, concentrated location. The actual sample container, which will be used to transport the sample to the laboratory, was used for sampling to eliminate the possibility of contamination by intermediate collection containers. Before sampling began each day, the entire sample collection system was rinsed with deionised water and then dried. During the compositing period, individual sample aliquots were preserved at the time of collection in the field using ice in a well-cleaned ice chest. The samples collected at the end of each day were immediately sent to the laboratory for analysis.

Results and Discussion

3.1 Rheological Characterisation of the Faecal Sludge (RMS)

A fundamental understanding of rheological principles is essential for better interpretation of the complex rheological responses of aged faecal sludge received for treatment in a typical large-scale faecal treatment plant. When Faecal sludge is treated with a polyelectrolyte (cationic or anionic), it exhibits flocculation and/or coagulation phase Behaviours depending on the polyelectrolyte applied. Under continuous shearing, faecal sludge tends to gradually align with the flow direction, in which case it may exhibit typical shear-thinning Behaviour. The flocculation and/or coagulation phase of faecal sludge and shear-induced orientation behaviours are critically relevant for their rheological properties. Fluids can be generally classified into Newtonian and non-Newtonian fluids (Li et al., 2021) (Figure 2). Newtonian fluids exhibit a constant viscosity, while the incorporation of a dispersed phase into a Newtonian fluid can lead to the occurrence of several types of non-Newtonian Behaviours. Fluids with non-Newtonian behaviours can either be Herschel-Buckley, such as Thermoplastics, Clay, Tar, Sludge or Bingham plastic or can be Bingham pseudoplastic such as paper pulp, soap, paint, grease; also, it can be Dilatant such as beach sand, starch in water, or can be Thixotropic fluid or Rheopectic fluid (Narayanan et al., 2024). Among these non-Newtonian fluids are those that depend on time and others that are time-independent (Figure 3). Those that depend on time and are thinned by the application of shear stress are classified as Thixotropic fluids, and Rheopatic fluids are those that are time-dependent but thicken under shear stress (Figure 3). Time-independent fluids are either Herschel-Bulkley fluids or Bingham fluids. The Bingham fluids that get thinned by the application of shear stress are Bingham-Pseudoplastics, while Bingham fluids that get thickened by the application of shear stress are Bingham-Dilatant (Figure 4). Bingham plastic fluids behave as rigid solids until a yield shear stress is reached, and above this value, they flow as Newtonian fluids. Bingham pseudoplastic fluids also exhibit a yield stress, but they show shear-thinning Behaviour above the yield stress. The viscosity of shear-thinning fluids gradually decreases with increased shear rate. Conversely, shear thickening fluids show increased viscosity with increased shear rate (Figure 2).

The flow curve obtained from the viscosity versus shear rate for the raw mixed sludge (Figure 5) does not pass through the origin and also does not exhibit constant velocity. Comparing the flow curve with other standard curves (Figures 2 and 3), the raw mixed sludge (RMS) did not exhibit the characteristic behaviour of a typical Newtonian fluid and therefore can be considered non-Newtonian, with varying velocity (Figures 5 and 6). This is supported by Wei et al (2023), Huang et al (2024), and Wang et al (2024). The RMS, having shown a non-Newtonian fluid characteristic, was important to determine which of the non-Newtonian characteristics it exhibited. In the curve obtained by plotting the shear stress versus the shear rate of the RMS (Figure 5), as the applied stress increases, the shear rate also increases, confirming the direct proportionality of the relationship between shear stress and shear rate for non-Newtonian fluids.

An important characteristic of non-Newtonian materials is the presence of a yield stress, which is the minimum stress required to initiate flow (Garg et al., 2025). Below the yield stress, a material exhibits solid-like characteristics, which are very important in process design and materials quality assessment (Liu et al., 2024). The RMS exhibited a yield stress of about 14.542Pa, an equivalent shear rate of about 50 1/s, and a viscosity of about 29.087 mPa.s. From Figures 5 and 6, it can be seen that the application of stress results in a respective thinning of the fluid. Also, by comparing the results obtained by plotting the shear stress-shear rate curve for the RMS (Figure 5) with standard non-Newtonian fluid curves (Figures 3 and 4), the RMS exhibited the characteristics of a Bingham-Pseudoplastic fluid. This is consistent with earlier works done by Almeida et al. (2025) and Sun et al. (2024). At homogeneity, the RMS will begin to flow well above a stress of 50 1/s. The characteristics of RMS that came to the plant resulted in a very high settling rate due to its physicochemical characteristics (Alnawajha et al., 2024; Arufe et al., 2021; Calix-Rivera et al., 2025). This implies that when the RMS is stored in a reservoir, and the agitation or mixing is insufficient to maintain sludge homogeneity, there is a high tendency for settling at the bottom of the tank, and the rheological characteristics may vary. In this case, the yield stress is likely to exceed 50 1/s; therefore, a high resistive force must be applied to get the fluid to flow. When such a scenario occurs, pumps used to transport the fluid will begin operating above their normal capacity. Once it happens, the efficiency and lifespan of the designed pumps in use become questionable.

The characteristics of faecal sludge at the Lavender Hill faecal treatment plant have high foreign material loads (Issahaku et al., 2023), as shown in Table 2, and therefore require strong mechanical screening systems. When these foreign materials enter the reservoirs and become entangled on the agitators or mixers, coupled with the sludge's tendency to settle at the bottom of the tank, the RMS will assume a completely different rheology, and the fluid cannot be convected away from the stirrer. Mixing, however, is achieved by the bulk movement of material caused by an agitator's physical displacement. In this regard, it is crucial to select an agitator for a reservoir that stores RMS. Considering the physicochemical and rheological characteristics of RMS arriving at the plant, it is important to select agitators that promote top-to-bottom motion, typically by fixing the blades at an angle less than 90 degrees to the rotation axis. It is also important to consider the agitator's anchor type, which will require very close clearance between the agitator's impeller and the reservoir tank.

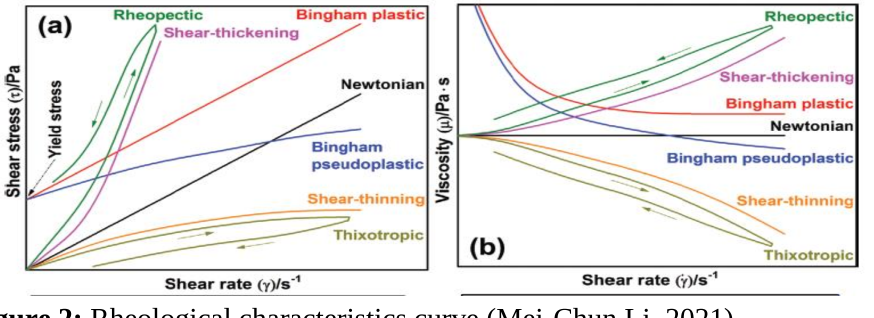

Figure 2: Rheological characteristics curve (Mei-Chun Li, 2021)

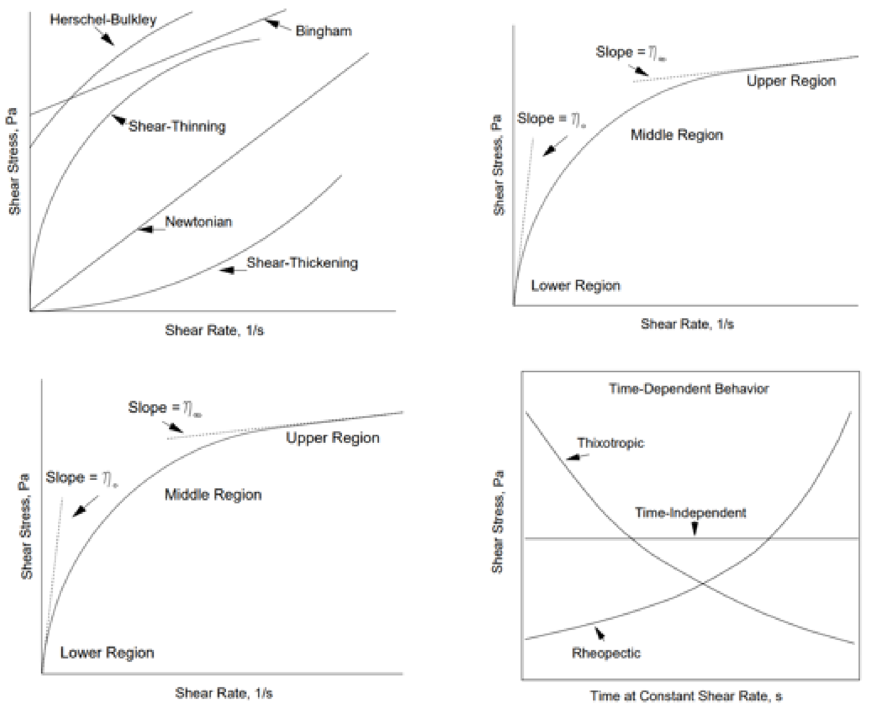

Figure 3: Selected Rheological characteristics curve (Steff, 1996)

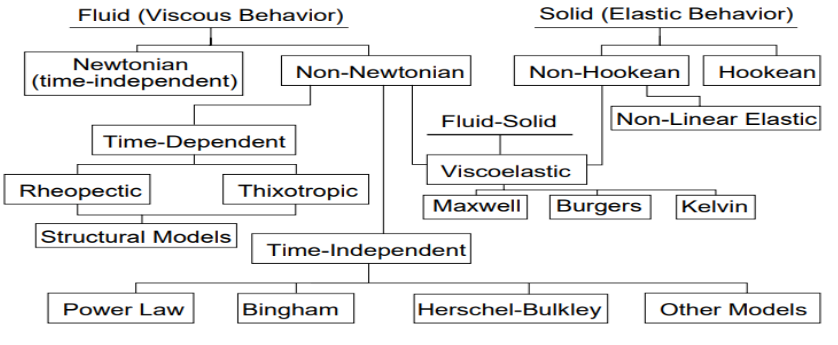

Figure 4: Simple classification of rheological Behaviour, Steff, 1996.

Table 2: Physico-chemical Characteristics of the Sample Sludge Matrix

Sample source	Total Solid (mg/L)	pH	Organic matter (%w/w Dry)	Moisture (%)	COD (mg/L)
Raw Mixed Primary Sludge	26,500	7.34	75	80	35,400

Dewatered Primary Sludge	56,800	7.55	82	67.5	40,300
Anaerobic Digested Sludge (UASB).	50,586	8.01	90	85.8	28,500
Aerobic Digested sludge (Activated Sludge)	12,194	7.85	93	90.5	1,850

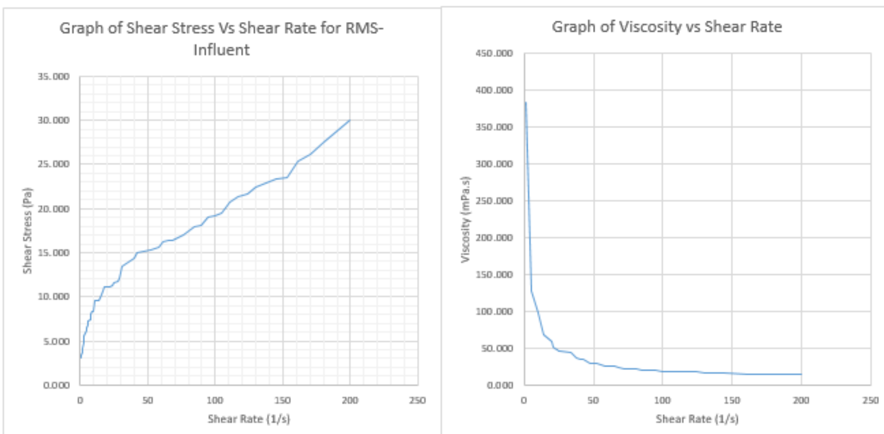

Figure 5: Curves of the Raw Mixed Sludge (Influent).

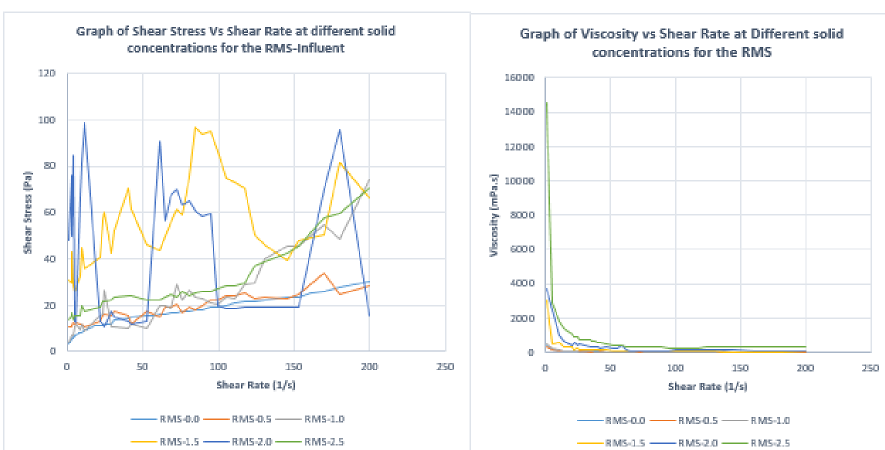

Figure 6: Curves of the Raw Mixed sludge at different solid concentrations

3.2 Effect of Solid on the Rheological Characteristics of the RMS

Generally, the characteristic behaviour of fluids, more specifically, sludge, is highlighted as dependent on the solid concentrations (Akhtar et al., 2021; Bhattad, 2023; Saide et al., 2021). As the solid concentration increased, sludge viscosity increased (Figure 6), and the rheological behaviour began to vary. The solid concentration in the original RMS, which made it non-Newtonian, did not deviate from being non-Newtonian upon increasing the solid concentration. As the solid concentrations of the RMS were increased, the sludge became more viscous, and the required stress to achieve the same shear rate also increased. This behaviour is consistent with earlier works conducted regarding sludge rheology (Hasanzadeh et al., 2023; He et al., 2024). Accordingly, there is a propensity of sludge to exhibit a Thixotropic behaviour with increasing solids concentrations through increased structural deformation (Collivignarelli et al., 2022).

An uneven shear rate ramp line, in addition to constant shear stress across all shear rates, was noted (Figure 6). This was consistent with earlier work by Mercer et al. (2021). Such characteristic behaviour of sludge suggests that the fluid at that point is no longer flowing or fracturing, as mentioned in earlier works (E. Zhang et al., 2021), or undergoing segregation, as highlighted by Das et al. (2022). This unusual characteristic is noted when the original RMS was concentrated with about 2.5g of solids. The high solids additions that lead to this unusual characteristic could also be attributed to the sludge structure's thixotropic breakdown. Noticing that high solid concentrations strongly increase flow resistivity signals, faecal sludge treatment plant operators are advised to monitor sludge solid concentrations in reservoirs. Every sludge has its limit in terms of solid concentrations, where the rheology of the sludge will begin to exhibit different characteristics above such limits (Infusino & Caloiero, 2021). In this regard, to curb such situations when operating a treatment plant, it is important to consistently ensure continuous feeding of the reservoir tanks holding the RMS to ensure dilution, as well as to select appropriate agitators to achieve homogeneity of the RMS in the tanks. This application is likely to prevent solid accumulation, which would lead to flow difficulties and frequent pump breakdowns or reduced pump efficiency during operation. If the pump efficiency does not decline, energy consumption may increase because it must draw more electrical current to deliver the same flow, or it may decrease at high solid concentrations. Continuous pump operation in such situations, without current control units to regulate current, will eventually lead to motor burnout, and maintenance costs will increase due to rheological deformation of the primary sludge.

3.3 Effect of Temperature on the Rheological Characteristics of the RMS

Temperature has a lesser influence on the rheological properties of cellulose nanomaterial (CNM) suspensions than other factors (Rana & Thakur, 2023), whereas sludge has been shown to be highly dependent on temperature (Devos et al., 2021; Z. Wang et al., 2022). Unlike the rheological behaviour of some fluids, which shows very stable rheology upon temperature change from 20 °C to 80 °C, faecal sludge rheology showed great change with temperature variation from 32 °C to 75 °C in this work. It was observed that as the temperature of the RMS increased, the sludge became less viscous (Figure 7), and less stress was required to achieve a significant shear rate. This implies, in contrast to CNM's fluids, which are less dependent on temperature (Anggono et al., 2023), faecal sludge rheology in this work is highly dependent on the temperature, and this is also consistent with earlier works done (Mercer et al., 2021; Rayavellore Suryakumar et al., 2024).

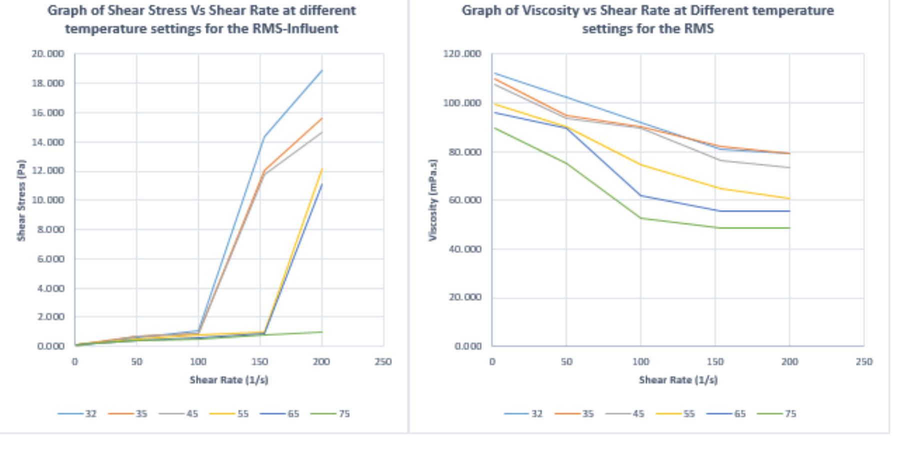

Figure 7: Graph of the Raw Mixed sludge at different temperatures

3.4 Rheological Characterisation of the Dewatered RMS

The rheological details of the raw mixed sludge had been discussed extensively in sections 3.1 to 3.3. In large-scale treatment of faecal sludge, when RMS is dewatered using cationic polyelectrolytes as flocculants, because it is a physical separation process rather than a secondary digestion process, the sludge remains as primary sludge. However, the separation process yields two outputs: thickened dewatered sludge (solid) and leachate (liquid). In typical faecal sludge processing, where dewatering is used to separate the biosolids from the leachate, it is important to understand the transport media of these two process outputs. Understanding the best transport medium to choose or employ cannot be achieved without a better understanding of its rheological properties.

Generally, the viscosity of shear-thinning fluids gradually decreases with increased shear rate and conversely, shear-thickening fluids show increased viscosity with increased shear rate (Rosti & Takagi, 2021). From Figure 8, a gradual decline in viscosity with a respective rise in shear rate was noted. One will be quick to say from the generalisation statement of viscosity versus shear rate that the dewatered sludge is a non-Newtonian shear-thinning fluid. However, a critical look at the shear stress-shear rate curve (Figure 8) for the dewatered sludge reveals two distinct regions. One region is concave, while the other is convex. The concave region has a very high shear stress and a correspondingly low shear rate, around 50 1/s or below, with a clear demonstration of shear-thinning behaviour relative to a standard flow curve of shear stress versus shear rate (Figures 2 and 3) for the fluids. A yield stress point was noted around 95.387 Pa at a respective shear rate of about 55.3 1/s, where a sudden drop of the shear stress took place into the convex region of the flow curve (Figure 8). The drop in the shear stress was from 95.387 Pa to 10.489 Pa. At that low shear stress, soon after the yield stress point, a very high shear rate was obtained, and followed a typical shear thickening property when compared to the standard curve of shear stress versus shear rate for fluids (Figures 2 and 3). This makes the dewatered sludge exhibit two characteristics: shear-thinning at rest, up to the onset of fluidity, and shear thickening after the yield stress. This means that the dewatered sludge exhibits both thixotropic (time-dependent decrease in viscosity) and rheopectic behaviour. Such situations and curves tend to imply that the dewatered sludge sample behaves like a thixotropic fluid with two types of structure (Terashima et al., 2022). The first structure, which is perceived to be the strong structure, is insensitive to shear rate (Figure 8) and serves to define the dynamic yield stress associated with the equilibrium flow curve, while the second structure, which is the weak structure, forms over a certain period of time when the sample is at rest. Combined, the two structures cause a resistance to flow, which determines the static yield stress. Fluids with starch-like or gel-like properties have been associated with such behaviours, being demonstrated by the dewatered sludge, for example, many food products: apple sauce, banana and peach baby food, mustard, tomato ketchup, meat and yeast extracts, as well as margarine (Bist et al., 2024; Lassen et al., 2024; Nguyen, 2025). The gel-like characteristics of the dewatered sludge are due to the polyelectrolyte used in aiding the separation process (dewatering). The formation of the sludge is somewhat gel-like, and when it stays for some time, it begins to undergo deformation by losing the gelatinous nature of its formation, which is why it exhibits the dual structured type of fluid. The use of pumps for transporting such fluids may not be ideal. Therefore, such fluids can better be transported by a conveyor (either chain, belt or screw) system for a continuous storage/disposal process or by a bulk collection container system that will be lifted when full by either a forklift or skip trucks for batch storage/disposal processes.

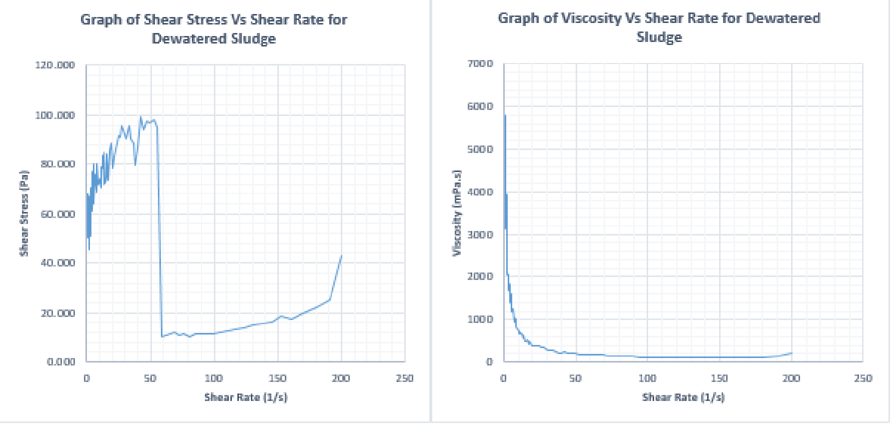

Figure 8: Curves of the Dewatered Sludge

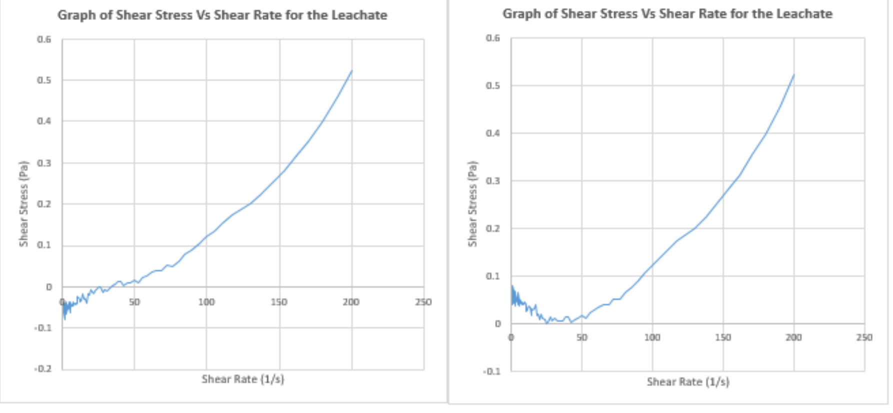

Figure 9: Curves of the Leachate for both with negative and positive shear stress

3.5 Rheological Characterisation of the Leachate from the Dewatering Process

The leachate is the liquid product of the dewatering process and, as a result, contains some flocs or biosolids. These biosolids may flocculate and/or settle in the leachate, depending on the leachate's transport conditions. In fluid rheology, where flocculation and/or sedimentation of particles is possible, the fluid is likely to thicken under shear. This was the case for the rheological information gathered from the leachate sample (Figure 9). But it is important to highlight that, compared with the other samples studied in this work, the leachate sample from the separation process required very low stress to be transported. At the highest shear rate of about 200 1/s, as low as a shear stress of 0.523 Pa was observed; this is a clear indication of a good fluid whose transportation with pumps will be very easy, irrespective of the channel medium (pipes) through which they may be transported. From Figure 9, the rheogram of the leachate is a clear indication of a non-Newtonian shear thickening fluid by comparing it with the standard curve of shear stress versus shear rate for fluids. But the leachate sample, when subjected to shearing, showed no time dependence, unlike the dewatered sludge (Figure 8). This implies that the leachate sample is a time-independent, non-Newtonian, shear-thickening fluid and is characterised as a dilatant fluid.

One deviation from Newton's law observed in real systems is shear thickening behaviour, which arises because the system crystallises under stress and behaves more like a solid than a solution (X. Zhang et al., 2022). Thus, the viscosity of a shear-thickening fluid is dependent on the shear rate. The presence of suspended particles often affects the viscosity of a solution. In fact, with the right particles, even a Newtonian fluid can exhibit non-Newtonian behaviour, and an example of this is corn starch (Chhabra & Patel, 2023). In this work, dewatered leachate from faecal sludge exhibited this characteristic. The parameters that control shear thickening behaviour are particle size and particle size distribution, particle volume fraction, particle shape, particle-particle interactions, continuous-phase viscosity, and the type, rate, and time of deformation (Prabhu & Singh, 2021). In addition to these parameters, all shear thickening fluids are stabilised suspensions with a relatively high volume fraction of solids (Prabhu & Singh, 2021). The leachate obtained from the dewatering process, which uses a polyelectrolyte as a flocculant, behaved as described by Khazaie et al. (2022). The flocculants used make the leachate somewhat starch-like, as mentioned earlier, and some of the biosolids remain in the leachate as suspended particles. The leachate under no deformation or application of shear is a stabilised suspension, but the volume fraction of the suspended bio-solids is moderately low, which is in contrast with Khazaie et al's (2022) assertion. However, the degree of the dewatering process could also result in a leachate with a volume fraction that is relatively high for suspended solids and will still exhibit the same behaviour, just as mentioned by Khazaie et al (2022)

The dominance of shear forces in the leachate caused the particles to flocculate and no longer remain in suspension, increasing the leachate sample's viscosity and causing it to begin to behave like a solid during deformation. This occurrence is consistent with earlier works (Xie et al., 2022). The shear rate at which the fluid transitions from Newtonian flow to shear-thickening behaviour is known as the critical shear rate (Rosti & Takagi, 2021). The critical shear rate here is defined as the shear rate at which the shear forces pushing the particles together are equivalent to the repulsive particle interactions (Edens et al., 2021). The critical shear rate was observed between 19 1/s and 90 1/s (Figure 10). If the flow rate is maintained within this range, the leachate will remain in its original suspension without thickening. However, regarding large-scale treatment of faecal sludge that employs dewatering as one of the quick methods of handling both organic and inorganic constituents in the sludge, with a daily treatment capacity ranging between 1,000 and 3,000 cubic meters, cannot rely on such a low flow rate to maintain leachate formation. This means that thickening of the leachate along the treatment process becomes inevitable.

Given this occurrence, plant operators need to be mindful of the next unit step in the treatment flow following dewatering. If an equalisation tank exists for leachate from the dewatering process, as at the Lavender Hill faecal treatment plant, the tank conditions must be maintained to prevent rapid thickening. The agitation in the tank must not be excessive to prevent thickening. In addition, the leachate retention time in the tank must not exceed 1 day, and continuous feed is required to prevent thickening. It is critical to note that, irrespective of the implementation of such conditions in the equalisation tank, operators must recognise that sludge will build up over time and that this needs to be part of the operational maintenance scheme or plan. The negative shear and negative viscosity observed in some values (Figures 9 and 10) result from repulsive particle interactions that sometimes occur in shear-thickening, dilatant fluids.

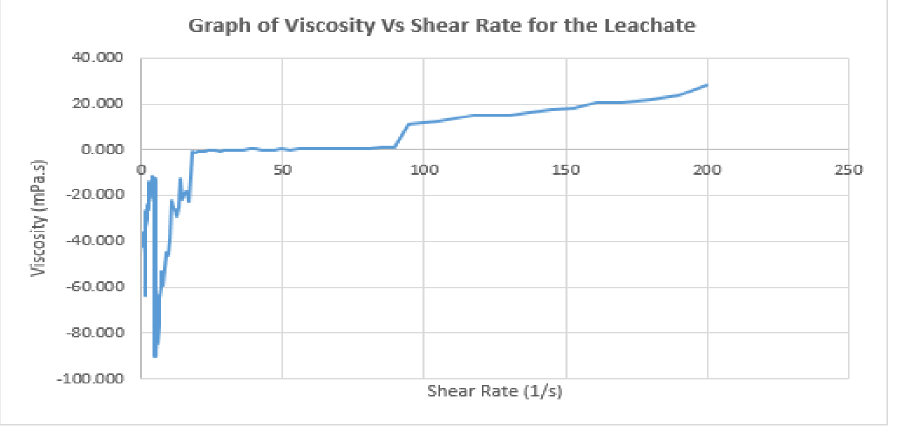

Figure 10: Curve of the Leachate for viscosity vs shear rate

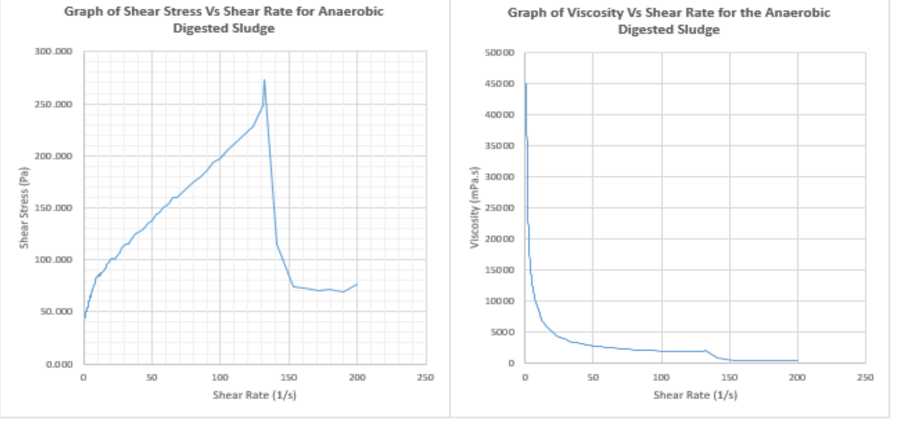

Figure 11: Curves of the Anaerobic Digested Sludge

3.6 Rheological Characterisation of the Anaerobic Digested Sludge (UASB)

In the large-scale treatment plant, after dewatering, the leachate is transported to an equalisation tank before being pumped into the UASB reactors. Arthur et al (2023) Recommended the use of UASB reactors for large-scale treatment of wastewater in Africa. The UASB is an anaerobic biological reactor in which anaerobic digestion generates biogas (methane) with varying compositions due to the activity of anaerobic bacteria. During digestion, sludge is generated. The sludge also contains the microbes that aid in digestion. When the bacteria become inactive, they form part of the sludge at the base of the UASB reactors. Circulation is practised to ensure sufficient contact between bacterial activity and the need to feed into the reactor. By convention, the sludge generated in the reactor, which is mostly found at the base, is thick, smooth, and a bit slimy. This sludge is described as an anaerobically digested sludge due to the conditions under which it was generated.

When the anaerobically digested sludge was subjected to rheological characterisation, the rheogram (Figure 11) showed a trend similar to that observed for the dewatered sludge (Figure 8). A gradual decrease in viscosity, with a corresponding increase in shear rate, was observed for the anaerobically digested sludge (Figure 11). The observed trend in the gradual decline of the viscosity with concomitant increase in the rate of shear is an indication of shear thinning. From the rheogram of the shear stress versus shear rate (Figure 11), within the region of 0 – 141 1/s, a concave curve occurred, while within the region of 141 – 200 1/s, a convex curve was observed. As with the dewatered sludge, the rheogram for the anaerobic sludge also exhibits a concave region at high stress and a convex region at low stress (Figure 11).

The observed yield stress point occurred at 273.24 Pa with its associated respective shear rate of about 132.0 1/s, where a sharp drop in the shear stress took place in the convex region of the flow curve (Figure 11), and it happened between a shear stress of 273.24 Pa and 141 Pa. The gradient, or steepness, of the drop is in excess of 100 Pa of stress for the anaerobically digested sludge, while that for the dewatered sludge is around 85 Pa. The change in drop is more pronounced in the anaerobically digested sludge than in the dewatered sludge. Again, for the dewatered sludge, fluidity began at a shear of about 45.4 Pa at a rate of 1.46 1/s, while for the anaerobically digested sludge, it began at 44.9 Pa at a rate of 1.11 1/s. The conditions for the initiation of fluidity for both sludge is virtually the same for both types of sludge. However, less stress is required (18 – 43 Pa) to achieve high flow after the yield stress point for the dewatered sludge compared (primary) to that of the anaerobic digested sludge (74 – 77 Pa). This implies that, of the two sludges, it would be easier to handle the primary dewatered sludge than the anaerobically digested sludge, and this is consistent with earlier reported work (Odirile et al., 2021).

The anaerobically digested sludge exhibited both thixotropic and rheopectic fluid characteristics, as characterised for the dewatered sludge. Because the UASB reactor is a closed unit of operation (tanks) with sludge settling at the base of the reactors, there is no alternative to transporting the sludge without disturbing the sludge bed other than pumping it to the designated storage. Given this, it is important to size pumps to suit such sludge characteristics, which require high intensity to initiate flow but low intensity once fluidity is established for continuous flow. Regardless of the unit's designed flow rating in the treatment process, high-intensity sludge pumps with shredding or stirring capabilities can be ideal for such situations.

3.7 Rheological Characterisation of the Aerobic Digested Sludge (Activated Sludge)

The viscosity of the activated sludge gradually decreased as the shear rate increased. The flow curve obtained from the viscosity versus shear rate for the activated sludge (Figure 12) does not pass through the origin and also does not exhibit constant velocity. Also, by comparing the results obtained by plotting the curve of shear stress versus shear rate of the activated sludge (Figure 12) with standard non-Newtonian fluid curves, the activated sludge exhibited the characteristics of a Bingham-Pseudoplastic fluid. The rheological characteristics of the activated sludge are similar to those of the RMS; however, it requires less stress to initiate fluidity. This is actually in contrast to the works reported by Ruiz-Hernando et al (2022). This will imply that, except for the leachate, among all the sludge studied in this work, in terms of ease of activation of flow, activated sludge (aerobic digested sludge) is the easiest and anaerobic digested sludge is difficult. The order of fluidity was: Activated Sludge > Raw Mixed Sludge > Dewatered Sludge > Anaerobic Digested Sludge. Except for the activated sludge, the order of fluidity is consistent with the works of Ruiz-Hernando et al (2022).

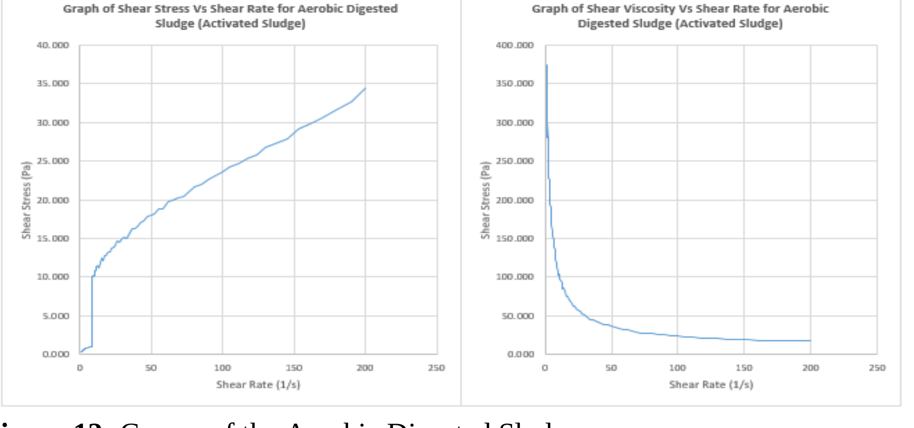

Figure 12: Curves of the Aerobic Digested Sludge

3.8 Rheological Characterisation Scheme for Faecal Sludge Perspective

Faecal sludge's wide variability in solid concentration, high viscosity at rest, profound shear-thinning and high tendency of thixotropic properties and tendency of high-water retention capacity are essential attributes for design criteria and operational optimisation (Rayavellore Suryakumar et al., 2024). However, faecal sludge presents a wide spectrum of characteristics depending on the type (primary or secondary), settling properties and flocculation or coagulation chemistries, which affect the rheology and treatment capability index (Tasnim et al., 2023). It is thus essential to have a comprehensive and accurate Characterisation of the faecal sludge before the design of treatment plants, and also during their operation. Even though the characteristics of faecal sludge vary greatly from region to region, the choice of treatment technology and the shear-induced orientations are critically relevant to the rheological behaviour of faecal sludge. Additionally, the rheological properties of faecal sludge are influenced by the type (primary or secondary), test protocols (e.g., shear rate, temperature, and time), and inherent properties (e.g., solids concentration, viscosity, and age). Regardless of the factors affecting the rheological behaviour of faecal sludge, whether in its fresh or aged form, it remains a non-Newtonian fluid. However, factors like solid concentration, the type of sludge, treatment method or process unit employed make it vary as Pseudoplastic, Dilatant, Thixotropic or Rheopectic (Santos et al., 2022). The rheological characteristics of the activated sludge (Secondary sludge) in this study were similar to those obtained for the RMS (primary), while that of dewatered sludge (primary sludge) was also similar to that of the anaerobic digested sludge (secondary sludge), but the requirement to initiate fluidity varies among each pair of resemblance. Among all the sludges studied in this work, except for the leachate, activated sludge (aerobically digested sludge) is the easiest to activate, and anaerobically digested sludge is the most difficult. The order of fluidity is in the order: Activated Sludge>Raw Mixed Sludge>Dewatered Sludge>Anaerobic Digested Sludge.

3.9 Guidelines for Operational Conditions and Implications

An important characteristic of non-Newtonian materials is the presence of a yield stress, which is the minimum stress required to initiate flow (Coussot & Rogers, 2021). Below the yield stress, a material exhibits solid-like characteristics, which are very important in process design and materials quality assessment (Liu et al., 2024). When a sludge exhibits the characteristics of a Bingham-Pseudoplastic fluid, and the sludge has a very high settling rate due to its physico-chemical characteristics, this will imply that such a sludge should not be stored in reservoirs without continuous agitation. This is to prevent sludge from settling at the bottom of the reactor, as its rheological characteristics may vary during settling. In this case, the yield stress is likely to be higher than expected; therefore, a high resistive force will be required to get the fluid to flow. When such a scenario occurs, pumps used to transport the fluid will begin operating above their normal capacity. Once such an occurrence occurs, the efficiency and lifespan of the designed pumps in use become questionable.

Mixing, however, is achieved by the bulk movement of material caused by an agitator's physical displacement. In this regard, it is crucial to select an agitator for a reservoir that stores RMS. Considering the physico-chemical and rheological characteristics of RMS exhibiting Bingham-Pseudoplastic behaviour, it is important to select agitators that promote top-to-bottom motion, typically by fixing blades at angles less than 90 degrees to the rotation. It is also important to consider the agitator's anchor type, which will require very close clearance between the agitator's impeller and the reservoir tank. This makes the dewatered sludge exhibit two characteristics: shear-thinning at rest, leading to increased fluidity, and shear thickening above the yield stress. This means that the dewatered sludge exhibits both thixotropic (time-dependent decrease in viscosity) and rheopectic behaviour. Such situations and curves tend to imply that the dewatered sample sludge behaves like a thixotropic fluid with two types of structure. The use of pumps for transporting such fluids may not be ideal. Therefore, such fluids are better transported by a conveyor (chain, belt, or screw) system for continuous storage/disposal, or by a bulk collection container system that will be lifted when full by either a forklift or skip trucks for batch storage/disposal.

For sludge that behaves like a Dilatant based on rheological characterisation, the flow of such fluids must be maintained near the critical shear rate; otherwise, thickening of the sludge will be observed. Regarding large-scale treatment of faecal sludge that employs dewatering as one of the quick methods for handling both organic and inorganic constituents, with a daily treatment capacity ranging from 1,000 to 3,000 cubic meters, it cannot operate at such a critical shear rate of flow to maintain fluid formation. This implies that thickening of the leachate throughout the treatment process becomes inevitable. Given this occurrence, plant operators need to be mindful of the next unit step in the treatment flow following dewatering. If an equalisation tank exists for leachate from the dewatering process, as at the Lavender Hill faecal treatment plant, the tank conditions must be maintained to prevent rapid thickening. The agitation in the tank must not be excessive to prevent thickening. In addition, the leachate retention time in the tank must not exceed 1 day, and continuous feed is required to prevent thickening. It is critical to note that, irrespective of the implementation of such conditions in the equalisation tank, operators must recognise that sludge will build up over time and that this needs to be part of the operational maintenance scheme or plan.

Conclusion

The study analysed the rheology of faecal sludge received at the Lavender Hill Treatment Plant, a large-scale treatment plant in Ghana. The sampling matrix was conducted at four (4) treatment sources: Raw Mixed Primary Sludge, Dewatered Primary Sludge, Anaerobic Digested Sludge, and Aerobic Digested Sludge, and their physicochemical parameters were measured according to standard methods. The analysis of the samples revealed that, even though the characteristics of faecal sludge varied greatly from region to region, the choice of treatment technology and the shear-induced orientations of the sludge were found to be critically relevant to the rheological behaviour of faecal sludge. The rheological properties of faecal sludge were influenced by the type (primary or secondary), test protocols (shear rate, temperature and time), and their inherent properties (solids concentration, viscosity, and age). Irrespective of the factors affecting the rheological behaviours of faecal sludge, it remained a non-Newtonian fluid. However, factors such as solids concentration, type of sludge, and the treatment method or process unit employed made it vary as pseudoplastic, dilatant, thixotropic, or rheopectic. The study demonstrated that in-depth knowledge of faecal sludge rheology is essential for faecal sludge treatment plant design, optimisation, and management, and influences the choice and operational conditions of the plant’s processing units, such as agitators, tanks, and transport modes. The authors admit some potential limitations to the study, as the study period spanned six months, encompassing both dry and rainy seasons. However, the quality of faecal sludge is affected by dry and rainy seasons in tropical areas.

Ethics Statement

The study did not involve human participants or animals, and therefore did require ethical approval.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. The corresponding author is responsible for data distribution and can be reached via the email p.a.bowan@dhltu.edu.gh. However, substantial data information on the research is provided in the manuscript.

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Author Contributions

A.I. and P.A.B. Conceptualisation, Data acquisition, Formal analysis, Methodology, Write-up and Visualisation. E.A. Conceptualisation, Resources, Supervision, Validation, Review of write-up. H.M.K.E. Supervision, Validation, Review of write-up. S.O.K. Supervision, Validation, Review of write-up. D.O.A. Data acquisition, Validation. F.C. Resources, Validation, Funds approval.

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