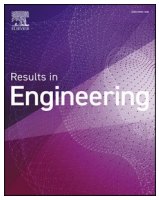
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Research paper

Insight into the stickiness of faecal sludge from dry sanitation technologies: A path toward sustainable and efficient FSM via thermal processes

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ABSTRACT

This study explores the stickiness behaviour of faecal sludge (FS) during thermal drying—an operational challenge that hampers the performance of faecal sludge management (FSM) systems. Samples were collected from ventilated improved pit (VIP) latrines and urine diversion dry toilets (UDDTs) in Durban, South Africa, and analysed using a texture analyser to measure adhesive and cohesive forces over a temperature range of 25–80 °C and moisture contents between 20 and 90 wt. %. Complementary tests were conducted to assess water activity, drying kinetics, rheological properties, and plastic behaviour. Maximum stickiness occurred in the 50–60 wt. % moisture range. In this region, FS transitioned from a viscoelastic fluid to lumpy and plastic consistency dominated by interstitial moisture, and eventually to a granular solid at the end of the sticky region, as interstitial water was depleted. The sticky phase coincided with the transition from the first to the second falling-rate period of drying, reflecting a shift from surface to internal moisture evaporation. Cohesive forces were consistently greater than adhesive forces and increased modestly at 80 °C. UDDT sludge was slightly stickier than VIP sludge under similar conditions. The results highlight the strong dependence of FS stickiness on moisture content and its binding properties. To address this issue, mitigation strategies such as bypassing the sticky range, using bulking agents, or applying pre-treatments could improve drying performance. These findings provide practical guidance for the design and operation of sludge treatment systems and contribute to more sustainable FSM practices.

1. Introduction

The United Nations' Millennium Development Goals, followed by the Sustainable Development Goals (SDGs), have set the target of achieving universal access to basic sanitation. However, as of 2022, 46 % of the global population still lacks adequate sanitation—primarily due to the absence of capital-intensive, centralised sewer infrastructure. In response, increasing attention has been directed toward improving FS management (FSM) within non-sewered sanitation (NSS) systems. A wide range of NSS technologies are documented in the Sanitation Compendium by Tilley et al. [1]. In South Africa, roughly one-third of the population relies on onsite sanitation systems, highlighting the critical need for effective FSM strategies.

A key limiting factor for a successful FSM chain is the moisture content (MC) of faecal sludge (FS). In the eThekwini municipality (Durban metropolis, South Africa), the MC of urine diversion dry toilets (UDDTs) and ventilated improved pit latrines (VIPs) ranges from 70 to 90 wt. % to over 95 wt. % [2]. To move towards economically and environmentally sustainable FSM, the water from the sludge removal must be removed. Firstly, this will reduce transport costs, estimated to represent 25 % of FSM costs [3]. For example, a truck with a capacity of 6000 L can only transport 300 kg of FS in dry basis containing 95 % water [4]. Secondly, faecal solids are a nutrient- and organic-rich resource that offers circular economy opportunities for local communities, with potential for valorisation as compost, soil conditioner, or fertiliser in agriculture, or as a fuel through pyrolysis, combustion, or gasification. Septien et al.[5] identified that dried VIP sludge from the peri-urban areas of eThekwini municipality have an energy density of 17 $MJ.kg^{-1}$ in a dry basis, which is similar to wood, while the nutrient content is comparable to chemically derived fertilisers [5]. Thirdly, removing water from faecal solids through thermal drying inactivates pathogens, including resilient Helminth eggs [6], enabling its safe reuse/disposal.

Current water removal processes include settling-thickening,

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dewatering and drying with the latter option able to reduce the MC of FS to <10 wt. % [7]. However, as the MC of faecally derived matrices decreases, the material becomes sticky. In this state, the material agglomerates into lumps which adhere to surfaces, thereby reducing heat and mass transfer, and requires high shear forces for mixing and conveyance [8–11]. With further drying, the material is no longer sticky, enabling mixing and sliding with minimal shear stress.

Stickiness results from both adhesion (material–surface interactions) and cohesion (interparticle forces). Adhesive stress reflects the force needed to detach sludge from a surface, while cohesive stress relates to the force required to split the material and can be inferred from rheological behaviour. Stickiness is largely governed by the water content and how strongly water binds to solids and surfaces [12]. Temperature also plays a significant role: as it increases, viscosity tends to decrease, potentially reducing stickiness; however, it can also modify the sludge's physical structure and influence water binding, with complex and material-dependent outcomes. The "sticky region"—the moisture and temperature range where stickiness peaks—, also known as the lumpy region, is critical as understanding this zone can enhance drying efficiency [13]. Mapping the distribution of bound water and characterising the sticky phase may help mitigate operational challenges. Stickiness complicates drying by promoting particle agglomeration, disrupting dryer hydrodynamics, and reducing thermal efficiency—primarily due to increased viscosity and concentration of solutes during drying.

Some investigations on stickiness have been conducted using sewage sludge from wastewater treatment plants. Peeters et al.[11] introduced a simple laboratory setup based on the Jenike shear test to assess sludge stickiness. This approach was later applied by Li et al.[14] to evaluate the adhesive and cohesive strength of dewatered sewage sludge and their impact on drying rate and stirring power in an agitated dryer. Their study revealed that stickiness arises from a complex interplay of factors, including organic matter, fine mineral particles, and metal salts, and is closely linked to moisture content. Yoo et al.[15] analysed the factors influencing adhesion in contact dryers and found that the changes in organic matter by increasing temperature during thermal drying contributed to increased adhesion. Li et al. [16] quantified and modelled sludge adhesion by measuring material accumulation on dryer walls. Arlabosse et al.[17] and Ferrase et al. [18] highlighted the effects of stickiness in a paddle dryer with a vertical agitator, noting increased torque requirements during the sticky phase, along with reduced heat flux and evaporation rates. Peeters et al.[12] explored the use of polyaluminium chloride (PACl) to mitigate stickiness, reporting a 35 % reduction in adhesion forces in laboratory tests and a 20 % decrease in industrial agitator torque, with PACl acting as a lubricant between sludge flocs. Deng et al.[19] investigated the influence of calcium oxide (CaO) and sawdust under both agitated and non-agitated drying conditions. In agitated systems, CaO reduced torque, while sawdust increased it; under non-agitated conditions, CaO raised both adhesive and cohesive forces, whereas sawdust primarily increased cohesion. Chen et al.[20] examined the adverse impact of sand on sludge stickiness and assessed pretreatment strategies to counteract this effect. Both CaO addition and ultrasound treatment effectively reduced cohesive and adhesive forces, while sodium dodecyl sulfonate showed efficacy only in reducing cohesion. Finally, Deng et al.[21] investigated the stickiness of sewage sludge following hydrothermal treatment and observed an increase in both adhesive and cohesive properties, primarily attributed to enhanced ash content and particle rigidity resulting from the degradation of extracellular polymeric substances and organic matter. The increase in stickiness was most strongly associated with higher CaO content, which emerged as the dominant factor influencing both adhesive and cohesive properties.

There is limited knowledge on the stickiness of FS and the related physical properties. Apart from sewage sludge, one study has been done to measure the adhesive yield stress for fresh faeces [10]. Although faecally derived, FS is distinct from fresh faeces and sewered wastewater sludge due to differing degrees of degradation which tends to be more anaerobic and often exclusive of greywater. To the best of the authors' knowledge, no studies have yet documented the relationship between the binding of water to the solid phase and the resulting stickiness as FS transitions from a slurry to a granular product, nor have standard analytical methods been established to characterise its stickiness behaviour. With improved knowledge on FS stickiness, the operation and maintenance of pit emptying devices, conveyance systems and treatment systems equipment could be improved and the costs consequently reduced [22], thereby making sanitation systems significantly more affordable and durable. These improvements can enhance service reliability and access for communities relying on NSS. Importantly, they can contribute to gender equity by reducing the disproportionate burden faced by women and girls, who are more vulnerable to health, safety, and dignity challenges linked to inadequate sanitation. Ensuring functional, affordable, and well-maintained systems thus plays a critical role in supporting inclusive and equitable sanitation services.

This study explores the stickiness of FS and its key physical properties to inform the development of efficient thermal treatment technologies, with a particular focus on thermal drying. The objectives are to: (i) map the sticky phase of FS by measuring adhesive and cohesive forces across a range of moisture contents and temperatures; (ii) evaluate physical properties that influence drying performance, including consistency, rheology, and drying kinetics; and (iii) examine the influence of bound water on stickiness and related material behaviour. The research centres on FS collected from ventilated improved pit latrines (VIPs) and urine diversion dry toilets (UDDTs), which are widely used in the eThekwini municipality, South Africa. In this region, approximately 45,000 VIPs and 85,000 UDDTs are in operation, underscoring the importance of effective sludge treatment solutions. This research was approved by the UKZN Biomedical Research Ethics Committee (reference number: BREC/00,000,204/2019).

2. Materials and methods

2.1. Sample collection and preparation

FS samples were collected from ventilated improved pit (VIP) latrines and urine diversion dry toilets (UDDTs) within the eThekwini Municipality (Durban metropolis, South Africa). Sampling took place at the FS treatment facility in Isipingo, which received sludge from a broad network of onsite sanitation systems, primarily from surrounding areas such as Folweni and Makhutha (Fig. 1). Durban experiences a subtropical climate with peak rainfall typically occurring between January and March, averaging around 130–140 mm per month during this period, and an annual average of approximately 1000 mm. The water table in the region typically ranges between 1.5 and 4 m below ground level, depending on location and season. The majority of UDDT and VIP latrines in the municipality are fully lined, which limits the ingress of both groundwater and surface rainwater, thereby helping to limit wetting of the sludge. Additionally, at the treatment plant, sludge is stored in covered areas to prevent exposure to rainfall and maintain its original moisture characteristics prior to analysis.

The eThekwini Municipality was responsible for maintaining and servicing the sanitation systems, including the collection and transport of FS, all provided free of charge to users. Scheduled emptying intervals were approximately five years for ventilated improved pit latrines (VIPs) and two years for urine-diverting dry toilets (UDDTs), meaning the age of the sludge at the time of emptying typically ranged from 0 to 5 years for VIPs and from 0 to 2 years for UDDTs. Pit emptying was typically performed manually, using tools such as shovels and pitchforks, without the use of water.

Upon delivery to the treatment facility, the FS was deposited into heaps and stored for up to three months prior to further processing. As the sludge originated from multiple locations, it was naturally mixed during storage. Grab samples collected from this mixed material were therefore considered representative of FS from the broader region.

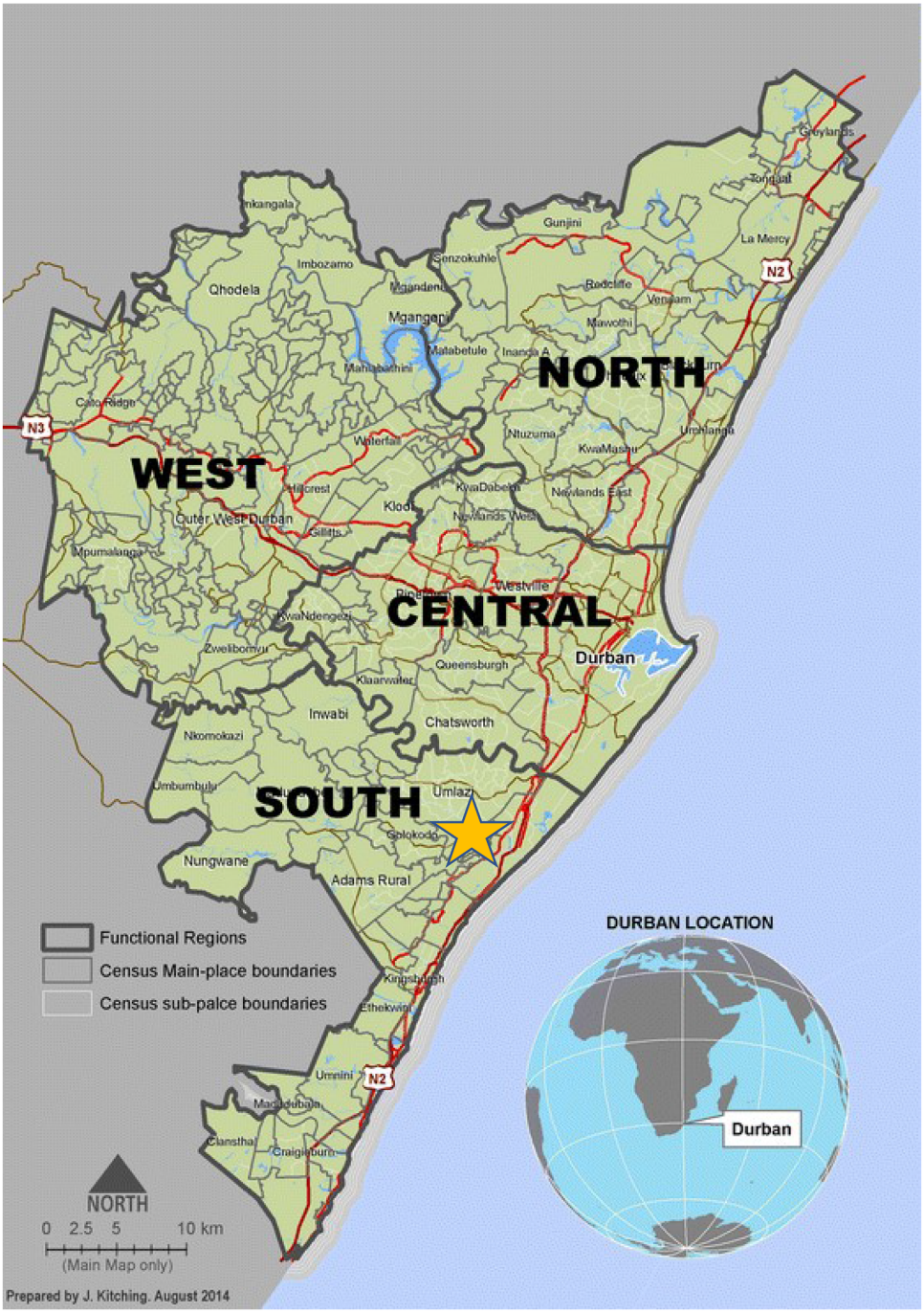


Fig. 1. Map of the eThekwini Municipality in South Africa, showing its five functional regions (North, South, Central, West, and Outer West), with the location of the Isipingo faecal sludge treatment plant marked with a yellow star.

Approximately 20 kg of sludge was manually sampled from the piles using shovels and stored in sealed buckets for subsequent analysis.

After transport of the samples to the laboratory, the samples were screened using a 5 mm mesh to remove household solid waste, as the sludge often contained a high load of non-biodegradable solid waste—such as plastics, textiles, glass, metal, and batteries—due to the frequent misuse of sanitation facilities for waste disposal. Subsequently, the samples were stored in a cold room at a temperature of 4 °C to prevent microbial activity and preserve their physico-chemical properties. The sampling, handling and laboratory analysis followed the standard methods for FS analysis [23]. Initial analysis of the physico-chemical properties of the VIP and UDDT samples include total and volatile solids using the oven drying method (overnight at 105 °C) and ignition in a muffle furnace (2 h at 550 °C) respectively (Table 1). Conductivity and pH were measured using a probe (*Hach MM150*).

The moisture contents (MC) of the samples were modified to represent a range of MCs during drying with the higher MCs (80 and 90 wt. %) achieved by adding distilled water. The lower MCs (< 80 wt. %) were achieved by evaporating water from the sample in an oven at 105 °C and manually mixing the sample for 5 min with a stainless-steel rod every 25 min. Mixing was done to ensure sample homogeneity and to avoid crust formation. At each mixing interval of time (25 min), the MC of the samples was measured using a thermal balance (Radwag max 50). The final MC was confirmed through the standard method in triplicate, i.e. drying the sample in an oven at 105 °C for 24 h [23].

Table 1
Characteristics of the urine diversion dry toilet (UDDT) and ventilated improved pit latrine (VIP) raw faecal sludge samples.

Characteristics	UDDT	VIP
Moisture content (wt. %)	71	74
Volatile solids (wt. %)	23	20
pH	7.7	7.9
Electrical conductivity (mS cm^{-1})	5.6	5.8
Trash	Mainly newspaper, small pieces of aluminium packages and plastic	Mainly newspaper, small pieces of hair and plastic

2.2. Stickiness tests

The stickiness of the samples was investigated using a texture analyser (*TA.XT ExpressC*, Sable Micro Systems, Surrey, UK) with a piston (*P7 compression platen, 5*75 mm diameter with a contact area of 4417.86 mm^2). This analytical instrument has been validated in the food industry, for example for the stickiness of flour doughs [24], and has been adapted for FS [23].

FS (100 g) was levelled in a stainless-steel petri dish (80 mm diameter and 80 mm depth), which was locked on the texture analyser and programmed for compression and tension modes, which allows to measure the cohesive bulk and surface adhesion forces, respectively. The tests were conducted on FS of varying MCs from 20–90 wt. % and temperatures at 25, 40, 60 and 80 °C, to replicate a drying process.

In the compression mode, the piston compressed the sample by 5 mm at a speed of 2 mm/s and the apparatus measured the force applied to the sludge. In the tension mode, the piston compressed the sample until the texture analyser read overload, which represented maximum compression. The piston then pulled away from the sample by 10 mm then recompressed the sample at 3 mm/s and returned to its initial position at the surface of the sample.

Experiments were replicated at least four times using different subsamples. The results were given by the apparatus software to determine the maximum force required to separate FS from the probe (a measure of adhesion) and compress the sample (a measure of cohesion). In this study, overall stickiness was considered as the sum of two contributions, adhesive force (negative) and the cohesive force (positive).

Temperature was controlled at ambient, 40 °C, 60 °C, and 80 °C using an oven for heating and a water bath for temperature maintenance. Foil-covered samples were heated in the oven to the target temperature, monitored via Type-K thermocouples inserted into the sludge and connected to data loggers. The foil prevented evaporation, ensuring consistent moisture content during testing. Once the target temperature was reached, samples were transferred to a slightly hotter water bath to compensate for heat losses, with continuous temperature monitoring in both the bath and the sludge.

2.3. Rheology

Rheological properties were measured using a rotational rheometer (*MCR72*, Anton Paar, Midrand, South Africa) fitted with a *BMC 90* cup and *ST59–2V-44.3/120* vane, a setup suitable for large-particle slurries like FS [25] and fresh faeces [10]. Shear rates ranged from 0.1 to 100 s^{-1}, with torque between 1 and 200 nNm. Shear stress, viscosity, and yield stress were calculated by the rheometer software from the measured torque. Each test used 150 g of sample and was replicated three to five times using subsamples.

Tests were limited to samples with 70–90 wt. % moisture content, as higher solids concentrations lead to a non-flowable material, consistent with previous findings [10,25]. Sample temperatures (25, 40, and 60 °C) were maintained using the integrated Peltier Plate (*P-PTD200/80/l*, 80 mm). For tests at 40 and 60 °C, foil-covered samples were preheated in an oven. Tests could not be conducted at 80 °C, as this temperature exceeded the operational limit of the rheometer's integrated heating system.

2.4. Consistency characterisation

A manual cone penetrometer was used to determine the liquid and plastic limits, as well as the shear strength of faecal sludge, following a method adapted from soil consistency testing [26,27]. Penetration depths were read manually. The plastic limit was measured using a 240 g pre-weighed stainless steel cone, and the liquid limit with an 80 g cone. Limits corresponded to the moisture content at which the cone penetrated 20 mm into the sample. All tests were conducted in triplicate.

Using the liquid and plastic limits, the plasticity index of the FS can be determined as the difference between the limits (Eq. (1)). This parameter is a measure of the cohesive properties of the FS and an indication of the extent of swelling or shrinkage of the FS. The higher the plasticity index, the more internal cohesive forces the FS has.

$$Plasticity\ Index = Liquid\ limit\ (LL) - Plastic\ limit\ (PL) \tag{1}$$

The liquidity index measures the FS MC relative to plasticity. As given in the study of soils, if the liquidity index value is between 0 and 1, then the soil will behave similarly to plastic material. If the value of the liquidity index exceeds one, the soil will behave like a liquid. The same principles were adopted for FS. The liquidity index of the sludge can be calculated by Eq. (2).

$$Liquidity\ Index = \frac{(Sample\ moisture\ content - Plastic\ Limit)}{(Liquid\ limit - Plastic\ Limit)} \tag{2}$$

Shear strength is defined by the plasticity index to solids concentration ratio of a material. According to O'Kelly [28], the shear strength of sewage sludge increases with solids concentration, due to a high organic content and colloidal activity. Increased colloidal activity indicates that the sludge particles have a high surface area to mass ratio. Therefore, interparticle bonding is more pronounced, facilitating cohesion between the solid particles. The shear strength (S_{ur}) was calculated by Eq. (3):

$$S_{ur} = \frac{k \times Q}{h^2 \times 1000}\left[\frac{kN}{m^2}\right] \tag{3}$$

Where: k is the drop cone factor (1.33), Q is the force of the cone (0.79 N), h is the penetration reading from the cone penetrometer (m) and 1000 is the conversion from N to kN. Plasticity governs the shear strength.

Sludge activity indicates a materials capacity to retain water, thereby influencing swelling and shrinkage behaviour [29]. It is the ratio of plasticity index to solids fraction as a percentage as given in Eq. (4):

$$Sludge\ Activity = \frac{Plasticity\ Index}{\%total\ solids\ of\ the\ faecal\ sludge} \times 100 \tag{4}$$

2.5. Sorption isotherms

The unbound and bound water of the FS was inferred through the measurement of water activity. Water activity was analysed for samples within a MC range of 20–90 wt. % at ambient temperature using a water activity meter (*Tunable Diode Laser*, Aqualab). An aliquot (5 g) was placed in a sealed chamber. In the headspace of the sealed chamber, a radiation beam was emitted by the tuneable laser at a wavelength range corresponding to the water absorption band and a detector measured the incident radiation, allowing to determine the relative humidity. At thermodynamic equilibrium, the relative humidity of air in the chamber headspace is equal to the water activity of the sample.

2.6. Drying kinetics

The FS samples were dried at 40, 60, and 80 °C in a moisture analyser (Max *50*, Radwag, Radom, Poland). The moisture analyser allowed for the continuous measurement of mass over drying time, in 30 s intervals until there is no further loss in mass. The initial average masses were 2.17 g and 3.45 g for the UDDT and VIP samples respectively, corresponding to a surface area of 4286.46 mm^2. These tests were carried out with the original sludges without moisture content alterations. The drying rate was determined by Eq. (5):

$$Drying\ rate = \frac{\Delta m}{A \times \Delta t} \times 100 \quad (5)$$

Where Δm is the difference of mass between two consecutive measurements (g), Δt is the time difference between two consecutive measurements (min), and A is the area of the sample being dried (mm^2). Both water activity and drying rate analysis were triplicated using subsamples from the main sample.

3. Results and discussion

3.1. Stickiness of FS

Fig. 1 illustrates the impact of moisture content on the adhesive and cohesive stickiness yield stress of VIP latrines and UDDT sludge. It is noteworthy that replicate tests were evaluated using analysis of variance (ANOVA), which showed no significant differences in either adhesive ($p = 0.90$) or cohesive ($p = 0.86$) properties.

FS stickiness was influenced by moisture content. The sticky phase of VIP and UDDT sludges was identified to be between a moisture content of 30–70 wt. %. The cohesive and adhesive forces peaked at 60 wt. % and 50 wt. % for VIP and UDDT, respectively (Fig. 2a–d). At ambient temperature, both the adhesive and cohesive forces increased by a factor of ~1.5 for every 10 % decrease in moisture content within the sticky region until the sticky peak after which the adhesive and cohesive forces decreased. This sticky phase was observed across all tested temperatures for the two sludge types. Both the adhesive and cohesive forces of the sludges increased until reaching a peak and then decreased with the UDDT sludge showing higher values of adhesive and cohesive forces than VIP sludges. This results could indicate that UDDT sludge was somewhat stickier than VIP sludge.

The sticky region was within a similar range to other faecally derived materials such as sewage sludge at MCs of 30–60 wt. % [15], 30–70 wt. % [14], 40–70 wt. % [16], 40–65 wt. % [19], 30–45 wt. % [30], 50–62 wt. % [31], 35–60 wt. % [32], 43–69 wt. % [18], 45–60 wt. % [11], and fresh faeces at 50–70 wt. % [10]. However, the sticky peak of FS observed in this study was significantly higher than those reported for other faecally derived materials (Fig. 3). For instance, the cohesive shear stress of FS reached 25,000–30,000 Pa, up to five times greater than that of dewatered sewage sludge, which ranged from 7000–8000 Pa [14,19]. Similarly, the adhesive peak of FS was several times higher than values reported for activated sludge [11], dewatered sludge [14,19], and fresh faeces [10], which ranged from 2000–4000 Pa, compared to 6000–18,000 Pa in this study.

It is interesting to note that the cohesive forces were substantially higher than the adhesive forces, indicating that sludge stickiness was primarily driven by internal cohesiveness. For both UDDT and VIP sludges, cohesive forces were up to four times greater than adhesive

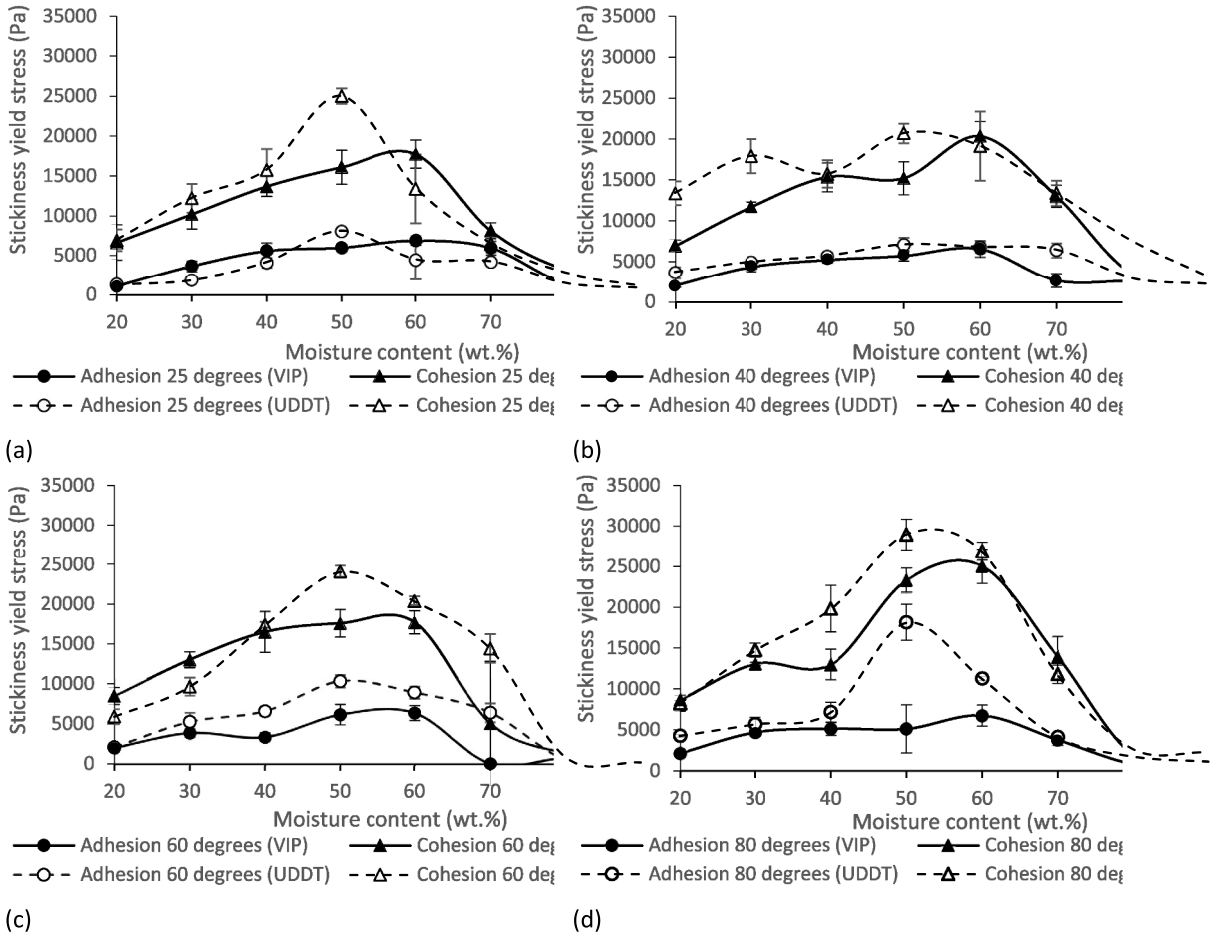


Fig. 2. Impact of moisture content on the adhesive and cohesive stickiness yield stress of VIP and UDDT FS at (a) 25 °C,(b) 40 °C,(c) 60 °C and (d) 80 °C.

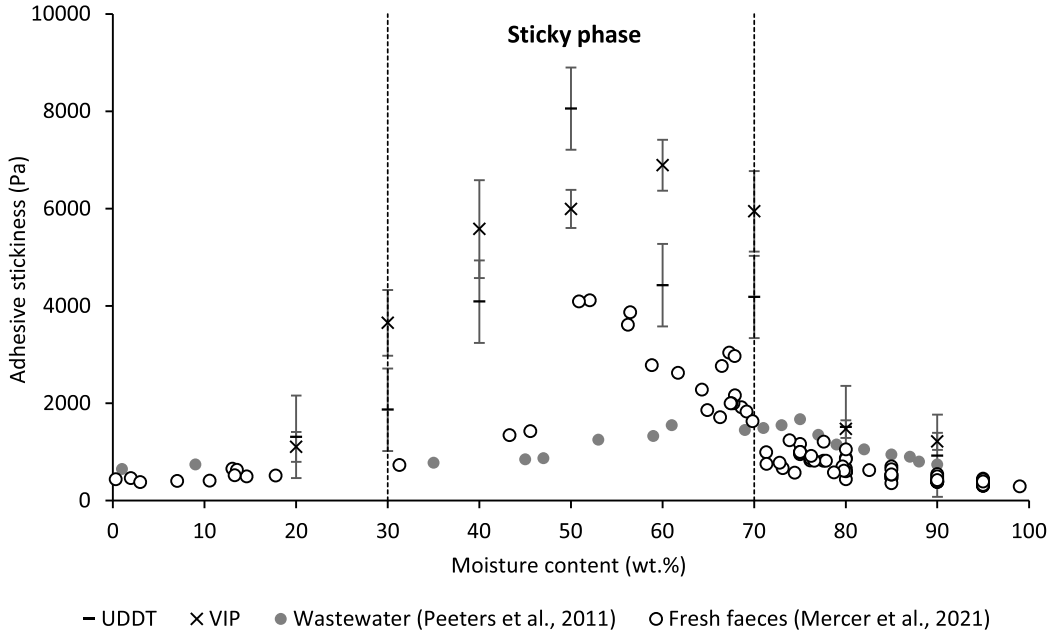


Fig. 3. Comparison of adhesive stickiness at ambient temperature for UDDT FS, VIP FS, wastewater sludge and fresh faeces.

forces—a trend consistent with previous observations for sewage sludge [14,19]. Regarding the effect of temperature, the sticky peak occurred at approximately the same moisture content across all tested conditions. However, for UDDT sludge, both adhesive and cohesive forces were slightly higher at 80 °C compared to lower temperatures. In contrast, VIP sludge exhibited an increase in cohesive force at 80 °C, while adhesive force remained largely unaffected. These results suggest that raising the temperature above 60 °C leads to a modest increase in overall stickiness shear stress, without shifting the sticky peak moisture content. A similar trend was reported by Yoo et al. [15] and Li et al. [16], who observed increasing stickiness with temperature from 80 °C to 180 °C. However, another study [14] found that, while cohesive and adhesive forces remained relatively constant between 120 °C and 200 °C, the sticky peak shifted with moisture content. Furthermore, Chen et al.[20] observed a decrease in both cohesive and adhesive forces as temperature increased, although their sludge contained 30–70 % sand, which likely altered its mechanical properties. In that study, adhesion exceeded cohesion—an atypical result, likely due to the influence of sand content.

When considering faecal sludge from other geographical locations, it is possible—though not assured—that the sticky region may fall within 30–70 wt. % moisture content (MC), with the sticky peak occurring somewhere around 40–60 wt. % MC, as observed in this study. However, these ranges are likely to vary depending on local sludge characteristics and treatment practices. The magnitude of cohesive and adhesive forces may also differ considerably depending on the type of sanitation system. Sludges from dry systems might exhibit cohesion and adhesion values similar to those reported here, whereas sludges from wet systems—such as septic tanks potentially mixed with greywater—could show lower stickiness, akin to sewage sludge. Moreover, the presence of materials such as sand, ash, or lime (CaO), which are commonly found in on-site sanitation systems, can significantly alter stickiness behaviour. Therefore, stickiness characteristics cannot be generalised across all sludge types. Variations in degradation levels, the organic and mineral composition, and the presence of specific additives make it essential to characterise the sticky phase individually for each sludge type.

3.2. Sorption isotherms

Fig. 4 illustrates the characterisation of bound water zones of UDDT and VIPb sludge types using water activity measurements at ambient temperature. Indeed, stickiness is influenced by the amount of water in the material and its binding strength to the solid phase and surfaces [12], which can be inferred by the water activity (aw) of the material to analyse. Values around 1 indicate free water and lower values represent an increasing water binding strength to the solid phase. A water activity of ~ 1 for both UDDT and VIP at ambient temperature was observed between 70–90 wt. % MC, demonstrating that stickiness was not observed when water was unbound, which was probably acting as a lubricant. It is worth noting that the raw sludge was positioned at the limit between unbound and bound moisture, indicating that the proportion of unbound moisture was either negligible or very limited (<18 % of total moisture content).

The sticky phase commenced when the unbound water was removed from the matrix causing the flocs and particles to approach, leading to the formation of interstices and capillaries where water was trapped. This was illustrated by the a_w values gradually decreasing from 1 a_w at 70 wt. % MC to ~0.96 a_w at 40 wt. % MC. According to the sorption isotherm theory, this zone represents interstitial water, where water is trapped within the sludge flocs and bound by osmotic and capillary forces [33]. As moisture was removed in the interstitial zone, the capillaries became smaller, leading to higher cohesiveness, until arriving to a peak (sticky peak). From this point, the water from capillaries was the most likely replaced by air as further moisture was removed, leading to the decrease of the cohesiveness until the material became granular solid after removing most of the interstitial moisture [34,35]. In this state, the tensile strength of the material increases and has reported to be three times than that of the dry lumps [34]. Below 40 wt. % MC, the water activity gradient steepened to infer vicinal water on the surface of the solid particles, bound by adsorptive forces [30]. Vicinal bound water is then located in the end of the sticky phase, where the sludge loses most of its interstitial moisture and air has replaced water in the interparticle spaces. leading to a material with poor wettability, and the cohesive and adhesive forces decrease until the material is no longer sticky [34]. These bound water regions agree with the findings of Getahun et al., [7]

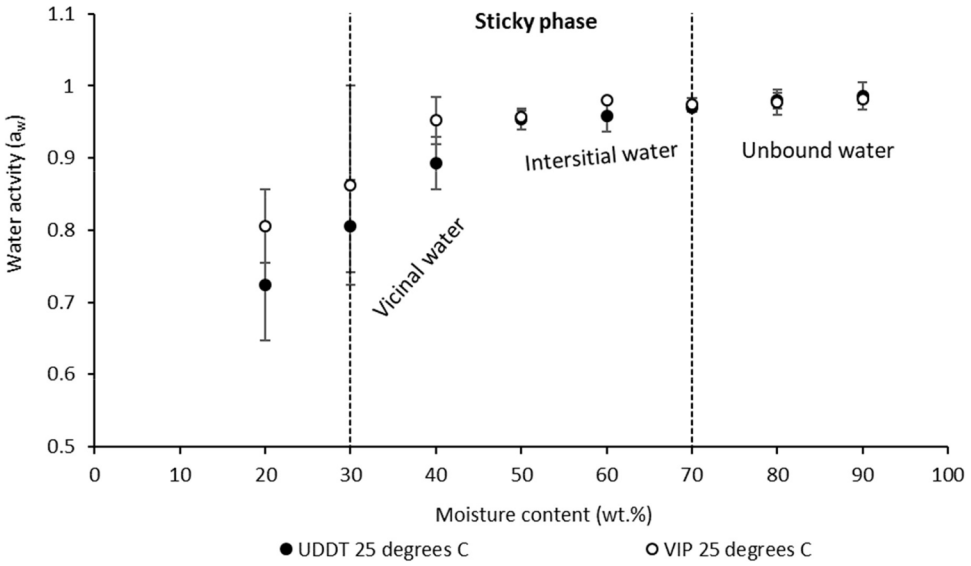


Fig. 4. Characterisation of bound water zones of UDDT and VIP sludge types using water activity measurements at ambient temperature.

who mapped VIP, UDDT and anaerobic baffle reactor (ABR) sludge. Importantly, this study has identified that mapping bound water can be used as an indicator of the sticky regions of FS.

Note that the internal water region, corresponding to the water bound chemically or biologically to the solid (e.g. water of hydration or intracellular water) was not observed in our results. Usually, this region is found at very low moisture content (<20 % wt).

3.3. Drying kinetics

The drying rates of UDDT and VIP sludge were assessed as a function of moisture (Krischer curve) at different temperatures (Fig. 5a and b). A decrease in drying rate occurred as water was removed and became increasingly bound to the solid phase. The drying kinetics increased with temperature as expected [7]. The drying rate decrease trend was most prominent at 80 °C where the drying kinetics were at their greatest and changes in gradients were more evident. For both sludge types (Fig. 5a and b), the drying rates decreased gradually at a constant rate as the moisture content approached the sticky peak at 1–1.5 g/g (50–60 wt. %). This corresponds to the first falling rate period where drying occurs at the external surface of the sludge, which is unsaturated in moisture because the mass transfer of water from the core of the material to the surface, driven mainly by capillary flow, was not sufficient to replace the water evaporated [8]. In this region, the drying rates were slightly greater for UDDT than VIP sludge, which could be related to differences in the sludge capillary structure, leading to different mass transfer rates and sticky behavior (as discussed in 3.1). The declining drying rate gradient steepened from the sticky peak, leading to the second falling rate period where the material surface was completely dried at the surface and drying occured from within the bulk material, suggesting the replacement of interstitial water by air and creation of pores with an overall decrease of the sludge cohesiveness, leading to the transition to a granular solid [8]. During the second falling rate period, most of the remaining water was adsorbed at the surface of the sludge particle in multi-layers according to the sorption theory (i.e. vicinal water), implying that drying occurred at the particle surface level.

A constant rate period, where drying occurs at the surface of a material saturated in water (encompassing unbound water zone), was not observed in this study, as drying commenced at the original MCs close to the interstitial water zone at 70 wt. % MC (UDDT: 71 wt % MC, VIP: 74 wt. %).

3.4. Rheological properties

The effect of moisture content on rheology was investigated on samples of 70, 80 and 90 wt. % MC at different temperatures (25, 40 and 60 °C). The rheological properties of the samples with a moisture content below 70 wt. % were not investigated as the material showed an inability to flow through signs of fracturing and segregation as similarly observed for fresh faeces at 68 wt. % MC [10]. This marks the start of the sticky zone where the sludge flocs start to clump together instead of behaving as a uniform solids network, highlighting the negative impact of stickiness for sludge pumping, stirring and transport. After this point, sludge can no longer flow as a fluid and relies on overcoming the adhesive stickiness to enable sliding (Fig. 3).

Fig. 6 shows comparison of viscosity as a function of shear rate at varying temperatures and moisture contents. Both the VIP and UDDT sludge types showed shear thinning behaviour through a decrease in viscosity with increasing shear rate (Fig. 6a and b). This behaviour was similar in literature for VIP FS, fresh and aging faeces [10,25,36]. Viscosity and shear yield stress for both sludge types increased exponentially with solids concentration (Figs. 6, 7 and S1), as also reported by Septien et al.[25], Mercer et al.[10] and Chatema et al. [36] for VIP sludge, fresh faeces and aged faeces respectively. The increased solids concentration caused the sludge particles to approach, strengthening interparticle bonds and therefore cohesive strength (Fig. 2). Fig. 7 illustrates the comparison of yield stress values at ambient temperature for UDDT sludge, VIP sludge, fresh faeces and aged faeces. The yield stress values of the UDDT sludge demonstrated a yield stress close to aged faeces simulating UDDT conditions [36], while VIP yield stress values from this study corresponded to the higher values of VIP sludge of a study by Septien et al.[25].

Although increasing temperature has been reported to decrease sludge viscosity [21,37], temperature range did not influence rheological behaviour under the explored conditions. The absence of a temperature effect could have been attributed to the relatively narrow temperature range for the rheology tests (up to 60 °C). As observed in the stickiness results, temperature-related changes only became apparent at 80 °C—a threshold that may also apply to rheology. However, measurements at 80 °C were not possible due to the operational limits of the rheometer's integrated heating system. To overcome this limitation, future studies should consider using external heating systems in the current rheometer or alternative rheometry setups capable of operating above 80 °C, which would enable a more accurate

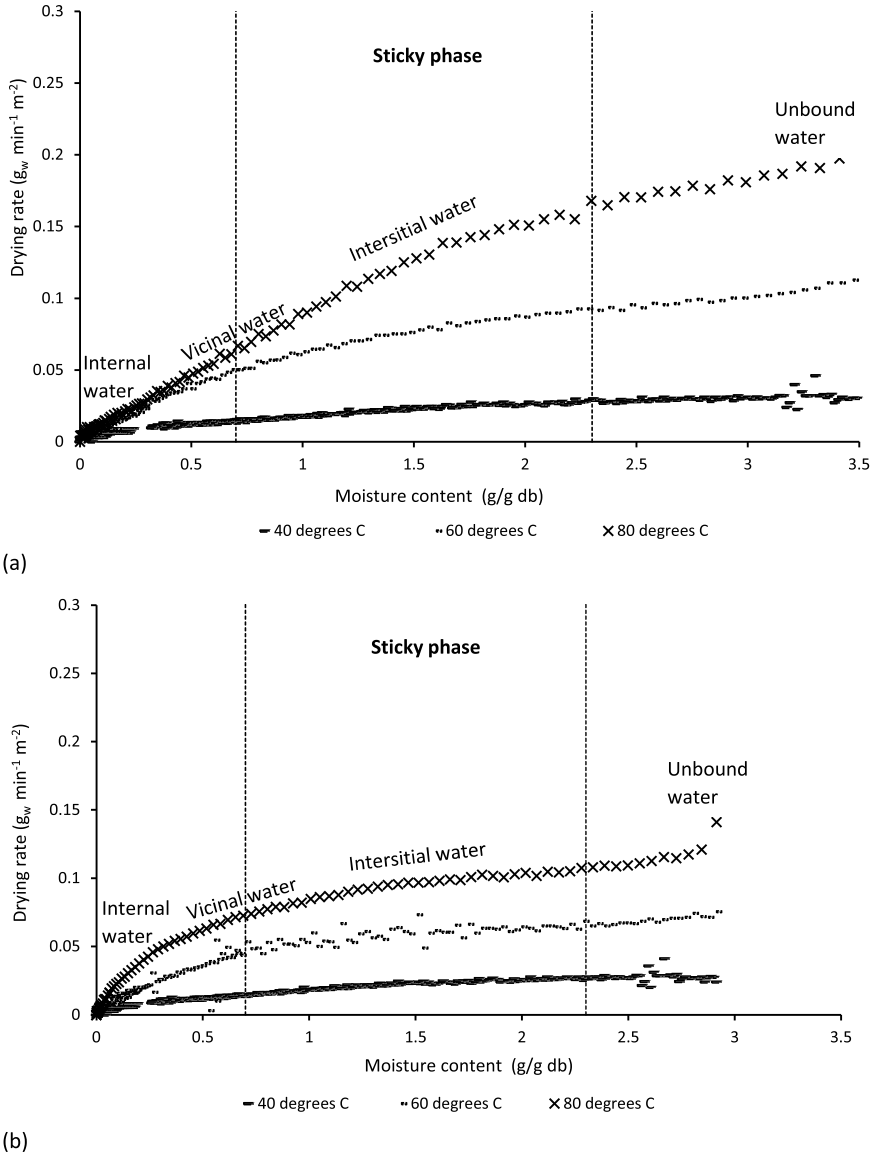


Fig. 5. Drying kinetics at 40 °C, 60 °C and 80 °C of (a) UDDT and (b) VIP sludge types.

characterisation of temperature effects on sludge rheology.

3.5. The Atterberg limits of FS

The Atterberg limits for VIP and UDDT sludge were investigated to characterise variations in consistency across a moisture content profile. Table 2 gives the Atterberg limits for VIP and UDDT sludge types. The liquid limit is the moisture content at which a material transitions from exhibiting plastic behaviour to liquid behaviour, while the plastic limit is the minimum moisture content at which a material exhibits plastic behaviour, below which the FS fractures [38]. The plastic limit for VIP and UDDT sludge types were 57.9 wt. % and 48.6 wt. % MC respectively, whereas the liquid limits were 77.5 wt. % and 67.2 wt. % MC for VIP and UDDT, respectively (Table 2). These limits were close to the results reported by Septien et al., [25], and the differences were regarded to be from the variation of the characteristics of the FS. The sticky peak of both sludge types (VIP: 60 wt. %, UDDT 50 wt. %) corresponds to the plastic limits observed (Fig. 2 and Table 2), while the liquid limits correspond to the moisture content above which the material exhibits "liquid behaviour" acting as a viscoelastic fluid with shear-tinning characteristics (Fig. 4). The sticky region starts when the sludge loses its liquid behaviour (loss of its flowability and complete removal of its unbound moisture), and the sticky peak occurs when the material becomes plastic. Therefore, the stickiness marks the transition from a viscoelastic to a solid material passing through an intermediary plastic behaviour.

The plasticity index is a measure of the cohesiveness of sludge [29]. Ventilated improved pit latrine sludge has a slightly higher plasticity index value than UDDT sludge (VIP = 19.59, UDDT = 18.65) which could explain the higher shear yield stress values (Table 2 and Fig. 7).

The liquidity index compares the sludge moisture content relative to its plasticity. The liquidity index is a measure that scales the water in the sludge to the plastic and liquid limits. For UDDT and VIP sludge types, the liquidity index was close to 1, implying that the sludge was almost at its liquid limit at its initial moisture content, agreeing with the liquid limit values that were measured. The sludge activity (the ration of plasticity index to solids fraction assessing the capacity of sludge to hold water) of both VIP and UDDT was relatively high, inferring a large capacity to retain water and thus prone to swelling and shrinkage. In fact, high activity soils (> 150 %) show large variations in volume [29]. FS shows variations in volume, noted mostly as shrinkage during drying, in our case particularly during the first falling rate period where drying

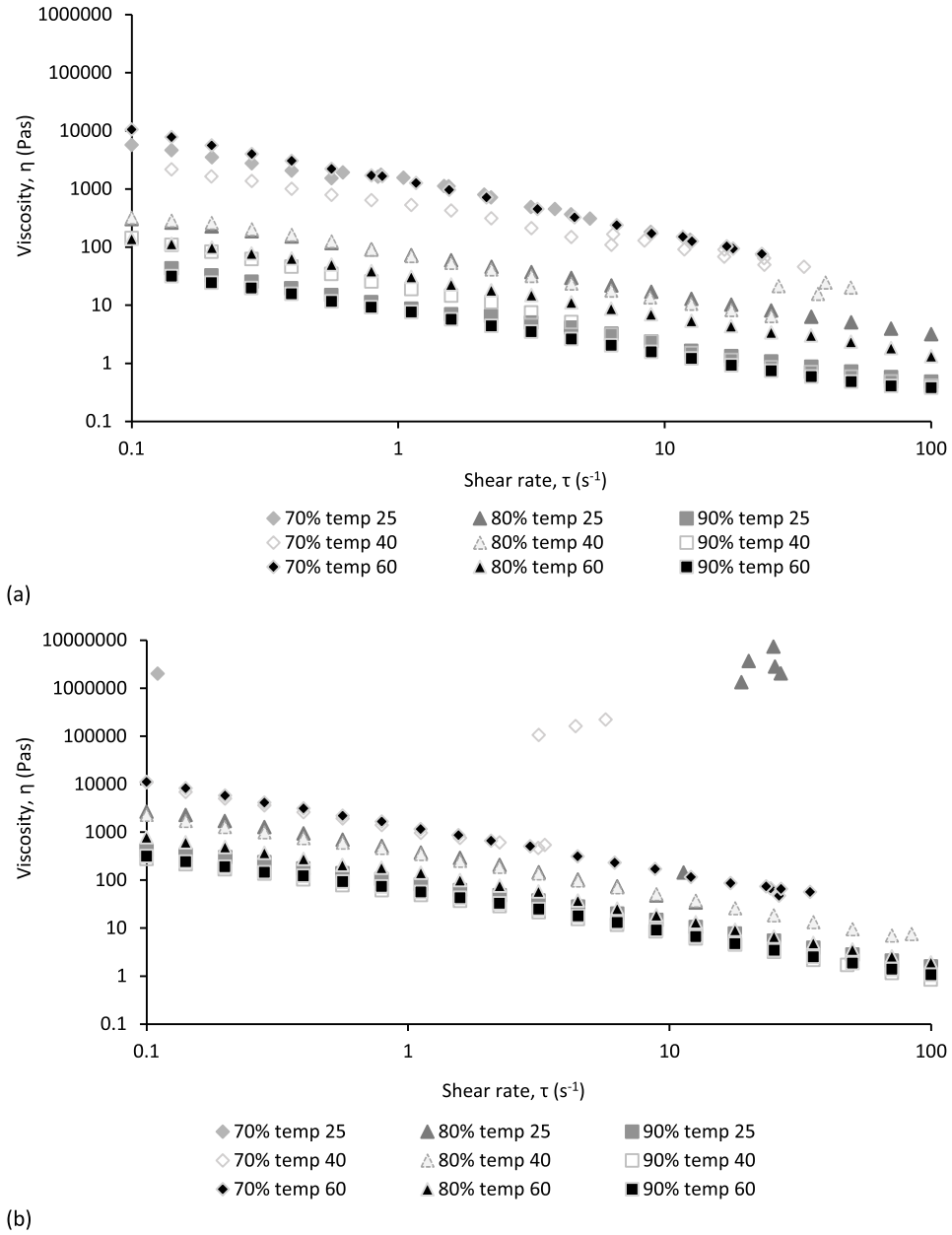


Fig. 6. Viscosity as a function of shear rate at varying temperatures and moisture contents for (a) UDDT (b) VIP sludge types.

occurs at the surface of the material. Most of the shrinkage during drying occurs before attaining the second falling rate period and thus before the sticky peak, as at this point drying will be occurring at the surface of the material. Drying occurs inside the material only during the second falling rate period which is technically after the sticky peak. The shrinkage of sewage sludge has been found to be in the range of 40–70 % [14,39,40].

The change of consistency from a viscoelastic fluid to granular solids can be depicted in Figure S2, showing the evolution of the look of the samples from liquid at a MC of 90%wt MC to solid material at MC of 20 %wt.

4. Conclusion

This study examined the stickiness behaviour of faecal sludge (FS) from ventilated improved pit latrines (VIP) and urine-diverting dry toilets (UDDT), using a texture analyser to quantify adhesive and cohesive forces, and explored how these stickiness characteristics correlate with drying, mechanical, and thermodynamic properties such as plasticity, viscoelasticity, flowability, moisture-binding states, and kinetic drying behaviour.

The sticky region, identified between 30 and 70 wt. % moisture content with a peak around 50–60 wt. %, corresponds to the interstitial moisture region, which begins once unbound moisture has been removed. The stickiness peak is assumed to occur when the capillary structure becomes minimised, just before the onset of internal moisture removal from within the capillaries, marking the transition from the first to the second falling rate period, a shift in drying behaviour from surface evaporation to internal diffusion-based moisture removal.

Within this sticky zone, FS exhibits increased plasticity and loses its initial viscoelastic behaviour following the removal of unbound moisture, resulting in higher resistance to handling. Cohesive forces exceeded adhesive forces throughout, with both showing a modest increase at 80 °C. UDDT sludge was found to be slightly stickier than VIP sludge,

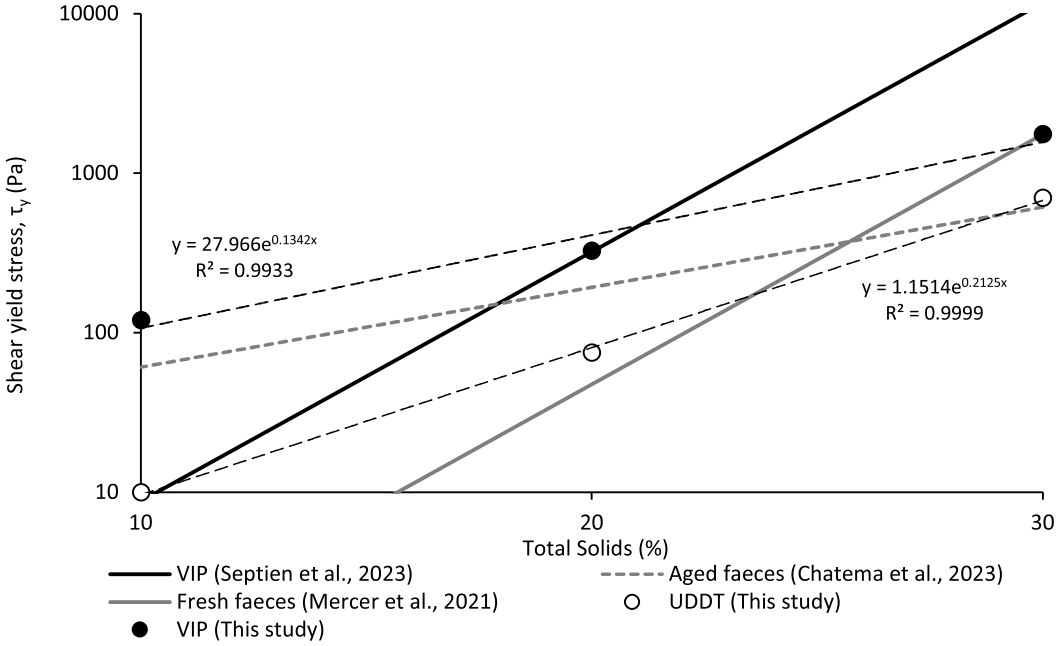


Fig. 7. Yield stress values at ambient temperature for UDDT and VIP sludges, fresh faeces and aged faeces.

Table 2
Atterberg limits for VIP and UDDT sludge types.

	VIP	UDDT
Liquid limit (%)	77.49	67.2
Plastic limit (%)	57.90	48.55
Plasticity index	19.59	18.65
Liquidity index	0.82	1.2
Sludge Activity (%)	275.72	285.6

and both were stickier than sewage sludge and fresh faeces reported in previous studies.

Stickiness decreased significantly below ~40 %wt. moisture content and disappeared around 30 %wt., coinciding with the removal of interstitial moisture, as the sludge transitioned into a friable, granular, and non-wettable state.

These findings provide critical guidance for the design and operation of FS drying systems. Thermal treatment systems and handling devices should take into account the sticky phase during design, considering how to manage its occurrence, mitigate operational disruptions, and address the maintenance demands it may generate. Strategies such as bypassing the sticky region, using bulking agents, applying pre-treatments to convert bound to unbound water, or even adding chemicals to alter the surface chemistry—all aiming to disrupt the capillary structure and limit the bridging or bonding between flocs and particles—can help reduce processing challenges and enhance drying performance.

Declaration of the use of generative AI

The authors declare that Grammarly was used as a tool for language correction and editing to ensure accurate and clear communication in the writing of this paper. No AI tools were used for data analysis, interpretation, or the generation of original content.

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CRediT authorship contribution statement

R.T. Mupinga: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E. Mercer:** Writing – review & editing, Validation, Data curation. **A. Rayavellore Suryakumar:** Writing – review & editing, Investigation, Data curation. **J. Pocock:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S. Septien:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2025.105453.

Data availability

Data will be made available on request.

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