Stickiness of faecal sludge for drying applications

By

Ratidzaishe Tracy Mupinga
218087128

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Supervisor: Dr. Santiago Septien Stringel

Co-Supervisor: Dr. Jon Pocock

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DECLARATION

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Supervisor: Dr. Santiago Septien Stringel,

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Co-supervisor: Dr. Jonathan Pocock,

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PUBLICATIONS AND PRESENTATIONS

The following papers are linked to this dissertation either have been written or are in the process of being written

1. Mupinga R. T, Septien S. S, Pocock J., Buckley C. A. An investigation into the stickiness of faecal sludge for drying applications (paper in progress).

2. Mupinga RT, Septien S, Pocock J and Buckley C. An investigation into the stickiness of faecal sludge: Preliminary investigation of VIP and UDDT sludge with varying moisture content at ambient temperature [version 1; not peer reviewed]. *Gates Open Res* 2020, **4**:78 (document) (doi:10.21955/gatesopenres.1116603.1)

The work in this dissertation has also been presented through a poster (attached as Appendix A) at the:

1. Sixth (6^{th}) South African Young Water Professionals Biennial Conference (October 2019).
2. University of KwaZulu-Natal (October) 2019 Post Graduate Research and Innovation Symposium.

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ABSTRACT

Faecal sludge management (FSM) seeks to achieve safe disposal of faecal sludge with minimum risks to the environment and overall human population with the possibility of attaining resource recovery. Thermal drying is a solution in FSM; however, the stickiness of the faecal sludge during the drying process can lead to clogging, and sludge build-up on dryer surfaces potentially causing equipment fouling. Stickiness is a physical property of faecal sludge that influences the drying processes, and thus an understanding of the phenomena allows for better design of drying systems. Faecal sludge samples from ventilated improved pit (VIP) latrines and urine diversion dry toilets (UDDT) were analysed to characterize their stickiness. The stickiness was studied through their cohesive and adhesive forces components in a texture analyser. The temperature and moisture content of the faecal sludge was varied within the experiments from 25 to 80^{o}C and moisture content from 20 to 90%wt to find limits of the sticky region and the sticky peak where the stickiness of faecal sludge is highest. The stickiness was correlated to the drying kinetics, water activity, rheological properties and consistency (Atterberg) limits. The sticky region was quantified by the use of the *Stable microsystems TA. XT express* texture analyser. The stickiness (cohesive and adhesive forces) of faecal sludge increased with increasing temperature and a decrease in moisture content. The increase in stickiness reached a peak for all temperatures investigated at a moisture content of 50%wt for UDDT sludge and a sticky peak of 60%wt for VIP sludge for all temperatures investigated. The maximum adhesive force required for the separation of the samples from the probe was lower than the force needed for the compression of the sample (cohesive force), implying that the faecal sludge has a greater cohesive force than adhesive force. The faecal sludge exhibited shear-thinning behaviour. The stickiness and viscosity at a shear rate of 1 s^{-1}, increased by a factor of approximately 1.5 for every 10% decrease in moisture content for the sticky region. Therefore, this implies that the rheology and stickiness of the sludge are directly proportional within the limits of the sticky region. The effect of moisture content was determined to influence the stickiness more significantly than temperature. As such, the drying rate in dryers is significantly decreased during the sticky region. The drying rate reduced significantly during the sticky region. The stickiness of the sludge was seen to start after free moisture was removed during drying (water activity less than 1), the moisture removed during the sticky phase was interstitial. The plastic and liquid limits gave the region in which the plastic behaviour is observed corresponding to the sticky phase of sludge.

Keywords: drying; faecal sludge; rheology; stickiness; sticky region; texture analyser.

Table of Contents

List of Figures

List of tables

List of abbreviations

ANOVA	Analysis of Variance
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
FSM	Faecal Sludge Management
UDDT	Urine Diversion Dry Toilets
VIP	Ventilated Improved Pit
SDG	Sustainable Development Goals
BMGF	Bill and Melinda Gates Foundation
UKZN	University of KwaZulu Natal
DWAF	Department of Water Affairs and Forestry
PRG-UKZN	Pollution Research Group - University of KwaZulu Natal
SOP	Standard Operating Procedures
VS	Volatile Solids
TSS	Total Suspended Solids
BREC	Biomedical Research Ethics Committee
PACI	Poly-Aluminium Chloride
LL	Liquid Limit
PL	Plastic Limit
TDL	Tuneable Diode Laser
TKN	Total Kjeldahl Nitrogen

Nomenclature

G_C	measured peeling energy	[J/m^2]
G_0	adhesive energy	[J/m^2]
$\boldsymbol{\psi}$	cohesive energy	[J/m^2]
γ	Surface energy	[J/m^2]
γ_{SL}	surface tension at the interface of solid-liquid	[J/m^2]
γ_{SV}	surface tension at the interface of solid-vapour	[J/m^2]
γ_{LV}	surface tension at the interface of liquid-vapour	[J/m^2]
x	inter particulate bridge radius	[mm]
a	particle radius	[mm]
t	time	[min]
μ	critical viscosity	[Pa.s]
A	area	[m^2]
m	mass	[g]
m_0	initial mass of the sample before drying	[g]
m_f	final mass of the sample after drying	[g]
M_{db}	moisture content on a dry basis	[g/g]
M_{wb}	moisture content on a wet basis	[g/g]
k	drop cone factor	[-]
Q	force of the cone	[N]
h	penetration reading from the cone penetrometer	[mm]
S_{ur}	shear strength	[N/m^2]
wb	wet basis	[%wt.]
db	dry basis	[g/g]
E	Surface energy of the interfaces	[Nm]

dm	dry mass	[g]
rpm	revolutions per minute	

1 INTRODUCTION

Investigation of faecal sludge is of importance in many fields of research such as operation and maintenance of onsite sanitation systems (Strande et al., 2017), and implementation of faecal sludge collection and treatment for onsite sanitation systems (Bassan and Robbins, 2014). The United Nations Millennium Development Goals, and the Sustainable Development Goals (SDG) implemented in 2016, have all focused on the provision of basic sanitation. As such, there has been attention on building and providing new toilets, but not enough on the toilets and their maintenance and systems supporting these toilets. There has been an increase in the extension of sanitation services according to the Sustainable Development Goals. There is an increase in the production of faecal sludge in South Africa with an increased number of onsite sanitation systems used. The management of the faecal sludge becomes a cause of importance.

The amount, density and rheology of faecal sludge are physical properties of importance for simulating phenomena such as faecal matter settling, convey systems, thermal drying and physical treatment processes (Strande et al., 2017, Zuma et al., 2015). As such, the treatment of the faecal sludge has also progressed, with sludge thermal drying treatment being an essential processing technology.

Handling and disposal of faecal sludge have been a persistent problem due to its high moisture content and pathogens concentration. The cost-effective and sustainable disposal of the sludge is the major challenge. Sludge drying is adopted as it provides an economically viable solution to the treatment of faecal sludge (Chai, 2007). Sludge drying reduces costs associated with transportation and significantly improves the combustion properties of the faecal sludge, as well as it leads to the deactivation of pathogens, so pasteurisation of the sludge.

During drying, the sludge has an intermediate moisture content in which it becomes sticky and agglomerates into lumps, adhering to drying surfaces. The stickiness is an undesirable effect in the process and is associated with reduced drying efficiency and equipment failure from unexpected hydrodynamic fluctuations. Faecal sludge is comparable to sewage sludge which tends to stick to surfaces in decanter centrifuges and sludge paddle dryers causing the torque requirements to be high (Bennamoun et al., 2013). The stickiness of the faecal sludge has also led to sludge buildup on dryer surfaces potentially causing equipment fouling and clogging. The stickiness noted in the pipework of sewers, requiring pipe-cleaning often due to faecal sludge buildup. As has been seen in the food industry, problems may also arise due to the downtime from cleaning equipment and equipment maintenance (Goode et al., 2010).

With an understanding of stickiness, a large number of problems that arise from this phenomenon could be solved. The information on the stickiness of faecal sludge will allow for effective use of energy in drying processes (Li et al., 2014). Despite the insight into the sticky behaviour of sludge during drying processes being critical, the stickiness of sludge is not a common topic. There are no current standard analytical methods used to determine the characteristics of the undesirable stickiness behavior of the faecal sludge. This can lead to problems arising from the stickiness of faecal sludge reducing the efficiency of the drying system.

It is imperative to emphasise that during the drying process, material undergoes physical property changes while being reduced in volume due to water removal (O'Callaghan and Hogan, 2013). Difficulties in solid-liquid separations, such as drying, arise because conventional design optimises only the unit operations and takes no account of the nature of the thickened product or possible handling problems that may be due to stickiness (Bennamoun et al., 2013). With improved knowledge on stickiness, the operation cost and maintenance costs of drying equipment and piping could be achievable (Fryer et al., 2011). This can allow for the cost of the sanitation system to be considerably more affordable. The knowledge of stickiness will improve the durability of drying equipment. It is important maintaining high and stringent standards for a reduction in substrate microbial growth but with a payoff to optimise the cleaning process avoiding faecal sludge build-up in equipment, downtime from cleaning equipment and equipment maintenance. An understanding of faecal sludge stickiness can positively influence drying parameters. The sticky region, as given by Hoseney (1999) is the range of moisture contents at which the stickiness phenomenon is highest. Insight on the sticky region of faecal sludge can increase the thermal drying system efficiency (Hoseney, 1999).

The development and implementation of new and sustainable technologies that are cost-effective and self-sustaining, is the main objective of the Bill and Melinda Gates Foundation (BMGF) initiative projects. The "Reinvent The Toilet Challenge" program can be achieved by the thorough knowledge of the physical properties of faecal sludge. The stickiness of faecal sludge is one of the physical properties that will allow for the efficient design of innovative onsite sanitation systems. Nevertheless, the information about the stickiness of faecal sludge for use in the design of drying systems and toilet design is not readily available in the literature, thus forming the basis of this particular study.

1.1 Aim and objectives

The aim of the study is to understand the stickiness of faecal sludge during the drying process.

The objectives of this thesis are to:

1. Characterise stickiness of faecal sludge as a function of temperature and moisture content.
2. Determine the sticky region of faecal sludge.
3. Determine how stickiness affects the drying process by determining the relationship between stickiness and drying kinetics.
4. Study the relationship of consistency, rheology and water activity with stickiness.

1.2 Scope of the research

The samples for this experimental work were obtained from ventilated improved pit (VIP) latrines and urine diversion dry toilets (UDDT) within the eThekwini municipality. The samples were considered to be representative of the sludge from these type of toilets in the area. Laboratory analyses were conducted following the Standard Operating Procedures from the Pollution Research Group. The stickiness of sludge was determined by the use of a *Stable Systems Texture Analyser*. The moisture content and temperature were varied to allow the determination of the sticky region. The characterisation of the sludge stickiness provided an understanding of the contribution of the cohesive and adhesive force components. Drying tests were conducted in a thermal balance to monitor the kinetics of the process and correlate them to the sticky region. In order to understand the relationship of consistency, rheology and water activity with stickiness, the samples of varying moisture and temperature were analyzed using the cone penetrometer, a rheometer and water activity meter. The research was approved by the UKZN Biomedical Research Ethics Committee approval number BREC/00000204/2019. The research does not study the effects of different factors like age of the faecal sludge and weather season on the faecal sludge characteristics.

1.3 Significance of the research

This research will help to generate information on the stickiness phenomenon, the sticky peak and the sticky region for each type of faecal sludge studied. The knowledge gained in this study will allow for more efficient energy use in the drying process, reduced downtime. The data from the research can help practitioners and faecal sludge treatment plant designers to optimise the drying process. The research serves to give the set of data to build knowledge and facilitate the learning of the stickiness phenomenon that has been posing challenges. Knowledge of the sticky region allows for the manipulation of the moisture content and temperature of sludge such that the effects of stickiness can be reduced in the drying process. Insight into the boundedness of water in the sludge allows for the stickiness of the sludge to be better understood. As it is the first study on faecal sludge in the best knowledge of the authors, it will map out the needed information for the on-site sanitation industry.

The research could also serve indirectly as a business aid as there will be an increased understanding of the drying process concerning stickiness and thus increase avenues in which faecal sludge can be processed without the negative impacts of stickiness. An overall reduction in the treatment costs of faecal sludge will achieve a step closer to attaining sustainable sanitation that is affordable as stated for Sustainable Development Goals.

2 LITERATURE REVIEW

In this section, faecal sludge material and the drying process was described. The stickiness phenomenon is presented, including the methods that have been used to determine stickiness. The description of how stickiness affects drying of faecal sludge is described. The chapter will describe the gap in understanding the stickiness of faecal sludge.

2.1 Faecal Sludge

2.1.1 Onsite sanitation

Sanitation refers to the public health conditions relating to safe drinking water and proper care and disposal of human excreta and sewage (Ali, 2015, Ward et al., 2017), with a sanitation scheme referring to the collection, transportation, transfer, treatment, and disposal or reuse of human excreta and wastewater (Ali, 2015, Ward et al., 2017). A sanitation system is one in which human excreta is managed from the time and point of generation by defecation until ultimate safe disposal (Bassan and Robbins, 2014, Ward et al., 2017). The type of sanitation systems is employed depending on the economic, social and geographical context. There are in two categories to describe sanitation systems according to their treatment, which is onsite and offsite sanitation. Off-site sanitation is a system in which a conveyance is employed to transport human excreta for treatment at a place away from where the excreta was generated. Onsite sanitation is system where the Human excreta is contained within the plot occupied by a dwelling and its immediate surrounding (Thye et al., 2011). These are quite predominant in urban areas of the developing countries and newly industrialised countries. Low-income and developing countries, mostly in Africa, use the pit latrines as their most dominant form of on-site sanitation because they are low-cost (Montangero and Strauss, 2002). In the eThekwini municipality that is located in the KwaZulu-Natal province of South Africa (where this research was conducted), there are over 90 000 urine diversion dry toilets (UDDT) and over 35 000 ventilated improved pit (VIP) latrines (Harrison et al., 2012).

2.1.1.1 The ventilated improved pit (VIP) latrine

The VIP latrines provide sanitation by having a vault in which the faeces, urine, water and other materials are collected, contained and stored for a long period. It includes a vent pipe with a fly screen fitted at the top through which smell in the facility is controlled. The blowing of the wind over the vent pipe causes air to be drawn into the pit, via the pedestal, and then through vent pipe into the atmosphere. The continual flow of air reduces unpleasant smells in the toilet. Flies are prevented from entering and leaving the pit by a screen at the top of the vent pipe. The light coming from the vent pipe will attract the flies that are already inside the pit (DWAF, 2003).

Figure 2-1 shows the structure of the VIP. The superstructure is a significant improvement between unimproved latrines and the VIP ones. The superstructure provides privacy to the user and provides safety to the users (it avoids toilet collapse which is common with the unimproved latrines) and additionally keeps flies from leaving the pit. The cover slab is typically made from concrete. The purpose of the cover slab is to support the pedestal and superstructure. It also stops the users from coming into contact with human excreta (Mara, 1984).

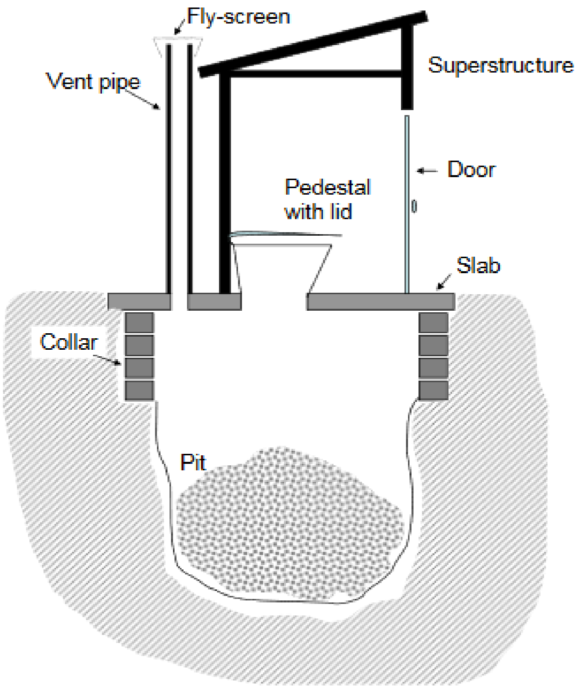


Figure 2-1 Structure of a VIP latrine toilet (Buckley et al., 2008)

2.1.1.2 Urine diversion dry toilets (UDDT)

Urine diversion dry toilet is waterless toilets designed to separate urine and faeces at source through the use of a specially designed seat and the presence of two vaults (Roma et al. (2013) and Rieck et al. (2013)). Figure 2-2 shows the schematic representation of the UDDT. Urine is collected from the front area of the toilet and diverted to the soak-away pit, while faeces fall through a hole in the back. The pedestal is located above one of the vaults. Once the first vault is full, the hole is sealed and allowed the faeces to decompose, and the pedestal is moved to the second vault. When the second vault gets full, which takes 6 – 12 months (Roma et al., 2013), the contents of the first vault are manually emptied via a removable vault cover. UDDT differs from VIP because it separates urine and faeces and anal cleansing material.

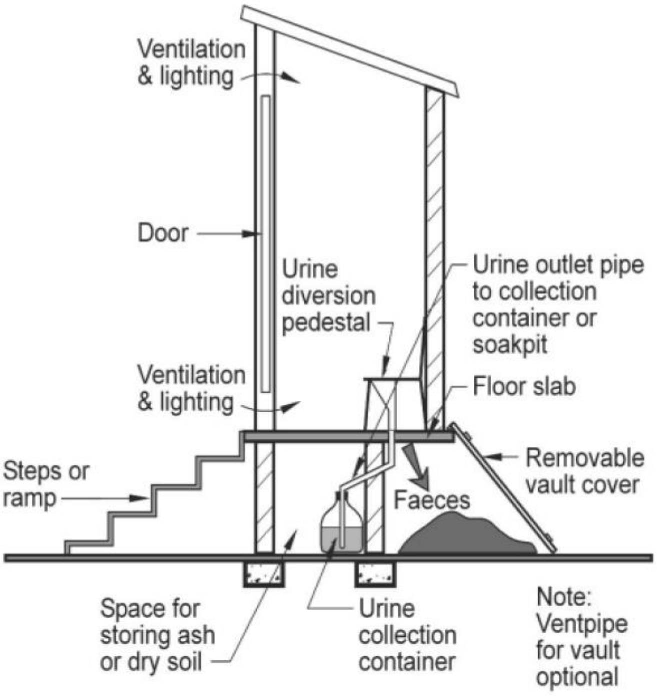


Figure 2-2 UDDT schematic representation (Strande, 2014)

2.1.2 Characteristics of faecal sludge

Faecal sludge is the mixture consists of mainly human excreta, water and other solid wastes like toilet paper and menstrual hygiene materials disposed of in various sanitation systems (Bassan et al., 2013, Bassan and Robbins, 2014, Strande et al., 2017). The sludge has not passed through a sewer system and thus originates from onsite sanitation facilities. Therefore, sludge consists of a mixture of excreta, black water and greywater. The faecal sludge may be undigested or partially digested combined with other solid waste materials and compounds (Ward et al., 2017). Faecal sludge characteristics are dependent on the onsite sanitation technology, how the faecal sludge is collected and the frequency of the collection. Other factors affecting the characteristics of the faecal sludge include the topography of the area and weather conditions. These variables cause differences in sludge within the same geographical location (Strande et al., 2017).

The quantities and content of faeces produced per day from people vary significantly based on diet, cultural background, geographical location, age group, gender thus associated with the income of the individuals. The main parameters considered for the characterisation of faecal sludge include solids content, pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), nutrients, volatile solids (VS), ash content, total suspended solids (TSS), pathogens and metals concentration (Bassan and Robbins, 2014). These parameters are influenced by the presence of other types of waste that is not faecal sludge. Table 2.1 gives the characteristics from literature for the faecal sludge from VIP latrines and UDDTs, which are the feedstock from this study. The samples from Table 2.1 were from the same area that the one from this study (eThekwini municipality).

Table 2-1 Summary of the characteristics of VIP latrine and UDDT sludge contents from the eThekwini municipality

Analyte	Sludge from VIP				Sludge from UDDT	
Source	(CA Buckley et al., 2008)	(Zuma et al., 2015)	(PRG-UKZN)	(Getahun et al., 2020)	(Getahun et al., 2020)	(PRG-UKZN)
Moisture content (%wt)	76	69-87	56	95	70	63
pH		4.7-8.6	7.59	7.43	8.13	7.54
Total COD (mg/g wet weight)	105	30-44	69	99	40.9	49
Volatile solids (g VS/g ash)		0.45-4.3	0.54	0.66	0.76	0.45
Ammonia (mg NH_3-N/g dry mass)	0.028	1.2-30	1.23			5.22
TKN (mg N/g dry mass)		9.3-74	6.14			29.62
Orthophosphate (mg PO_4^{3-}/mg dry mass)		0.035-4.5	0.9	0.003	0.005	1.0
Thermal conductivity (W/(m.K))		0.48-0.58	0.55			0.38
Calorific value (kJ/g dry basis)		9.5-91	13.08			12.93
Heat capacity (kJ/kg K)		1970-3430	2422			2150

2.1.3 Moisture distribution in faecal sludge

The faecal sludge characteristics stem from the different colloidal materials, particles in suspension and extracellular polymeric substances in a similar way that the municipal wastewater sludge. These materials bind tightly with water particles and with other particles. Even though the particular bonding structures for sewage sludge are not known, the particle size, distribution and compressibility play a role in the bonding structures of sewage sludge and thus, expected to play a role in faecal sludge as well. The detailed understanding of the faecal sludge structure is also unknown, although hypothetically the water distribution inside the material should follow that of municipal sewage sludge. Figure 2-3 shows the moisture distribution in typical sludge, including:

a) Free or unbound moisture;
b) Interstitial moisture;
c) Surface moisture;

d) Intracellular and chemically bound moisture.

The unbound moisture can be removed mechanically from the sludge. It is not contained within the particles. The interstitial moisture is within the sludge capillaries and is retained by adhesive and cohesive forces within the sludge (Mowla et al., 2013). Intracellular moisture is contained inside the cells, so it can be removed only by breaking the cell walls. The surface moisture is bound to the particle surface by adsorption or attached to the surface of the flocs. Mechanical dewatering methods will remove unbound moisture, interstitial moisture and partially remove the surface moisture in the presence of a flocculant (Mujumdar, 2006). Bound moisture can only be removed by thermal drying and is the moisture that is bounded to the sludge by physical, chemical or biological interactions. (Mowla et al., 2013). Only a part of this moisture can be removed mechanically (mostly the physically bounded moisture). In order to reduce the transportation costs associated with faecal sludge treatment, the unbound moisture could be removed through mechanical dewatering, and then thermal drying could be employed to remove the bound moisture.

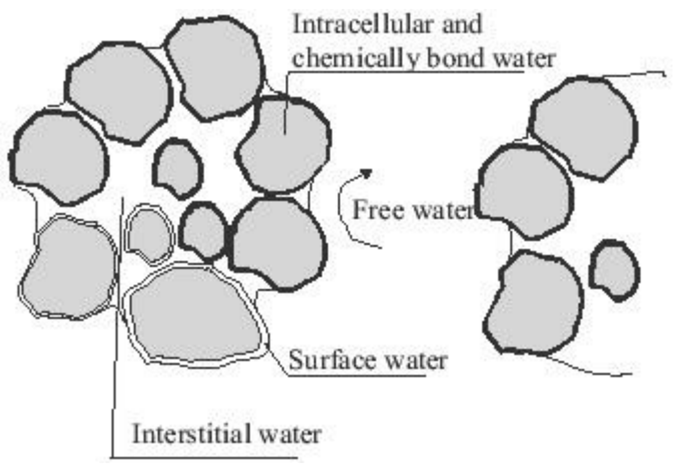


Figure 2-3 Water distribution in a typical sludge sample (Chen et al., 2002)

2.2 Drying of faecal sludge

Dewatering can reduce the amount of water in the faecal sludge. However, after dewatering the moisture content of the faecal sludge decreases to about 40% of initial moisture content (that is lowering moisture content up to 60-70%wt) as reported by Getahun et al., (2020) at which further dewatering would be expensive or entirely not possible (Geanna Hovey et al., 2017). Further loss in moisture could be achieved by drying. Drying provides a way to remove the residual moisture, including the bound water by the degradation of cell walls, as well as the chemically and physically bounded moisture.

Drying of the material involves removal of moisture in the sludge through evaporation. As discussed, firstly, drying can primarily reduce the amount of moisture and result in a significant reduction of mass and volume of sludge, directly leading to a cost reduction in transport, handling and storage (Bennamoun et al., 2013). Secondly, high-temperature drying can kill pathogen organisms and stabilise the sludge to a certain extent. Thirdly, the calorific value of the sludge will increase with the loss of water to levels that are acceptable for reuse as combustible (Chai, 2007). Drying is a dehydration technique that involves momentum, heat and mass transfer as water evaporates from the faecal sludge. Drying process allows for moisture in the faecal sludge to reduce to a level at which microbial activity, biological and chemical reactions are minimal (Srikiatden and Roberts, 2007).

Heat transfer occurs when the heat provided from the heating source is transferred within the sludge. The transferred heat is mainly utilised for moisture evaporation (to provide the latent heat required for moisture evaporation). Mass transfer occurs when the moisture moves from the interior to the surface of the solids, then to the environment. The drying process consumes a substantial amount of energy (the latent heat of water vaporisation is usually high) and thus to allow for the optimisation of the process, an understanding of the heat and mass transfer mechanisms is essential.

There are two main mass transfer mechanisms in the drying process, and these include:

a) External mass transfer
   The evaporation of moisture for a moist product at the surface to the environment.
b) Internal mass transfer
   Movement of the moisture from the core to the surface. This could be done by capillary flow, gas or liquid molecular diffusion and flow induced by pressure or temperature gradients. Usually all these phenomena are termed together as effective diffusivity. Capillary flow becomes challenging to distinguish from diffusion when the water activity is proportional to the surface tension potential (Peeters, 2010). The effective diffusivity follows Fick's second law of diffusion and is analogous to the Fourier law of heat transfer.

The drying of faecal sludge relies on the effective diffusivity of water. The diffusivity is a function of temperature and water content within a sludge sample. The external mass transfer is governed by exterior conditions such as air humidity, temperature and surface area. The temperature, moisture content and physical structure of the material contribute to the removal of bound water (Mujumdar, 2006).

2.2.1 Drying phases

The behaviour of sludge during drying can be expressed as the variation of the sludge moisture content with the drying time, commonly known as the drying curve. Figure 2-4 illustrates the typical drying rate curve and the periods that the sludge undergoes during the drying process.

Drying can be divide into stages, the constant and the falling drying rate period, which can be broke down into the first and second falling rate period. Constant drying rate is the period in which the evaporation occurs only at the surface. During this period, the sludge is saturated in moisture. When the moisture evaporates from the surface, it is replaced by the moisture coming from within the product. At this stage, the sludge is at constant temperature (isothermal) at the wet-bulb temperature.

When the rate of evaporation at the material's surface exceeds the rate of moisture transfer within the material to the surface, the first dropping rate cycle occurs. As a result, the material's surface is no longer saturated with moisture. During the falling drying rate period, the internal structure of the material is modified, as there is a rearrangement of the dry bone of the material due to the removal of moisture. At this stage, the rate of drying is heavily influenced by the flow of water inside the material. When the surface of the material is dry, drying happens at the centre of the material, and the temperature of the sludge rises in the regions where the moisture has been removed, the second falling rate cycle begins.

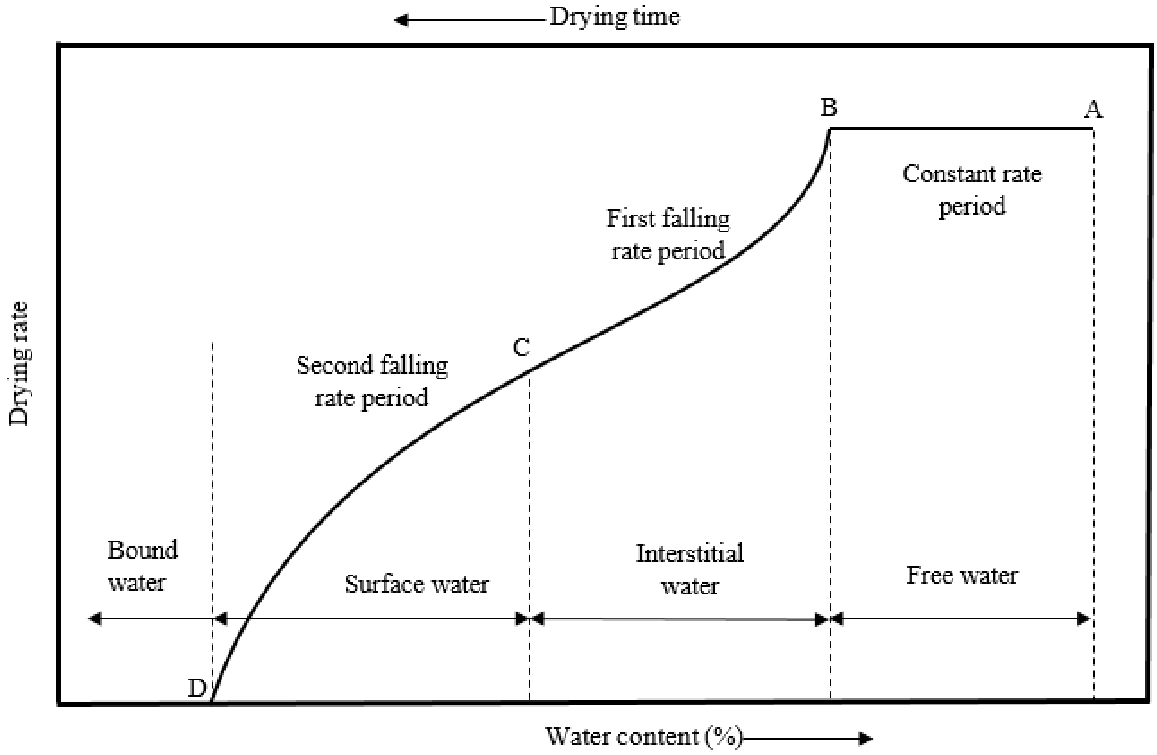


Figure 2-4 Typical drying curve (Bennamoun et al., 2013)

The drying rate curve, as shown in Figure 2-4, shows the constant and falling rate periods. The drying kinetics are affected by the origin of the sludge and operating conditions. The constant rate period marked by line AB in figure 2-4 is when the surface of the sludge is saturated in moisture. If mechanical dewatering has taken place, the constant rate phase may be observed for a short time or entirely not observed because most of the free moisture is removed during the constant rate period (Bennamoun et al., 2013). During the constant rate period, the temperature of the material is constant (at the wet-bulb temperature). Line BC shows the first falling rate period. This period has a decrease in the drying rate as the sludge is not anymore saturated at the surface. During this period, mainly the interstitial moisture is removed. The first falling phase continues until the surface film is entirely evaporated at the surface (Mujumdar, 2006, Geanna Hovey et al., 2017). Line CD marks the evaporation front moving from the surface to the bulk of the solid. In this phase, the remaining water in the sludge evaporates (mainly bound water and surface moisture) and the temperature of the sludge increases. The critical moisture, defined as the moisture content that recorded at the end of the constant rate period, varies according to the drying method and operating conditions (Geanna Hovey et al., 2017). The critical moisture also varies as a function of the characteristics of the material.

2.2.2 Types of drying

The mass and heat transfer between the drying medium and material to dry governs the drying process. The different drying techniques are grouped into three modes according to the type of heating, namely convective, conductive and radiative (Bennamoun et al., 2013). These have also been combined in some instances to give hybrid dryers.

- Convective drying uses air or a gas stream as the heat carrier and contact medium with the material to be dried. The convective dryers increase the evaporation rates by maximising the surface exchange area between the product and the hot gas, which can be done by extrusion or granulation (Bennamoun et al., 2013). Industrial examples of these dryers include belt dryers, fluidised bed dryers and rotary dryers.

- Conduction drying has a hot surface in contact with the material to be dried, and the evaporated moisture is taken away by a low to medium intensity air flow rate. Industry examples of these dryers include the thin film dryers and the paddle dryers.

- Radiative drying transmits the heat to the material by radiation. Ventilation or wind is utilised for the evacuation of the humidified air to maintain low the moisture gradient. The radiation can be infrared, microwave, dielectric or solar. The sludge requires turning to maximise the surface exposed to the radiation and reduce the formation of a crust (Bennamoun et al., 2013).

2.2.3 Factors affecting the drying process

In the different mechanisms of drying, the process depends directly on the structure of the material to dry. Drying can be affected by factors that can either be external or internal. The external factors that affect drying make changes to the removal of moisture on the surface of the material whilst the internal factors affect the movement of moisture within the material (Chen et al., 2002).

The factors that influence moisture removal per unit time include: the operating conditions (including temperature, humidity and air velocity), moisture content, dimensions and geometry (influencing the surface area of the material as more exposed surface area allows for more moisture removal per unit time). Higher temperatures during drying leads to more energy for vaporisation and thus increase the drying rate. An increase of temperature allows to increase the heat transfer rates due to the higher temperature gradient, as the mass transfer rates due to the higher agitation of the molecules leading to a faster movement of moisture. The relative humidity affects the drying process as it influences the external mass transfer. A decrease in humidity results in an increased difference in moisture concentration between the material (faecal sludge) and the surrounding air (Makununika, 2016), increasing the movement of moisture from the material into the atmosphere and thereby increasing the drying rate. The relative humidity also plays a role in the thermodynamic equilibrium. The lower the humidity, the lower the moisture content at the thermodynamic equilibrium. Increasing the air velocity allows for the faster removal of moisture from the surface of the material, creating a difference in the moisture concentration as well and thereby affecting the drying rate. The size of material/particulates to be dried affect the drying process. The smaller the particulates of the material to be dried, the more increased the drying rate as the surface area to which the drying occurs would have increased. The geometry of the material also influences the surface area and thus a geometry that allows for a greater surface area such as that facing the heating source in a solar drying case, allows for increased drying rates and thus more favourable for the drying process

2.2.4 Behaviour of sludge during drying

The drying phenomena described in this section corresponds to sewage sludge drying and it is assumed that faecal sludge behaves in a similar manner. During the drying process, there is a generation of a gradient of moisture content within the sludge (Bennamoun et al., 2013). As the sludge dries, solid displacement within the structure of the material is also generated. The combination of the moisture content gradient and the displacement of the solid creates mechanical stresses. The moisture loss that occurs as the drying process proceeds causes the dimensions of the sludge to change leading to shrinkage (Bennamoun et al., 2013). The mechanical stress may lead to deformations on the structure o and the formation of cracks (Mihoubi and Bellagi, 2008, Srikiatden and Roberts, 2007). The deformation of the structure of the sludge during drying alters the heat and mass transfer mechanisms.

The initial sludge can be typically found at the wet phase as a viscoelastic material with a shear-thinning behaviour (Geanna Hovey et al., 2017). Shear thinning occurs as the viscosity of a material reduces as the shear rate rises. This time-independent non-Newtonian behaviour can also be referred to as pseudo plasticity (Braun and Rosen, 1999). In the wet phase, the sludge can flow by applying a stress. During drying, the evaporation flux in this stage is constant at a maximum value (constant rate period). After further drying the sludge starts to show a plastic behaviour, defined as the pasty or sticky phase (Deng et al., 2019b). The sludge exhibits a constant deformation in the sticky phase (Peeters, 2011, Bennamoun et al., 2013). At this stage, the sludge is paste-like and can develop a skin layer. The sludge may require larger shearing forces to achieve proper mixing. The highest shear stress values and highest torque values identify the sticky phase of the sludge (Peeters, 2011, Peeters et al., 2011, Geanna Hovey et al., 2017). There is a reduction in the drying rate, and the convey of the sludge within the dryers or on a belt becomes more difficult. There is little information on the stickiness of the sludge, and hence it is difficult to reduce the effects of this phase during drying.

Further drying of the sludge causes the sludge to take a solid form and becomes granular. There is decreased deformation and shrinkage of the sludge. The deformations come along with the decrease in the evaporation flux as it approaches zero during the second falling rate period (Peeters, 2011).

2.2.5 Challenges of drying faecal sludge

The faecal sludge content and characteristics, as discussed in early sections, is dependent on income and the diet of individuals using the sanitation facilities. As a result, the composition of sludge varies between treatment plants, and these variations can also occur in the same plant across different days. The variations that are in the faecal sludge characteristics could affect the energy consumption and processing times of faecal sludge drying, making it difficult to have set limits and timeframes for the process. The process control of the drying systems should be also dynamic because of the varying composition of the sludge.

Drying of faecal sludge is an energy-intensive process and thus is usually associated with high capital and operating costs. The system has to have equipment that can withstand high temperatures. The running costs are also high as the amount of energy needed for vaporisation is relatively high. Therefore, this brings a need to minimise costs by making the process more efficient and minimising energy losses during the process.

The emission of odours during the drying process is a challenge as this makes the setup and operation of the process highly undesirable, especially in areas close to residential spaces. As drying proceeds, the sludge undergoes modification in the mechanical properties as the moisture is removed from the material, which causes the sludge to be sticky. At this stage of drying, the sludge has a high viscosity and the stickiness could give problems of clogging and fouling on the dryer walls. The stickiness could also potentially increase the cost of drying as the energy requirements of the drying increase. Stickiness must be mitigated in order to reduce the operating costs of the process, the high costs of maintenance and the process downtime related to the removal of the fouling and clogging from the drying equipment due to stickiness, but this needs the understanding of this phenomenon. However, there is no information about this topic related to faecal sludge, but some indications can be obtained from sewage sludge.

2.3 Stickiness

2.3.1 Definitions and concepts of stickiness

The stickiness of a material can be defined as a combination of the adhesion, i.e. the interaction between a particular material and a surface or a different material, and cohesion, i.e. the interactions that are inside the material. Therefore, it is the result of combining surface and bulk rheological properties (Tock et al., 2013). The adhesive failure and the cohesive failure are two different processes that can cause stickiness to fail (Kilcast and Roberts, 1998, Hoseney, 1999). A clean parting or separation from the surface with minimal necking distortion of the sticking material is known as an adhesive failure. It illustrates the strength of cohesion within the material as they stick together more than they stick to the surface. A cohesive failure, on the other hand, involves the sticking material necking and fracturing, leaving residues on the surfaces or the other material. It shows the strength of the adhesive force of the material to the surface as the particles of the material stick more to the surface than they stick together, as shown in Figure 2-5 (Chen et al., 2008). The term sticky material is when its tendency to break apart is low or when the tendency to stick on a surface is high.

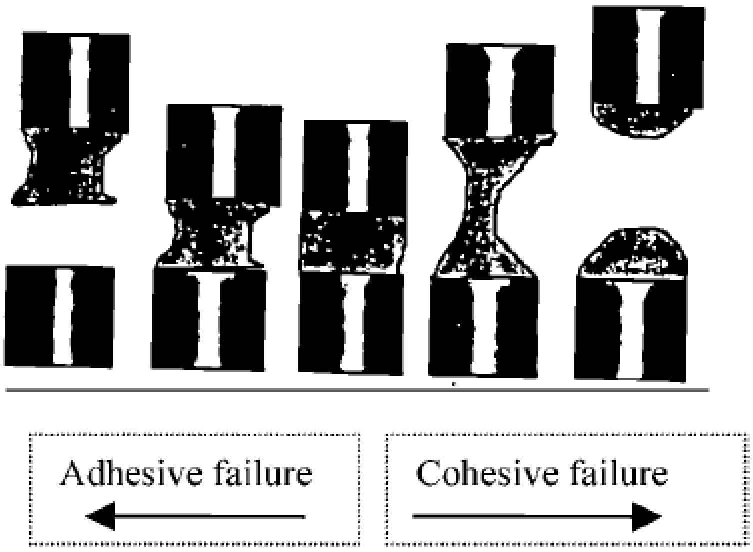


Figure 2-5 Diagrammatic presentation of stickiness failure mechanism between adhesive and adherent surfaces (Kilcast and Roberts, 1998)

2.3.1.1 Types of stickiness

2.3.1.1.1 Stickiness within a material

The stickiness within a material can be expressed by the cohesive energy or cohesive forces of a material. The cohesive energy term contributes a considerable amount to the measured adhesive fracture/failure energy and is strongly dependent on the viscoelastic properties of the adhesive (Dobraszczyk, 1997). An amalgamation of adhesive polymers within the material, mineral materials and crystal media gives the cohesion properties of sludge (Kudra, 2003). Chemical bonds, intermolecular interactions, crosslinking, and mechanical forces can bind naturally occurring and organic materials together. Mineral materials with small particle sizes allow sludge plastic and water-retaining material in the presence of moisture (Li et al., 2014). As stickiness is reliant on the viscoelastic properties of the material, it will be dependent on the temperature, imposed rate and deformation (Cao et al., 2016).

2.3.1.1.2 Stickiness of a material to a surface or different material

The cohesive failure has expressed the stickiness of a material to a different material or a surface. The term adhesion bonding describes the interaction of the particles of a material to a surface or a different material. The material will thus be sticky to the material if the surface of the material to which it will stick highly favours the formation of bonds with the material. If the adhesion forces of the material exceed the cohesive forces, the material is able to attach to a surface and leave a layer on the surface. The amount of matter from the layer depends on the cohesiveness of the material, the less cohesive, the more the material left on the surface. In adhesion bonding, there is a disjointedness in the physical properties of the material, leading to a stress concentration. Thus the term adhesion refers to the bond between different species (Bhandari and Howes, 2005). Minimising stickiness by adhesion can be achieved by either changing the surfaces involved or by altering product composition or operational conditions (Kilcast and Roberts, 1998).

2.3.1.1.3 Combined stickiness

As the name suggests, the combined stickiness can be expressed when the cohesive and adhesive forces of the material are in the same magnitude. The combined sticky material depends on factors affecting the adhesion and cohesion. The term stickiness is loosely used to define any of the two scenarios (the adhesion of a material to a surface and the adhesion of material particles within a material), and the combined stickiness would be the stickiness of a material as measured without reference to a surface. As has been shown in figure 2-5, the combined stickiness would fall on either side of the initial sample before the cohesive and adhesive failure.

2.3.1.2 Mechanisms of stickiness

Stickiness of a material can be described as the summation of two energy contributions, the surface energy (adhesive) and the cohesive energy (Hoseney, 1999, Dobraszczyk, 1997), as shown in Equation 2-1:

$$G_C = G_0 + \boldsymbol{\psi} \quad \text{Equation 2-1}$$

Where G_C = measured peeling energy (J/m^2)

G_0 = adhesive energy (J/m^2)

$\boldsymbol{\psi}$ = cohesive energy (J/m^2)

2.3.1.2.1 Adhesion

The adhesive energy depends on the type and strength of bonding between the surface and the material. It is a recurrent hypothesis that from equation 2-1, G_0 is related to the thermodynamic surface energy, which is able to estimate from surface tension experiments direct measurement (Dobraszczyk, 1997). The thermodynamic surface energy is a measure of the sum of molecular interactions across an interface. It's the contrast between the interfacial and individual materials' surface energies. The thermodynamic surface energy can link the apparent adhesive strength to the volume of the material, the surface area and the deposit thickness. The adhesive strength gives an assumption that the work required to fracture the deposit is independent of the surface energy (Hoseney, 1999).

The process of creating continuous contact between a material and a surface is known as wetting. Wettability indicates when a substance can extend as an uninterrupted film on a surface or, on the contrary, will pull back as drops. As the sludge wets the surface, the sludge expands rapidly when the bond forms at a high moisture content (Chen et al., 2008). In the case of strong interaction between the sludge and the dryer surface, secondary intermolecular forces at the interface result in adhesive pressure (Ghorbel and Launay, 2014, Li et al., 2014). Stickiness of faecal sludge to dissimilar surfaces is not possible unless the faecal sludge has good spreadability or wettability to the surface (Chen and Özkan, 2007). The contact angle is defined as the angle that is between the surface of the liquid (in this case, moisture in the faecal sludge) and the outline of a surface. Figure 2-6 illustrates the relationship of substrate-surface to wetting. This shows how the contact angle of faecal sludge would affect its stickiness property as the contact angle decreases from 0-90^o; there is a transition from complete wetting to non-wetting, meaning that the force of adhesion will decrease. At angles above 90^o, the stickiness would further decrease and at 180^{o,} the influence of stickiness caused by wetting could have ceased entirely, although other phenomena could affect stickiness (Cheng et al., 2010). Surface forces and surface energy influence the adhesive property of the material. While the contact angle of the liquid determines the surface energy of the solid substance, the concept of surface tension does not extend to solids (Bhandari and Howes, 2005).

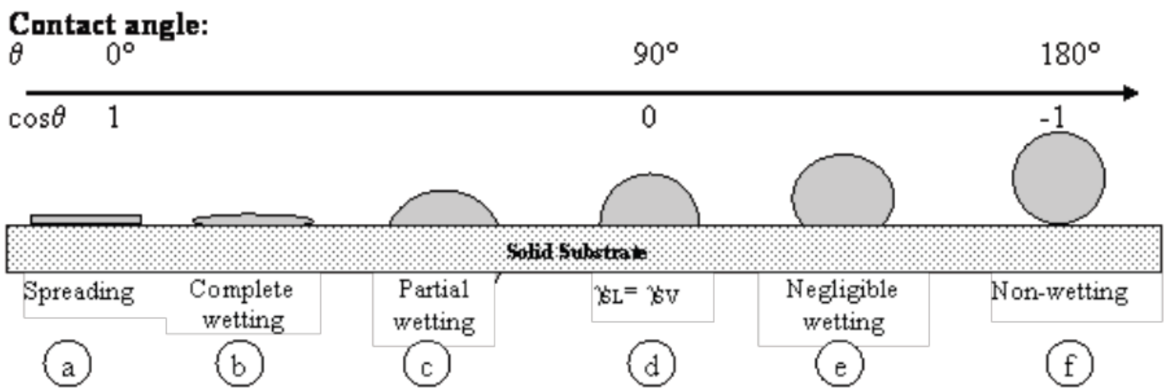


Figure 2-6 Substrate-surface correlation to wetting (Goode, 2012)

$\theta < 90^o$ = wet

$\theta > 90^o$ = non-wetting

$\theta = 0$ = complete wetting

$\theta = 180^o$=non- complete wetting

On a microscopic level, all surfaces have cracks, crevices, and pores; thus, the sludge infiltrates the cracks and voids on the dryer surfaces, displacing the locked in air at the interface. The material attaches mechanically onto the surface leading to the formation of a strong surface bond. The penetrated sludge layer can bond the contact surface and sludge bulk together (Li et al., 2014). Fibrous, crumbly, and bulky particles can net or fold about each other resulting in “form-closed” bonds (Adhikari et al., 2001). The bonds can form when there is a temperature rise to reach a specific viscosity. The molecules or particles at the interface tend to flow into each other at this viscosity. Bonding/ adhesion can occur when the temperature drops again, due to the creation of mechanical interlocking/ meshing between the particles (Adhikari et al., 2003). Adhesion can occur through sintering, i.e. when there is compaction of particles leading to interparticle interactions (Heinrich Grausgruber et al., 2003).

When particles retain excess opposing charges, electrostatic adhesion occurs, and this can likely occur when particles are in connection or contact attributable to different contact potential values. The contact potential is defined as the difference that arises from the electric potentials of two bodies that are in contact at thermodynamic equilibrium. This charge is loosely termed as the surface charge of the particles. When electrically conducting particles make contact, electrostatic adhesion happens as a result of the contact potential (Huault et al., 2019).

Adhesion between two surfaces that are not of the same material thus do not have material linking the surfaces is primarily attributable to Van der Waals forces, and electrostatic forces. Van Der Waals' forces are at the highest when particles are in close contact with each other. It is well accepted that the Van Der Waals force between a sphere and a plane surface is two times that of the force between the two domains, and that this force increases if a liquid layer exists between the solid particles (Adhikari et al., 2001).

2.3.1.2.2 Cohesion

The mechanisms of stickiness related to the cohesive energy are affected by the amount of energy dissipated in the viscoelastic deformation and the plastic deformation within the material. Cohesion can occur by binding of material (usually by water) as it leads to a bridge of material. This bridging is localised at the roughness peaks of the particle surfaces. When the binder liquid (usually water) liquefies a substantial amount of solids from the material at the same time than development of the liquid bridges, the consequent drying process of the binder leads to the creation of solid bridges within the material. Solid bridges are seen prominently during drying (Chen et al., 2008, Liu et al., 2006).

Liquid bridges are usually associated with stickiness within the material or stickiness on materials of similar surfaces. The solid particles are held together by liquid bridges. The available liquid bridges can divide into two main groups which include: mobile and immobile.

1. Mobile liquid bridges

Wet lumps are held together by the forces from the mobile liquid that is between the particles. The amount of voidage occupied by the water additionally allows for the mobile liquid bridges to be subdivided as pendular, funicular and capillary. Figure 2-7 shows the different types of mobile liquid bridges in sludges.

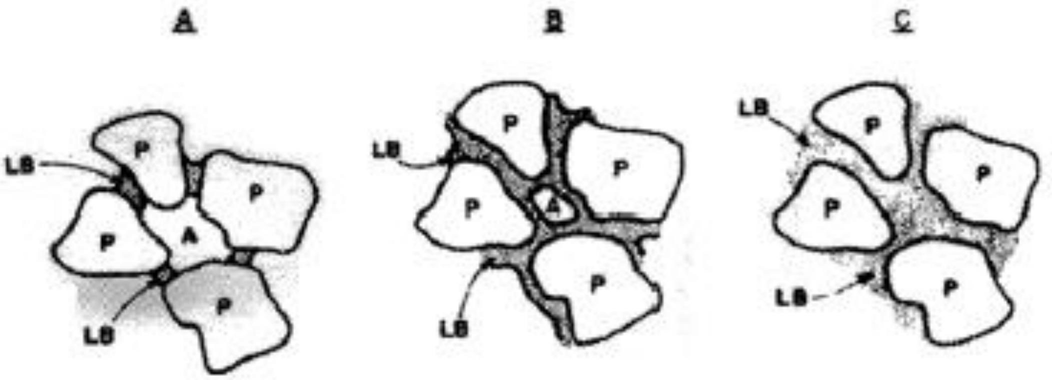


Figure 2-7 Schematic illustration of liquid bridges a) pendular state, b) funicular state, c) capillary state - p-particle, LB-liquid bridge, A- air (Adhikari et al., 2001)

a) Pendular state: Where a portion of the available voidage between the particles is filled by liquid and the other component by air, it is referred to as a pendular condition. If the liquid bridges form through the curve of the liquid meniscus and the interfacial stress exerted by the liquid along the moistened border, the pressure drop inside the substance increases their intensity (Adhikari et al., 2001).

b) Funicular state: The funicular condition is the transition between the pendular and capillary states. The tensile strength of the water is located between that of capillary moisture and pendular water in this state, in which a small fraction of the voidage is filled by gas.

c) Capillary state: The capillary condition occurs as water fills the gaps between the particles and spreads to the pore's side, forming a curved-in film. In the conduit, the whole liquid is under negative pressure, which increases the tensile strength of the wet lumps (Adhikari et al., 2001). In the capillary condition, the tensile strength of the wet lumps is almost three times that of the dry lumps. In a capillary state, the stickiness of the faecal sludge expects to be higher than when there is less unbound moisture (Ghorbel and Launay, 2014).

2. Immobile liquid bridges

There are viscous binders between the particles, where liquid bridges form. The viscous binder is more effective than the mobile liquid bridges. Such binders are thermoplastic materials, for example amorphous carbohydrates and soluble particles, ultimately leading to lumping (Sangbae et al., 2008, Intipunya et al., 2004). These binders have been identified in the food industries and are assumed to be present in faecal sludge as the faecal sludge binders exhibit almost the same changes when subjected to carbonisation or pyrolysis. The binders undergo physical changes such as crystallisation during the drying process. This form of liquid bridge maintains the capability to convert itself into solid bridges in later drying. This kind of bridge formation is determined by surface energy in viscous flow. However, despite presence of a natural occurring binder, the increase of the particle diameter of the material and the viscosity considerably decrease the affinity of the particles to agglomerate and thus artificial or added binders maybe required (Adhikari et al., 2001).

2.3.1.2.3 Rheological characteristics

The knowledge of the rheological properties of faecal sludge is necessary for the design of the waste collection and transport systems. Rheology is the description of the deformation of a material under the influence of stresses. Materials can categorise into Newtonian and non-Newtonian materials.

In Newtonian fluids, the shear stress is linear to the shear rate. The viscosity will be, therefore, constant at given conditions of pressure, temperature and solids concentration. Non-Newtonian materials have the shear rate relationship to shear stress being non-linear. The viscosity of the materials is then a function of the shear rate. Faecal sludge is a non-Newtonian material. Faecal matter exhibits shear-thinning and thixotropic behaviour (Septien et al., 2018, Woolley et al., 2014b). The faecal sludge follows the pattern where there is a decrease in viscosity with an increase in the shear rate. A decrease in viscosity occurs as moisture content of the sludge increases (Woolley et al., 2014b, Septien et al., 2018).

Faecal sludge is a viscoelastic material, which means it has both viscous (a part of the mechanical energy provided to the device dissipates as heat) and elastic (a part of the mechanical energy is temporarily retained mechanically) properties at the same time (Septien et al., 2018). When adhering to surfaces, attachments are created due to attraction forces between the surface and the material (Ghorbel and Launay, 2014). Rheological properties of the adhesive (faecal sludge) can influence both the time scales for the adhesive bond formation and the failure characteristics of the bond once formed (Kilcast and Roberts, 1998). The stickiness properties of faecal sludge depend on the viscoelastic reaction of the material when subjected to specific conditions and the surface energies of the sludge and the surface. The cohesive forces of the sludge are greatly affected by the rheology of the sludge as these forces are dependent on interactions of particles within the sludge.

The adhesive's and surfaces' physicochemical properties allow bonding through intermolecular attractions, without which no relation can be made. Not only the degree of these attractions, but also the viscoelastic properties of the sticky material where energy dissipation occurs, will affect the energy used during the removal of the material from the surface (Seyssiecq et al., 2003, Ghorbel and Launay, 2014). When a failure occurs between the sludge and the solid surface (interfacial or adhesive failure), energy is dissipated; however, in some situations, the failure can occur inside the sludge (cohesive failure).

The deformation mechanism that occurs during bond separation and its dependence on the adhesive structure are still poorly understood in adhesion chemistry. It has been accepted as true that if the cohesive force is high, the stickiness of the material to other surfaces is low. The phenomenon is known as the Dahlquist criterion. It is when the adhesive forces are higher than the cohesive forces, the stickiness to the surface is manifested (Hoseney, 1999). The higher the separation rate of the material and the surface, the larger the work of de-bonding of the particles at the surface, indicating that rheology partly controls material adhesion. If the material is elastic, the adhesive force can be overcome, and the material will separate from the surface, meaning that the material is not sticky to the surface. If the material is viscous, it will flow and not overcome the adhesive force that is; the material is sticky to the surface (Heinrich Grausgruber et al., 2003).

The organic matter (proteins and polysaccharides) in the fiber, as well as their interactions with moisture, are critical factors in determining viscosity and stickiness (Huault et al., 2019, Li et al., 2014). In a study on fresh faeces, there is a decrease in viscosity with an increase in temperature (Woolley et al., 2014a, Woolley et al., 2014b). This has been defined in sewage sludge to be attributed to the disintegration of organic matters and the transformation of the bound moisture to unbound moisture before mechanical dewatering is done on the sludge (Deng et al., 2019a). As such the interaction of the sludge particles at increased temperature affects the cohesiveness of the sludge. The yield stress at which the faecal sludge starts to deform in a viscous way can be identified for faecal sludge from the relationship between the viscosity and the shear stress (Septien et al., 2018). Yield stress gives the shear stress value required to induce flow in a material. This can be taken as an indicator by definition for the sticky region discussed in more detail in section 2.3.2.

2.3.1.3 Factors affecting stickiness

2.3.1.3.1 Moisture content

Stickiness is affected by wettability as established in the last section. The moisture found in the sludge thus contributes to the stickiness. The water activity influences cohesive and adhesive forces in the sludge. The ratio of the partial vapour pressure of water in a sample to the normal state partial vapour pressure of pure water determined at the material's temperature is known as the water activity. The water activity gives an indicator of the unbound and bounded moisture in a material. It gives a measure of water availability for the hydration of materials. This measure of the water available for hydration is an indication of the moisture that may aid in the wettability of the sludge, facilitating stickiness of the sludge. It gives an indication of the amount of “free water”, a measure of the amount of water available for physical, chemical or biological reactions. Hence it is a good predictor for the survival and growth of microorganisms in a material, mostly used in the food industry. The water activity ranges from zero (dry solid) to one (completely wetted material).

Adhesive force is affected by the wettability of the sludge, as a good wettability allows the sludge to stick to a surface. The unbound water in the sludge, therefore, becomes the significant contribution to the wettability of the sludge. When the material's surface energy is greater than the surface's, a thorough wetting of the surface occurs. More unbound water in the sludge is expected to increase the wettability of the sludge and in turn, increase the stickiness to surfaces if they are hydrophilic.

Water that exists on particle surfaces can be adsorbed as mono/multilayers or as duct condensation. This can allow particles to come together (stick together) as there is a reduction of surface micro-roughness thus increasing forces of attraction between the particles (Chen and Özkan, 2007, Adhikari et al., 2001). Fundamental stickiness signifies the energy necessary to break chemical bonds at the weakest plane of a film-substrate sticking system. It gives the summation of all interfacial intermolecular interactions between contacting materials (Ashokkumar and Adler-Nissen, 2011). If a liquid is in contact with solids, air (or any other type of gas) is also present, so there are three interfaces at the point of contact acting together, as illustrated in Figure 2-6 Therefore, it seems that the surface tension of both of these determines the overall material's adhesion property. The Young's equation expresses this (Equation 2-2).

$$\gamma_{SL} = \gamma_{SV} + \gamma_{LV} \cos\theta$$ *Equation 2-2*

Where γ_{SL}= surface tension at the interface of solid-liquid (N/m)

γ_{SV}= surface tension at the interface of solid-vapour (N/m)

γ_{LV}= surface tension at the interface of liquid-vapour (N/m)

θ= contact angle

The surface energy of the interfaces is directly proportional to the contact angle.

$$E = \gamma A$$ *Equation 2-3*

Where A = interfacial area (m^2)

E = Surface energy of the interfaces (Nm)

γ = Surface tension (N/m)

Knowledge of surface energy can help for material selection in the design of technologies.

The liquid bridges are significant contributors to the cohesive forces in the stickiness of sludge as discussed in section 2.3.3.2. The liquid bridges are between particles within the sludge and make the cohesive forces higher.

The properties which include surface tension, viscosity, and good solvation make water an appropriate catalytic agent for stickiness (Thota Radhakrishnan et al., 2018, Adhikari et al., 2001) as intermolecular forces between water molecules are due to hydrogen bonds. The hydrogen bonds require high energy to break (Gaffney et al., 2002); surface tension for water is therefore more significant than many other liquids.

The sludge adhesion and cohesion properties are a composite of its components (polymers and organic minerals) and their moisture relationship. At different moisture contents, organic matter and mineral material with small particles could contribute to adhesion and cohesion. (Li et al., 2014). Water is a ubiquitous plasticiser for biological materials as it aids in the process of softening and increasing the flexibility of a material (Heinrich Grausgruber et al., 2003).

2.3.1.3.2 Temperature

There are extensive studies on stickiness in the food industry on how temperature affects stickiness. The temperature of a material governs whether the movement of its molecules is in a frozen state (glassy) or viscous or mobile state (rubbery). It has been widely accepted that viscosity is a function of temperature. Particularly in food industry, if the temperature exceeds the glass transition temperature, the material will transform into a liquid-like state that is related to stickiness. This implies that if a material is at a temperature lower than the glass transition temperature, the stickiness and also the adhesion phenomena will not occur (Bhandari and Howes, 2005). Thus an essential indicator for stickiness would be the difference between the temperature of the material during the process and the glass transition temperature of the material. This also gives the sticky range region temperature of the material. Sludge, on the other hand, does not have a glass transition temperature, and the conversion of the sludge from liquid to solid is not reversible. Studies with sewage sludge have concluded that there is no change in the stickiness property at both temperatures 120^{o}C and 200^{o}C (Geanna Hovey et al., 2017). However, the studies do not indicate how the combined variation of temperature and moisture content affect the sticky region location. Other researchers also noticed that the temperature at which the sewage sludge is dried only has a minor effect on the sticky range location (Huault et al., 2019).

2.3.1.3.3 Applied force

Increased stress or compression of a material enhances caking and stickiness in the case of small sized particles which may include powders. This phenomenon assists the soluble components of a system by assisting in fostering the proximity for development of van der Waals forces and is dependent on the humidity and temperature of the surrounding environment (Heinrich Grausgruber et al., 2003). Pressure influence is not instantaneous, and thus the time factor will also influence the effect of applied forces on the stickiness (Chen et al., 2008). Pressure brings the particles of material close together, reducing the distance between them, thus increasing the surface area of contact allowing for bridges to form and for forces like van der Waals forces to come into play (Adhikari et al., 2003).

2.3.1.3.4 Surface geometry and properties

The surface geometry plays a vital role in determining the stickiness property. For certain flat surfaces, a water droplet comes to rest at a local energy minimum due to chemical composition or topography (Cheng et al., 2010). As a result, advancing and receding water droplet movements encounter energy barriers, resulting in contact angle hysteresis (the difference between advancing and receding contact angles) (Sangbae et al., 2008). This principle could also be applied to other materials like faecal sludge, as its stickiness could be expected to increases when the sludge is entirely wetted and on a flat surface with high roughness. The wetting of the solid surface is associated with the surface energy of the liquid and the solid surface. The surface energy of the solid substance must be greater than that of the liquid in order to achieve wetting (Palabiyik et al., 2014). It has been accepted that hydrophobic surfaces are characterised by large contact angle and small sliding angle (i.e. the angle of the surface inclination at which liquid begins to slide due to gravity), and thus they are less prone to cause stickiness (Cheng et al., 2010). Super-hydrophobic surfaces can be made by combining appropriate surface roughness with low surface energy. Usually, inorganic materials exhibit higher surface energy as compared to that of organic materials. As a result, organic products have a low wettability or stickiness propensity. Since metals have a high surface energy, materials tend to adhere to them more. Due to their low surface energy, polymers are difficult to wet (Sangbae et al., 2008). Concave tips characterise hydrophilic surfaces, and thus high wettability is achievable (Cheng et al., 2010).

Surface energetics influence the adhesion forces. The surface energetics include hydrophobicity and surface charge (Bhandari and Howes, 2005). If the contact area is large with a low contact angle, the liquid bridge between the material and the surface will increase with time, thus causing an increased adhesive bond. It has been established in the food industry that during the sticky phase, the surface energy of a material increases. This leads to greater interactions between the material and the surface, thus increased stickiness is recorded (Muzaffar et al., 2015). In order to reduce the contact area between the material and surface, the surface must have low surface energy. the cohesion of wet or semisolid particles happening because of a viscous flow driven by surface energy is explained by Frenkel's equation which states that (Kudra, 2003):

$$\left(\frac{x}{a}\right)^2 = \left(\frac{3}{2}\right)\left(\frac{\gamma t}{a\mu}\right)$$

Equation 2-4

Where x= inter particulate bridge radius (m),

a= particle radius(m)

γ= surface tension (N/m)

t= contact time(s)

μ= critical viscosity (N.s/m^2) /(Pa.s)

According to this equation, a higher viscosity, which allows for more flowability, a greater particle radius, and a lower surface energy (tension) of the material will help to avoid stickiness (Bhandari and Howes, 2005).

2.3.2 Sticky region during drying

The sticky region is the moisture content given by a range in which materials exhibit the highest stickiness (Cao et al., 2016, Bhadra et al., 2013). The sludge's sticky region in the drying process is mostly due to the sludge's composition. During the drying process, the variations in moisture content and drying rate are essential to allow for an understanding of the varying changes in the physical properties of the sludge, as explained in section 2.2.5. Since cohesion and adhesion (stickiness) impact heat and mass transfer coefficients, residence time spread, and local solids keep up in dryers, drying rates drop significantly as sticky materials are dried in them (Kudra, 2003, Tock et al., 2013). Figure 2-8 shows the sticky region as represented on a temperature against moisture content curve. In the wet phase, the sludge can flow. With further moisture evaporation, the sludge transitions into a plastic-like state which requires a resilient shearing force to attain an increased degree of mixing and the drying rate drops. This phase is defined as the sticky region (Li et al., 2014, Bennamoun et al., 2013, Geanna Hovey et al., 2017).

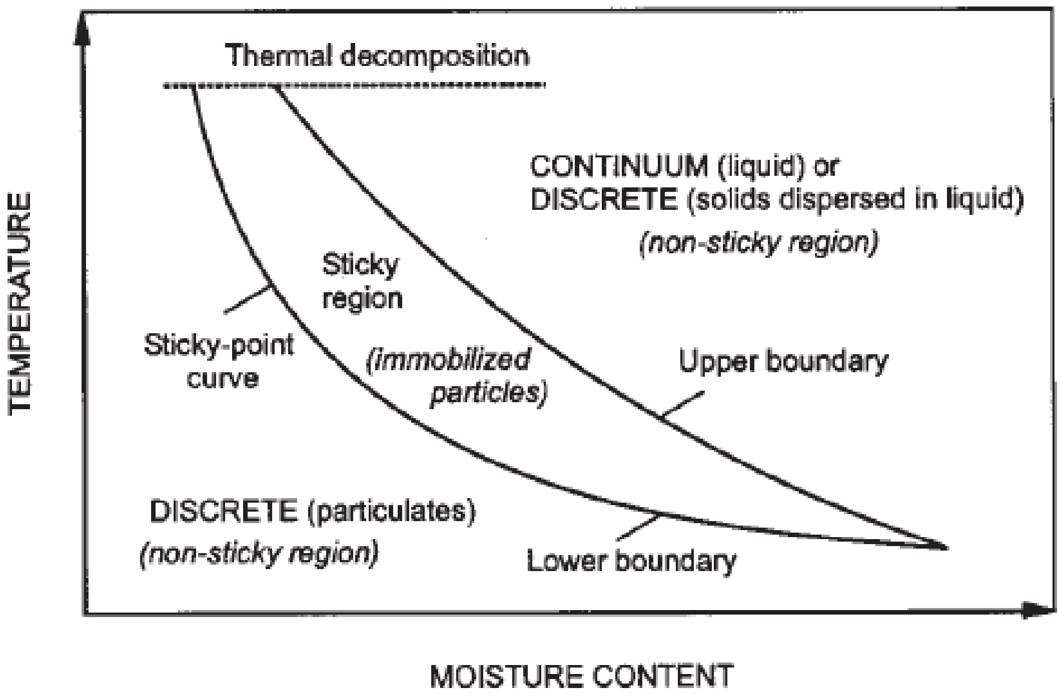


Figure 2-8 Sticky region graph (Kudra, 2003)

The sticky point temperature, which is measured by heating a previously dry material to the required or predetermined moisture content, is poorly understood (Kudra, 2003). The sticking point or peak is described as the point at which the bulk material resists movement and is no longer free-flowing for a given combination of temperature and moisture content. The sticky phase corresponds to the range of moisture content where the material exhibits the highest stickiness. In moisture content-temperature coordinates, the sticky point curve (stickiness curve) describes the boundary between the sticky region below the curve and the non-sticky region above the curve. The sticky peak is relevant to drying since it correlates material moisture content with temperature (Kudra, 2003).

2.3.2.1 Atterberg limits and stickiness

The phenomenon of faecal sludge remoulding without crumbling can be explained by the cohesion forces that exist between the particles and the water surrounding them within the material. Sludge has been found to behave in a similar way to mineral clays (Leonard et al., 2008). The method used to describe the variations in the consistency of soils concerning the change in moisture content is described by a Swedish scientist, Atterberg. As such in the same manner that physical properties of soils significantly depend on the plasticity of the soil and are expressed by the Atterberg limits, the sludge physical properties also depend on plasticity. They can be hence expressed by the Atterberg limits (Radford et al., 2015). Plasticity is the ability of the faecal sludge to be deformed without cracking or fracturing and to remain deformed under any externally exerted force.

The Atterberg consistency proposed limits consist in the liquid limit and the plastic limit. The liquid limit is described as the moisture content at which the faecal sludge transitions from exhibiting plastic behaviour to exhibiting liquid behaviour. The plastic limit is described as the minimum moisture content at which the faecal sludge exhibits plastic behaviour, below which the faecal sludge fractures. Seif (2017) states that the amount of organic matter in the soils greatly contributes to plasticity. This is assumed to be valid for faecal sludge as has been reported by earlier researchers (Radford et al., 2015); thus for faecal sludge with high total solids values, the plastic limit is lower as the region of plasticity increases. The plastic and liquid limit give a region that the stickiness phenomenon is expected to be highest, hence the sticky region. The stickiness peak is located between the plastic and the liquid limit.

The knowledge of the plastic and liquid limits allows for the shear strength, plasticity index, consistency index and liquidity index values to be evaluated, giving a more detailed understanding of the faecal sludge (Haigh, 2012). The plasticity index can give an indication of the cohesive internal forces of the faecal sludge when the value is high. Due to the high cohesive forces, the faecal sludge will also exhibit high compressibility as seen in soils. A high plasticity index will indicate low shear strength of the sludge.

As explained earlier, the shear strength of the faecal sludge gives an indication of the cohesive forces within the faecal sludge. The shear strength can also be deduced from the Atterberg limits. According to O'Kelly (2005), shear strength of sewage sludge increases with reducing moisture content mainly due to high organic content and colloidal activity. This is defined by the plasticity index to clay fraction ratio which corresponds to the total solids content ratio in the sludge material. The increased colloidal activity shows that the faecal sludge particles have a high surface area relative to their mass. Inter particle bonding is more pronounced and thus more cohesion between the solid particles.

The correlation of the liquid limit with clay strength and the plastic limit with the soil capillary suction has been shown by Basma et al., (1994); where capillary suction is the movement of liquids through a material due to the surface tension, it will be assumed that the same theories apply for faecal sludge (Basma et al., 1994, Haigh, 2012). Considering that the liquid limit gives the indication of minimal strength of the soil in the region in which it behaves as a plastic, the correlation of the plastic limit and the capillary suction of the faecal sludge would indicate how the plastic limit and consequently stickiness are affected by the drying process. The Atterberg limits on their own, however, do not give an adequate measure of the stickiness but can be used to give an indication of the presence of stickiness within the sludge and of the sludge interaction with surfaces.

2.3.2.2 Sticky behaviour of sludge

Research done on municipal sewage sludge has shown the presence of the sticky region during the drying process, and it can be assumed that these results can be translated to faecal sludge. In the sticky phase, the sewage sludge tends to adhere to the dryer surfaces. The heat transfer coefficients of the sludge are decreased by 60% for sticky materials compared to materials that are not sticky and this can affect the drying rate (Geanna Hovey et al., 2017, Bennamoun et al., 2013).The sticky region is affected by the nature of the sludge. Table 2-2 shows the sticky regions as defined by various researchers. The results in table 2.2 are within the same range between 30-70%wt and can be taken to have been almost similar.

Table 2-2 Municipal sewage sludge sticky region

Source	Sticky region (%wt moisture)
(Chen et al., 2002)	30-45
(Flaga, 2005)	45-65
(Kudra, 2003)	50-62
(Chun and Lee, 2004)	35-60
(Ferrasse et al., 2006)	43-69

Figure 2-9 shows the relationship of the dry solids content of the sludge with time, indicating the phases undergone by the sludge during the drying process. These include the wet zone, sticky zone and granules zone. These zones can be related to the typical drying curve in figure 2-4. The wet phase is characterized by a low dry solids content and free moisture. As the drying progresses, the free moisture is removed and the solids content increases with the interstitial moisture being predominant during the sticky zone. The surface moisture and bound moisture are removed in the granules zone, presenting the highest dry solids content. In practical situations the sludge may have deviations with respect to the zones described, as the variations in the sludge also make a contribution to these variations. According to a review done by Bennamoun et al. (2013), in a rheological view as the sludge dries, it begins to show a plastic tendency with a moisture content that is equivalent to that in the wet phase.

Ferrasse et al., (2006) studied the consistency change of faecal sludge in a conductive dryer. The authors state that as the sludge enters an agitated conductive dryer, the sludge is in the wet phase, i.e. saturated with water. After some time in the dryer, the sludge has experienced an increase in temperature, and the sludge starts looking thicker as it was dried and its viscosity increased. The torque of the agitated dryer was maintained constant or slightly reduced during the pasty phase, which corresponds to the wet zone from Figure 2-9. At this phase, the sludge had the highest heat transfer coefficient. As the moisture content further decreased, the sludge thus became lumpy with an increased in torque. This region of moisture content corresponded to the sticky zone. After this stage, the sludge became granular, corresponding to the granules zone where the heat transfer coefficient was almost constant and the torque was low (Bennamoun et al., 2013, Gold et al., 2016). Changes in torque variations distinguish the phases in the drying of sludge. Figure 2-10 shows the drying rate and the evolution of torque during conductive or contact drying. The torque varied with time, so with moisture content. The highest torque values were obtained during the transition from the lumpy phase to the granular phase (sticky region). The sticky region has been shown from experiments to have lower drying rates and heat transfer coefficients than the other phases (Bennamoun et al., 2013, Geanna Hovey et al., 2017). It can also be noted that the drying regime in an agitated conductive dryer can differ from the classical approach of convective drying (constant rate period followed by the falling rate periods) as it can be altered by the change of consistency.

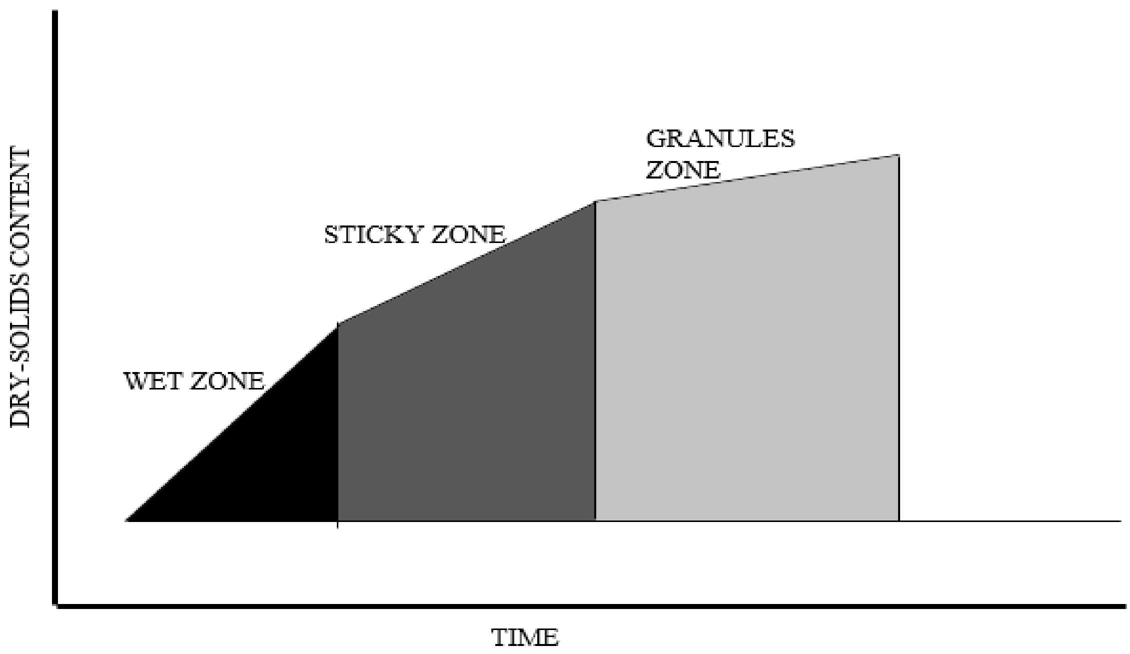


Figure 2-9 Phases of the sludge as a function of the solids content during the drying process (LOWE, 1995)

During drying, the material is converted from a liquid or semisolid to a granular state due to the removal of the plasticiser, i.e. water (Chen and Özkan, 2007). An increase in cohesive force inside the molecules could explain the increased tension in the microstructure of the substance. If the material does not transition from semi-solid to granular state due to higher drying temperatures, the material will remain in an increased energy “sticky” state. Therefore, if it comes into an interaction with a high energy solid surface, stickiness will occur and it will stick to it (Tock et al., 2013). The phenomenon in which the materials will detach from a surface during drying cannot be fully explained by granulation only. The sticky peak of a material is defined as the moisture content and temperature at which the stickiness of the material is at its highest. This is found within the sticky region.

2.3.3 Reducing stickiness in the sludge drying industry

In industrial sewage sludge drying operations, stickiness is a prevalent issue. During the drying process, the sludge passes through the sticky phase, which causes challenges, as discussed earlier. The equipment failure and increased downtime associated with stickiness in drying systems affects the feasibility of the sludge drying process in economic and technical perspectives. The challenges include drop of the performance of the equipment, reduction in heat transfer efficiencies and damage to the final product (Fryer and Asteriadou, 2009).

In order to enhance process control of the stickiness phenomena in industrial sludge dryers, charting the sticky sludge phase is necessary. Depending on the dryness range where the sludge reaches its sticky point, changes in moisture content or temperature will control the stickiness phenomenon for a particular sludge dryer. In order to curb the stickiness problem, additives have been researched as solutions although with limitations (Geanna Hovey et al., 2017). Back mixing has been used in trial and error experimentation to determine the conditions that avoids or limit the sticky characteristics of the faecal sludge (Deng et al., 2017, Leonard et al., 2008). The addition of sawdust to sewage sludge was found to increase the cohesive property of the sludge due to mechanical interlocking; the sawdust reduced the adhesiveness of the sludge. The overall stickiness of the sludge to the dryer surface would be reduced, and thus the problem of clogging averted (Deng et al., 2017). In industry, it has been a common practice to increase the torque capability of driers to cope with the sticky phase in drying. Lubricants, including poly aluminium chloride (PACI), have also been developed to reduce stickiness during drying (Peeters et al., 2013).

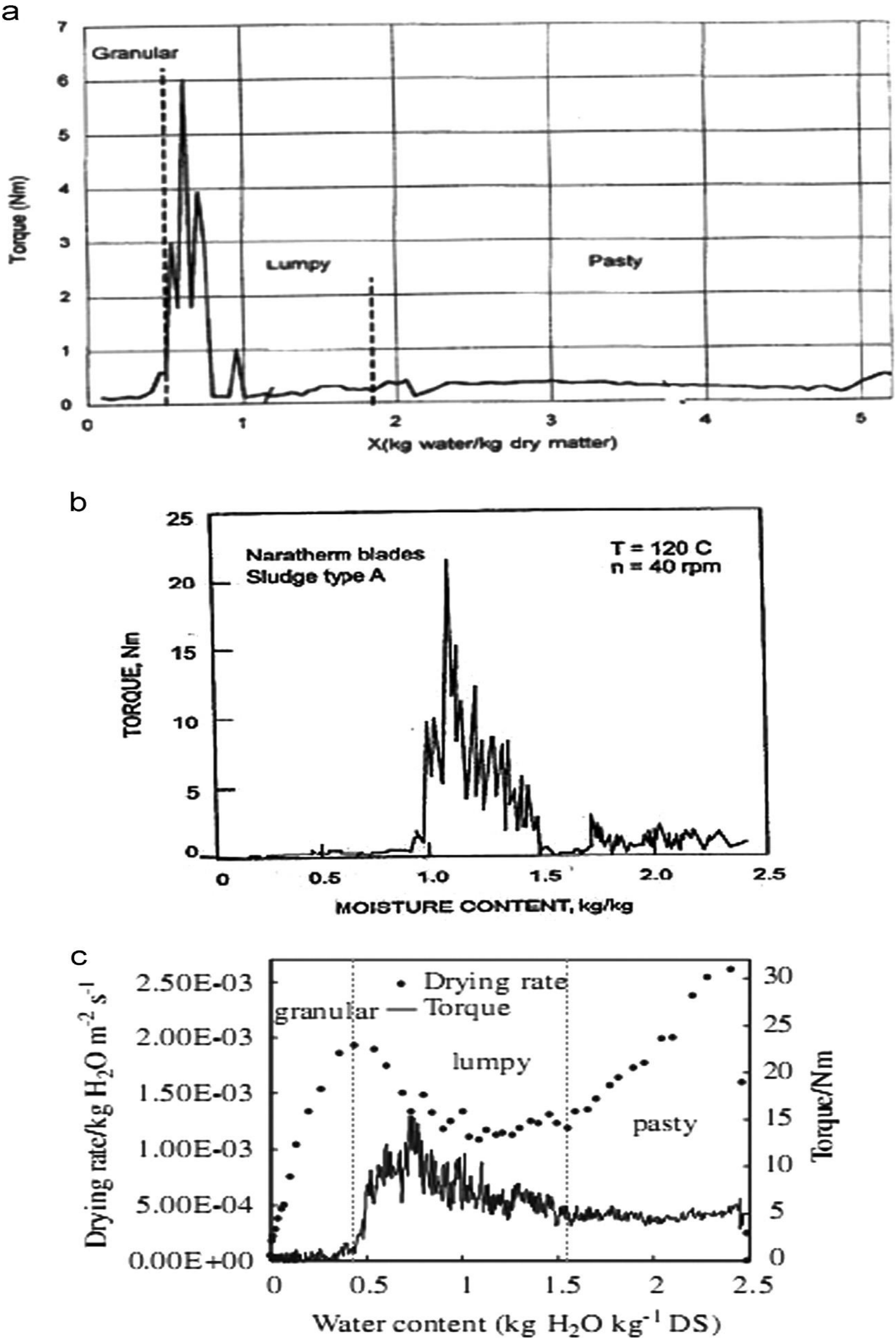


Figure 2-10 Evolution of torque during conductive drying (Bennamoun et al., 2013, Kudra, 2003, Ferrasse et al., 2006, Deng et al., 2017)

2.3.4 Analytical methods to measure stickiness

Many methods have been employed to determine stickiness in different materials. Most of the methods come the food industry with some of the methods adopted to determine stickiness in sewage sludge. However, the tests quantify the adhesive forces of the sludge, and the cohesive forces would have to be determined using other methods. The quantification of the forces using different methods could potentially give discrepancies in the overall stickiness values of the sludge.

2.3.4.1 Jenike and shear test method

The Jenike shear test has been used by researchers to define the sticky region. Figure 2-11 shows the schematic diagram of the Jenike shear test adapted from Peeters et al., (2011). Sludge is placed inside the open hollow cylinder (2) and compacted by the pressing action of a second cylinder. The open cylinder is attached to a flexible steel cable (5) that is used to increase shear stress on the sludge by use of weights that are added at the end of the cable until the cylinder starts sliding only to stop when the final mark (B') on the bench is reached. The test shows in sewage sludge that when the adhesive shearing stress is at its maximum, the cohesive stress continues to rise (Peeters et al., 2011). The results imply that the resistance between the sludge and the surface is less than the resistance of the sludge particles (Li et al., 2014). The tests performed using the Jenike shear test showed that the temperature of the sludge at 120ºC and 200ºC does not contribute to the sewage sludge stickiness (Li et al., 2014, Geanna Hovey et al., 2017, Peeters et al., 2011). The Jenike shear test was originally designed for analysis of the flow behaviour of the dry powders and thus is not well suited to determine the stickiness of wet sludge as it does not accommodate in its calculations the forces that are due to the wet properties of the sludge, despite modifications that have been done to the protocol leading to the development of the shear test method (Deng et al., 2019a).

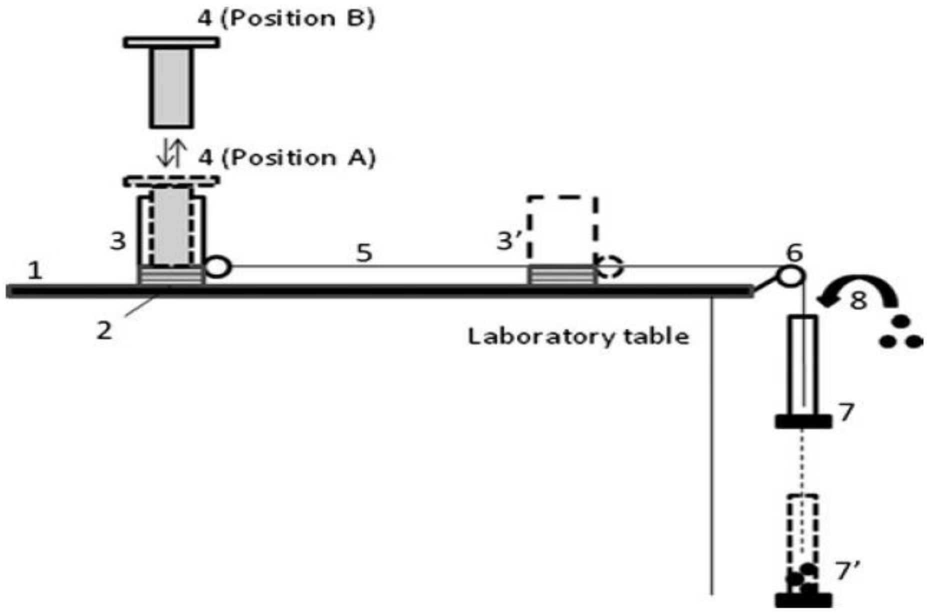
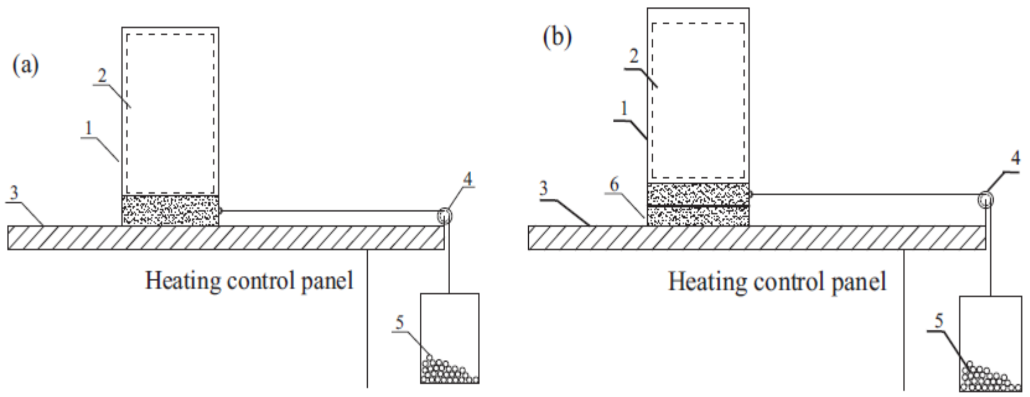


Figure 2-11 Schematic diagram of the Jenike shear testing device (Peeters et al., 2011)

The shear test method has also been used to determine the adhesive and cohesive stresses of sticky materials and was adapted from the Jenike shear cell (Peeters et al., 2011). Figure 2-12 shows a typical setup for the shear test method. The operational procedure involves placing the material shear device and applying a predetermined normal stress. This provides the necessary conditions for draining or wetting of the material through the porous and lower perforated plate as shown in figure 2-12 and finally consolidating the material under normal stress. Figure 2-12 illustrates the adhesive stress in (a) and the cohesive stress in (b). The test initially was designed to characterise powders and thus is limited in application for the characterisation of sludge. Studies by Deng (2019) have been done for stickiness, including temperature effect analysis on sewage sludge.



1 hollow cylinder; 2 massive cylinder; 3 stainless-steel heating plate; 4 pulley; 5 steel ball; 6 circular ring

Figure 2-12 Schematic diagram of sludge shear test a) adhesive stress test, b) cohesive stress test (Deng et al., 2019b)

2.3.4.2 The agitation method

Kudra (2003) has proposed to define the sticky region of materials by the stirring method. In this method, the force required to stir the material is measured to identify an increase corresponding to the beginning of the sticky region. This method has been referred to as the agitation method (Deng et al., 2017). The torque of agitation is regarded as the measure of the adhesive and cohesive stresses in the sludge. Figure 2-13 shows the schematic diagram of the agitated drying test.

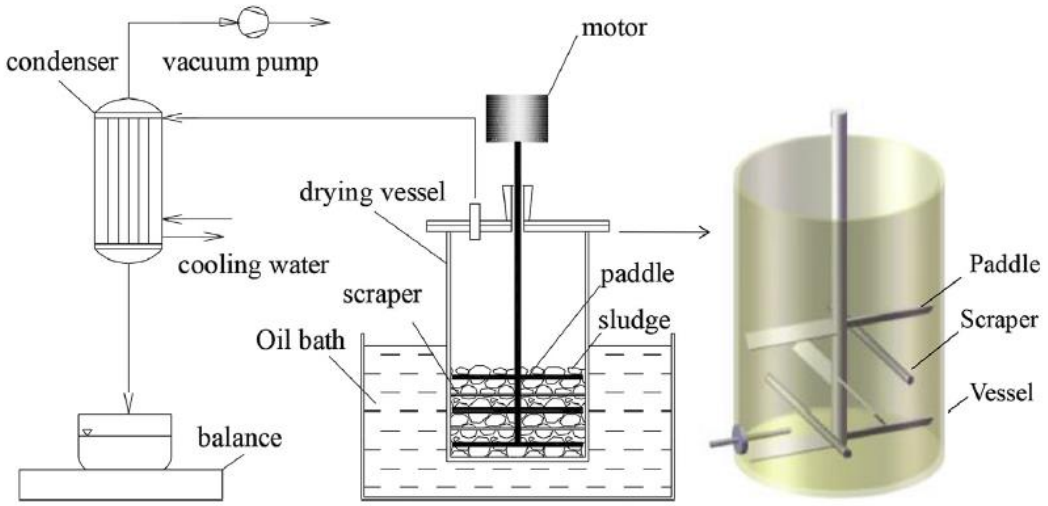


Figure 2-13 Schematic diagram of the agitated drying test (Deng et al., 2019b)

2.3.4.3 The probe tack method

The probe tack method has also been used to quantify the adhesion and the cohesion failure modes by use of a probe under very low contact pressure into touching a sticky material for a predetermined time and to pull away with a fixed speed (Liu et al., 2006). The probe tack test, however, does not quantify the cohesive stress of the sludge. Further developments from the probe tack method have been proposed; however, they do not allow for temperature analysis.

2.3.4.4 Texture analyser

In this type of methods, the texture analysis quantifies the stickiness of faecal sludge. The principle of operation for the texture analyser is similar to the probe tack method; however, the equipment quantifies both the adhesive and cohesive stress of the sludge to give a more detailed understanding of the material stickiness. The equipment has been used in the determination of stickiness in flour doughs reliably (Heinrich Grausgruber et al., 2003). The texture analyser presents the following advantages over the other methods described:

- Quantifies both adhesive and cohesive forces contribution individually under the same conditions.
- The pressure applied on the sludge is fixed and not affected by the errors of the experimenter.
- The time and speed of the probe is well controlled, allowing replication of the results.
- It allows for a range of materials, hence it can be adopted for both low moisture and higher moisture materials.

2.4 Summary

The stickiness of faecal sludge is considered as the combination of adhesion and cohesive forces, determining if the sludge will adhere to a surface or its particles will adhere to each other more than they adhere to a surface. Faecal sludge has cohesion and adhesion properties that affect its overall stickiness property (Woolley et al., 2014a, Adhikari et al., 2001, Li et al., 2014, Thota Radhakrishnan et al., 2018). The cohesion property of the faecal sludge can be investigated from the rheological properties of the faecal sludge, and the adhesive property can be investigated by force required to separate the sludge from a surface. Stickiness poses a negative impact on the drying process except in the agglomeration of the sludge, where cohesion is essential for binding the particles (Bhandari and Howes, 2005). The stickiness of drying materials is a general concern since clustering of particles can alter the hydrodynamics of dryers. The increase in the concentration of solutes during drying can decrease the surface tension of the material dried, but the most influential factor is the increase in viscosity (Chen et al., 2008). The cohesive and adhesive forces on the surface of the material in the food industry during drying varies from the cohesive and adhesive forces within the bulk of the material (Muzaffar et al., 2015).

Stickiness is influenced by the amount of water in the sludge as moisture content and water activity referring to the boundedness of the water in the sludge. The structure of the sludge and the amount of organic polymers also affect the bonds that are present in the material, thus affecting the cohesive forces and the overall stickiness of the sludge. The temperature, the applied force on the sample and the surface geometry of the surface to which the sludge will stick are factors that have also been seen to affect the overall stickiness of the sludge.

Literature has little information on the stickiness of the faecal sludge in the best knowledge of the author with only limited information available on the stickiness of sewage sludge. The information on sewage sludge forms the basis of this study by relating the sewage sludge to faecal sludge. The available information on sewage sludge indicates the presence of sticky region at which the sludge exhibits the highest stickiness. The sticky peak is a combination of the temperature and moisture content at which the stickiness is recorded at the highest point.

This research tried to define and determine the sticky region of the VIP and UDDT sludge, including the sticky region and sticky peak. It also gave the relationship of the rheology of faecal sludge to the stickiness of the faecal sludge. The rheology gave an indication of the cohesive component of the stickiness. In literature it has been found that the rheology is influenced by moisture content and temperature (Septien et al., 2018, Thota Radhakrishnan et al., 2018, Tietze et al., 2016), therefore the same parameters were also investigated for stickiness. . The plastic and liquid limit were correlated to the stickiness results as the region between the plastic and liquid limits gave the moisture content region in which the faecal sludge exhibits plastic behaviour. Thus, it can be taken as an indicator of the sticky region. Experimental work to support these correlations was insufficient, and thus this research attempted to give a relationship between different types of measurements and the stickiness of the faecal sludge. As the drying process occurs, the moisture that is removed moves from free moisture during the constant rate period and transitions to interstitial moisture and surface water during the falling rate period in which the stickiness of the sludge was identified to be most significant and thus understanding the drying kinetics would give an indication of the relationship to stickiness and the moisture boundedness of the sludge. The research experimental work attempted to give the correlation of the drying kinetics, stickiness and the water activity.

3 MATERIALS AND METHODS

In this chapter, the faecal sludge feedstock, the equipment and experimental procedures employed to investigate the stickiness phenomenon are described. The analytical methods used for the treatment of data is also described. The research was approved by the UKZN Biomedical Research Ethics Committee approval number BREC/00000204/2019. The ethical clearance certificate is given in **Appendix B.**

3.1 Description of the feedstock

3.1.1 Sampling

Faecal sludge samples were collected from ventilated improved pit (VIP) latrines and urine diversion dry toilets (UDDTs) located in the eThekwini Municipality (Durban metropolis, South Africa). The samples were collected from a faecal sludge treatment plant located in Isipingo (known as the "black soldier flies" plant) where sludge from a vast number of onsite sanitation facilities is delivered for their treatment. The samples can be considered as a composite from various numbers of toilets, which allows the sludge to be considered as representative of the area.

The samples after collection were transported to the Pollution Research Group (PRG) facilities, at the University of KwaZulu Natal (KZN), where it was screened using a 5 mm mesh to remove household solid waste. The screened sample was stored in a cold room at a temperature of 4ºC. The sampling, handling and all tests on the faecal sludge were done following the PRG-UKZN Standard Operating Procedures (SOP) accessible at http://prg.ukzn.ac.za/laboratory-facilities/standard-operating-procedures.

3.1.2 Faecal sludge characterisation

The samples for both VIP and UDDT were analysed for an initial characterization before experiments were conducted. Table 3-1 shows the results of the faecal sludge characteristics. The results are within the range given by other authors who reported on faecal sludge from eThekwini municipality (Table 2.1). Throughout the experimentation process, moisture content verification was conducted randomly to ensure the samples maintain their moisture content even after being stored for a long period.

Table 3-1 Characterisation of the initial faecal sludge samples

Characteristics	**Type of faecal sludge**	
	UDDT	**VIP**
Date and location of the collection	21 November 2018 Black soldier flies plant at Isipingo, eThekwini municipality	21 January 2019 Black soldier flies plant at Isipingo, eThekwini municipality
Colour of the sample	Brown/ Green	Dark brown
Odour of the sample	Strong	Strong
Moisture content	71%wt	74%wt
COD	<500mg/l	<500mg/l
Ash content	13%wt	10%wt
pH	7.7	7.9
Electrical conductivity	5.6mS/cm	5.8mS/cm
Trash	Mainly newspaper, small pieces of aluminium packages and plastic	Mainly newspaper, small pieces of hair and plastic

3.1.3 Moisture content adjustment and analysis

The initial moisture content of the faecal sludge samples was measured using the PRG-UKZN SOP (Appendix A). The samples were manipulated for the modification of their moisture content. The higher moisture contents (80 and 90%wt) were achieved by adding distilled water. The lower moisture content (< 80%wt) were achieved by evaporating water from the sample in an oven at 105ºC and manually mixing the sample for 5 minutes with a stainless steel rod every 25 minutes. Mixing was done to ensure sample homogeneity and to avoid crust formation. At each mixing interval of time (25 minutes), the moisture content of the samples was measured in a thermal balance *Radwag max 50* Moisture Analyser balance, according to the PRG-UKZN SOP. This was done to check when the target moisture content during the sample preparation was achieved. The final moisture content was confirmed through the standard method (drying the sample in an oven at 105ºC for 24 hours), as stated by the PRG SOP. This was adapted from the Standard Methods of Water and Wastewater Examination (Tran, 2017). Triplicates were tested to give the average moisture content. The moisture content was evaluated as a wet basis (wb) and dry basis (db) evaluated as:

$$\%M_{db} = \frac{m_0 - m_f}{m_f} \times 100 \quad ; \quad \%M_{wb} = \frac{m_0 - m_f}{m_0} \times 100$$

Equation 3-1

Where m_0 is the initial mass of the sample before drying;

m_f is the final mass of the sample after drying;

M_{db} is the moisture content in dry basis;

M_{wb} is the moisture content in wet basis.

3.2 Laboratory experiments

3.2.1 Stickiness tests

The stickiness of the samples was investigated by the use of the *Stable microsystems TA. XT express* texture analyser. This analytical instrument is used extensively in the food industry and has been adapted in this study for faecal sludge. The probe used for the analysis was the *P75* compression platen. The experiments were conducted as stated by the PRG-UKZN SOP. The experiments were conducted using the compression and tension modes of operation as explained in the following sections. The tests gave the combined contributions of the cohesive bulk and surface adhesion forces. The tests were conducted on faecal sludge of varying moisture content from 90-20%wt and temperature varying from 25, 40, 60 and 80°C, as likely to be encountered during the drying process. The mass of sample used for the experiments was determined after a series of experiments that depicted how this factor affected the stickiness of the sample. Results of this analysis is given in **Appendix A1.**

Each of the tension and compression modes was more suitable to be applied to samples at a given moisture content range. The tension mode was used for samples with moisture content lower than 60%wt, whereas the compression mode was employed for the samples with moisture content above and including 70%wt. The results from the texture analyser compression mode and tension modes were compared by performing tests in triplicates using the VIP and UDDT samples. The experiments were done at ambient temperature and moisture content of 70%wt. The results were compared using the analysis of variance (ANOVA), which gave p-value of 0.90 and 0.86 for the adhesive and cohesive, respectively. Through this comparison, the assumption that the compression and tension modes give the same results is accepted. Results for this analysis and comparison are given in **Appendix A2**.

Overall stickiness of the faecal sludge was derived as the sum of two contributions, adhesive force (negative force) and the cohesive force (positive force), as displayed in Equation3-2 (Hoseney, 1999).

$$Overall\ stickiness = cohesive\ force + adhesive\ force$$

Equation 3-2

3.2.1.1 Compression mode

For the compression mode tests, an amount of 100g sample of faecal sludge was introduced in a stainless steel petri dish (80mm diameter and 80mm depth). After that the sludge sample surface was allowed to sit and levelled by the use of a spatula, the petri dish with the sample was placed on the work area of the texture analyser and locked in order to avoid any movements during the experiment. The testing piston (75mm diameter compression platen with contact area 4417.86mm^2) was used in the experiments. Preliminary tests were conducted in order to find working conditions of the experiments. The piston was moved until it reached the top surface of the sludge sample, from where it started to compress the sludge at a speed of 2mm/s and force of 0.098N (equivalent to 10g) until the probe has moved a distance of 5mm. Afterwards, the probe was driven back up to its initial position at a speed of 10mm/s, thus exerting the pulling force on the faecal sludge. The force exerted on the faecal sludge to compress it (cohesion component of the sludge), and the force exerted to pull away the probe (adhesion component of the sludge) contribute to the overall stickiness of the material. The distance the probe moved as it exerted the constant force of 0.098N was maintained for each test at 5 mm. Experiments were conducted in replicates of at least five tests using different subsamples of the main sample. The results were given by the apparatus software to determine the maximum force and work used to separate faecal sludge from the probe (a measure of adhesion) and compress the sample (a measure of cohesion).

3.2.1.2 Texture analyser tension mode

An amount of 100g sample of faecal sludge was placed in a stainless steel petri dish. When the sludge sample was prepared and the petri dish secured not to move during the experiment, the testing piston was moved to compress the sample until the texture analyser read overload. At this stage, the faecal sludge sample was assumed to have been compressed to the maximum. The tension mode was then run at a test speed of 3mm/s at which the probe moved a distance of 10mm from the faecal sludge and compresses the faecal sludge again to return to its initial position. These conditions of experiment were determined from preliminary tests to find the most suitable settings. Results were given by the software to determine the maximum force and work used to separate (adhesion component) and compress (cohesive component) the faecal sludge, providing the measure of adhesion and cohesiveness respectively.

3.2.1.3 Stickiness tests at high temperature

Temperature was varied for all the moisture contents from 20-90%wt experiments from ambient temperature, 40^{o}C, 60^{o}C and 80^{o}C. The temperature was controlled using an oven and a water bath. The samples were covered by foil paper to avoid moisture evaporation during heating and placed in the oven at the temperature that the tests were to be conducted. The temperature was monitored by type-k thermocouples inserted into the sludge and connected to data loggers.

Figure 3-1 Texture analyser setup with temperature control

After the desired temperature was achieved (40, 60 or 80^{o}C), the sample was moved to the texture analyser setup. A water bath was situated next to the texture analyser in order to maintain the temperature of the sample at the desired value. Figure 3-1 shows the laboratory texture analyzer set-up with the temperature control system (water bath). The temperature in the water bath was slightly higher than the set temperature to offset the heat losses to the environment. The sample crucible wall was heated by a spiral copper tube where the heated water from the bath circulated. The temperature in the water bath and the samples were continuously monitored by the use of thermocouples. Both types of sludge (VIP and UDDT) showed a notable increase in volume when the samples are heated in the water bath whilst covered with foil paper. The results and analysis of the volume changes are given in **Appendix A3.**

3.2.2 Rheometry

Rheological measurements provide an insight into the viscoelastic behaviour of a material. Thus the viscoelastic properties of the faecal sludge were measured using an *MCR72* rotational rheometer from *Anton Paar*. Rheology measurement was conducted at varying sample moisture content from 70 to 90%wt. No experiments at lower moisture content could be performed in the rheometer as the samples were not able to flow under the experimental conditions. Rotational tests were conducted to characterize the flow properties of the sludge. The cup and vane configuration was selected for these tests as it is the most adapted for viscous materials with the presence of solid particles (as faecal sludge), and it also minimises the effect of wall slip during the tests.

Figure 3-2 shows the *MCR72* rotational rheometer from *Anton Paar*. The cup used is a *BMC 90* model (including an inner cage to prevent slippage of samples) and the vane used is a stirrer *ST59-2V-44.3/120* model. The shear rate was varied from 0.1 to 100s^{-1}. The rotational torque of the vane was in the range of 1 to 200nNm. The experiments were done by having the vane rotating inside the cup. The shear stress range and viscosity were determined by the software of the rheometer from the measurement of the torque from the rotation of the vane. Each test took a total time of analysis between 25 to 30 minutes.

The temperatures (25, 40 and 60ºC) of the samples was maintained during analysis by use of the in-built P*eltier Plate P-PTD200/80/l*. The temperature at 80ºC was not investigated as it was not in the operational limit of the rheometer. For the experiments at 40 and 60ºC, the foil-covered samples were heated to the set temperature in the oven and then transferred to a water bath maintaining the respective temperature before analysis. The foil cover avoided moisture evaporation and ensured that the moisture content of the sample was maintained constant throughout the process. The inset Peltier plate which was 80mm in diameter. This procedure was performed per the SOP from the PRG-UKZN.

The sample mass for each test was 150g. Each experiment was repeated three to five times using subsamples from the main sample. Analysis of moisture content after the rheology tests and texture analysis tests were conducted to verify that no losses of moisture occurred during the experiments.

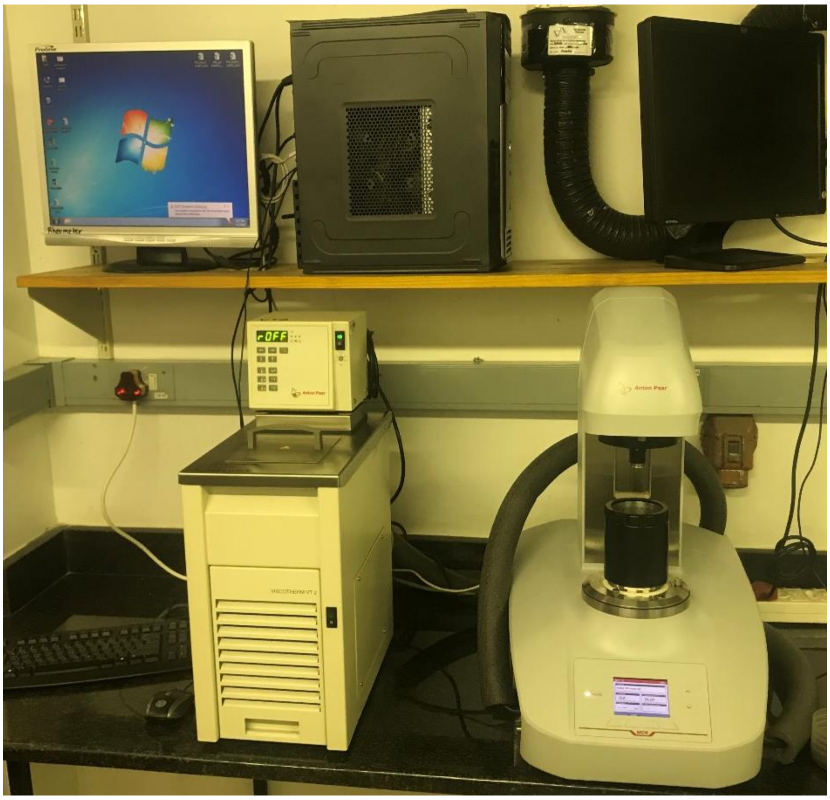


Figure 3-2 Laboratory set-up of the rheometer

3.2.3 Shear stress

A semi-automatic cone penetrometer was used to carry out penetration tests, and to calculate the shear stress, as well as the liquid and plastic limits of the faecal sludge. The experiments were done with manual reading of the penetration depths. The plastic limit of the faecal sludge was determined using a 240g stainless steel pre-weighed load, and the liquid limit of the faecal sludge was determined using an

80g load. The analysis of the tests was based on the depth of penetration of the standardised cone into the faecal sludge sample. The plastic limit and liquid limit are given by the moisture content of the faecal sludge when the penetration is 20mm with the respective loads. This approach to characterize the consistency of faecal sludge is adapted from the soil field. As such, the liquid limit gave the moisture content above which the sludge behaved as a liquid and plastic limits gave the moisture content above which the faecal sludge behaved plastically. Triplicate experiments were conducted for each sample. This procedure was performed per the SOPs from the PRG-UKZN.

The plasticity index of the faecal sludge is the difference between the liquid limit and the plastic limit and is dimensionless (Equation 3-3). This parameter is a measure of the cohesive properties of the faecal sludge and the indication of the extent of swelling or shrinkage of the faecal sludge in the moisture content range tested. The higher the plasticity index, the more internal cohesive forces the faecal sludge has.

$$Plasticity\ Index = Liquid\ limit\ (LL) - Plastic\ limit\ (PL)$$ *Equation 3-3*

The liquidity index measures the faecal sludge moisture relative to plasticity such that the liquidity index is 0.0 at the plastic limit and 1.0 at the liquid limit. As given in the study of soils, if the liquidity index value is between 0.0 and 1, then the soil will behave similarly to plastic material. If the value of the liquidity index exceeds one, the soil will behave similar to a liquid. The same principles were adopted for faecal sludge; the behaviour of the soil will be likened to that of the faecal sludge. The liquidity index of the sludge can be calculated by Equation 3-4.

$$Liquidity\ Index = \frac{(sample\ moisture\ content - Plastic\ Limit)}{(Liquid\ limit - Plastic\ Limit)}$$ *Equation 3-4*

The shear strength *(S_{ur})* was evaluated using the formula:

$$S_{ur} = \frac{k \times Q}{h^2 \times 1000}\ [\frac{kN}{m^2}]$$ *Equation 3-5*

Where: *k* is the drop cone factor = 1.33

Q is the force of the cone = 0.79N

h is the penetration reading from the cone penetrometer (m)

1000 is the conversion from N to kN

The sludge activity of the faecal sludge is the ratio of plasticity index to solids fraction of the sludge as a percentage. Faecal sludge activity is adapted from the calculation of soil activity and is given by Equation 3-6.

$$Sludge\ Activity = \frac{Plasticity\ Index}{\%total\ solids\ of\ the\ faecal\ sludge} \times 100$$ *Equation 3-6*

3.2.4 Water activity measurement

The water activity for faecal sludge samples at varying moisture contents from 20-90%wt was measured and the temperature varied at ambient temperature and at 40^{o}C. An *AquaLab* Tuneable Diode Laser (TDL) water activity meter was employed to characterize the binding of moisture with the dry matter within the faecal sludge. Figure 3-3 displays the water activity meter used in the laboratory. The water activity was analysed for samples with a moisture content from 20 to 90%wt in triplicates, using subsamples from the main sample. The tests were done at ambient temperature (22^{o}C) and 40^{o}C. Temperatures above 50^{o}C were beyond the experimental limit of the equipment.

A mass of 5g in average was placed in a sealed chamber during the analyses. In the head-space of the sealed chamber, a radiation beam was emitted by the tuneable laser at a specific wavelength range, corresponding to the water absorption band. A detector measured the incident radiation. At thermodynamic equilibrium, the relative humidity of air in the chamber headspace was equal to the water activity of the sample. The equilibrium relative humidity was determined by the analyser from the attenuation of the radiation emitted by the laser due to the water vapour absorption in the head–space, leading to the determination of the water activity of the sample. The time of analysis was 20 minutes for each analysis. The experiments followed the procedure stipulated from the PRG - UKZN laboratory SOP.

Figure 3-3 Water activity analyser

3.2.5 Drying rate analysis

Drying rate analysis was conducted on the faecal sludge samples at different temperatures. The faecal sludge samples were dried by exposing them to temperatures of 40, 60, and 80^{o}C in a *Radwag max 50* Moisture Analyser balance. Each experiment was done in triplicates using subsamples from the main sample. The initial average mass was 2.17 and 3.45g for the UDDT and VIP samples respectively. The surface area of the samples during the drying tests was constant at 4286.46mm^2. The Moisture Analyser instrument allowed to measure continuously the mass of the sample as time progressed during drying, recording the mass at 30-seconds interval until the sample is thoroughly dried and there is no further loss in mass due to water evaporation. This procedure was performed following the SOPs from the PRG-UKZN. The results were analysed to correlate the sticky region and the drying rate variations. The initial moisture content of the faecal sludge samples was 90%wt for all experiments. The drying rate was evaluated as:

$$Drying\ rate = \frac{\Delta m}{A \times \Delta t} \times 100; \qquad \textit{Equation 3-7}$$

Where: Δm = difference of mass between two consecutive measurements (grams)

Δt = difference of time between two consecutive measurements (minutes)

A = area of the sample being dried (mm^2)

3.3 Data treatment

Correlation of data from the texture analyser with measurements from the rheometer, water activity analyser, moisture analyser and cone penetrometer was done using Microsoft excel. All data was recorded for experiments done as triplicates or sets of 5 or more replicates. The uncertainty bar of the measurements was determined by applying the t-student distribution law with a confidence interval of 95%. Other statistical methods including regression analysis were also employed for the data analysis.

3.4 Qualitative observations

As the experiments were conducted, any visual changes in the aspect of the sludge were noted. These included the visual observation related to the consistency change of the sludge as it moved from liquid to granular solid. Other observations included sample volume. The volume changes were given by semi-quantitative measuring the height of sludge before and after the sample was placed in the water bath for heating. The volume changes are recorded in **Appendix A3**.

4 RESULTS AND DISCUSSIONS

This section presents the results of the experiments and their analysis, as well as comparison to findings from literature.

4.1 Stickiness

4.1.1 Effect of moisture content on the stickiness of faecal sludge

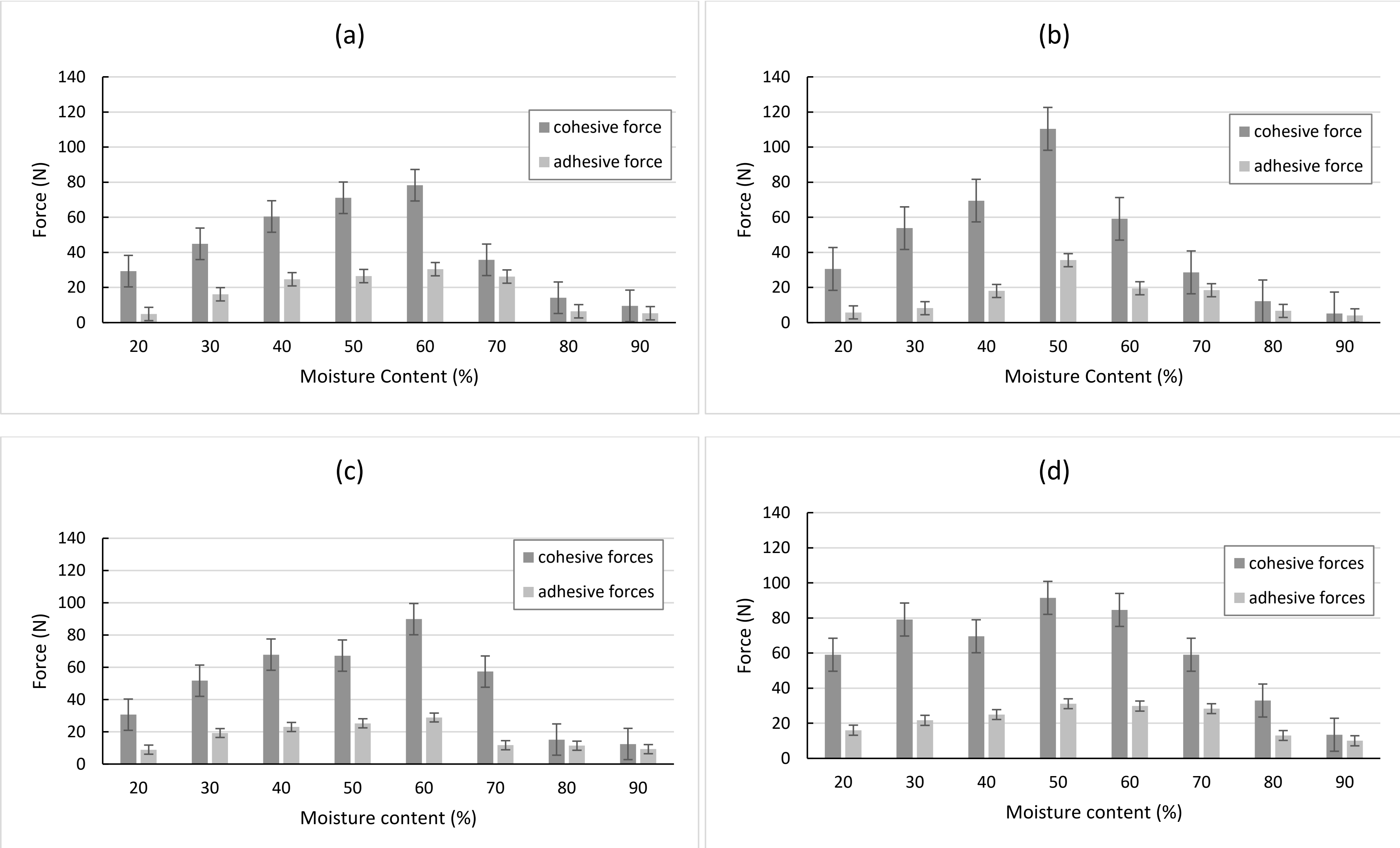
The force needed to compress and separate the probe from the sludge against moisture content is presented in Figure 4-1, which shows the cohesive/ adhesive force versus moisture content for UDDT and VIP at varying temperatures. The results in Figure 4-1 show that there is an increase in the force required for compression (cohesive) and the force required for the separation (adhesive) of the probe from the sludge as the moisture content decreased in the range of 50-90%wt.

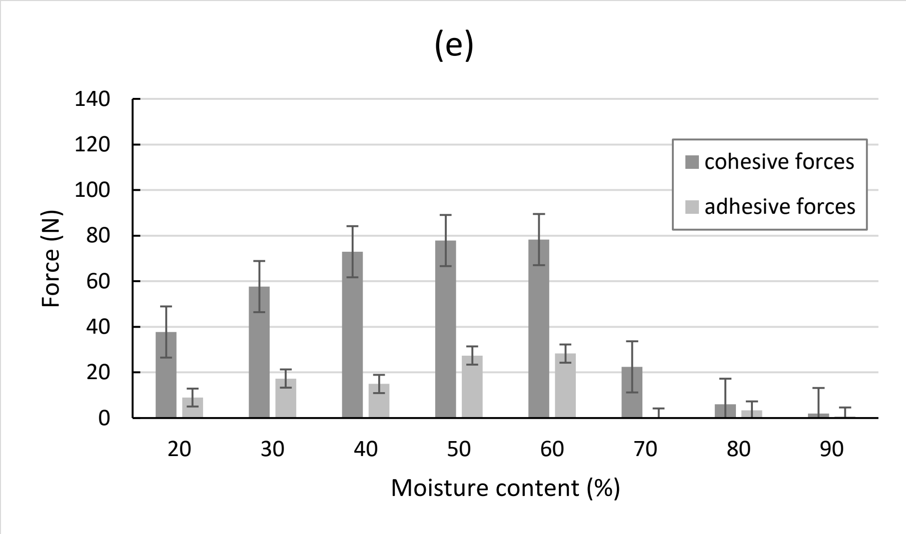
The increase got to a peak at 50%wt moisture content for the UDDT sludge for all temperatures after which the decrease in moisture content no longer increased the stickiness. This result suggested that the sticky peak for the UDDT sludge occurred at 50%wt moisture content for all temperatures. The higher cohesive and adhesive forces from a moisture content of 40 to 60%wt moisture indicated the sticky region for the UDDT sludge. The sticky region was the moisture content range in which the highest stickiness values were experienced for a particular temperature.

The VIP sludge results showed the sticky region being between 40% to 70%wt moisture content for all temperatures. The sticky peak for the VIP sludge was reported to be at 60%wt moisture content. The sticky region for both sludges fell within the ranges reported for sewage sludge (Peeters, 2010). The sticky peak for UDDT at ambient temperature was 110.43N (cohesive force) and 35.60N (adhesive force). The sticky peak for VIP at ambient temperature was 78.30N (cohesive force) and 30.45N (adhesive force). The relative stickiness of the sludge at the stickiness peaks is discussed in the following sections.

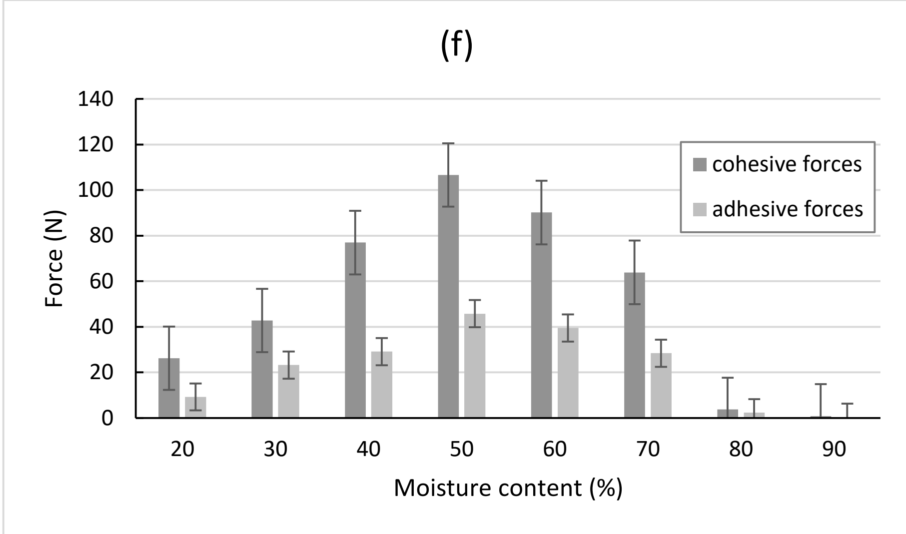
Both the adhesion and cohesion forces increased by a factor of ≈1.5 for every 10% decrease in moisture content for the sticky region range (40-70%wt moisture content) at ambient temperature. The standard deviation of the results was 7% with respect to the average stickiness value. The results showed that the average values of the adhesive force were half of the cohesive force of the sludge. It, therefore, implied that the overall resistance between the sludge and the contact surface (adhesion) was smaller than the internal resistance (cohesion) of the sludge components. This resistance has also been stated by Li et al. (2014) in his research on sewage sludge adhesion. The difference between the cohesive and adhesive forces greatly increased when the moisture content fell below 40%wt for both sludges. This has also been reported in sewage sludge by Deng (2017).

The cohesive and adhesive forces were low at high moisture content as the wettability of the faecal sludge was high. Thus as explained in section (2.3.4), the stickiness of the sludge to a surface was significantly reduced: the moisture acted as lubricant on the contact surfaces (inter-particle and particles-surface). Deng (2017) also found a similar trend in sewage sludge stickiness. Deng (2017) explains further that the cohesive forces at higher moisture contents decrease significantly due to the reduced internal resistance to the flow of sludge.

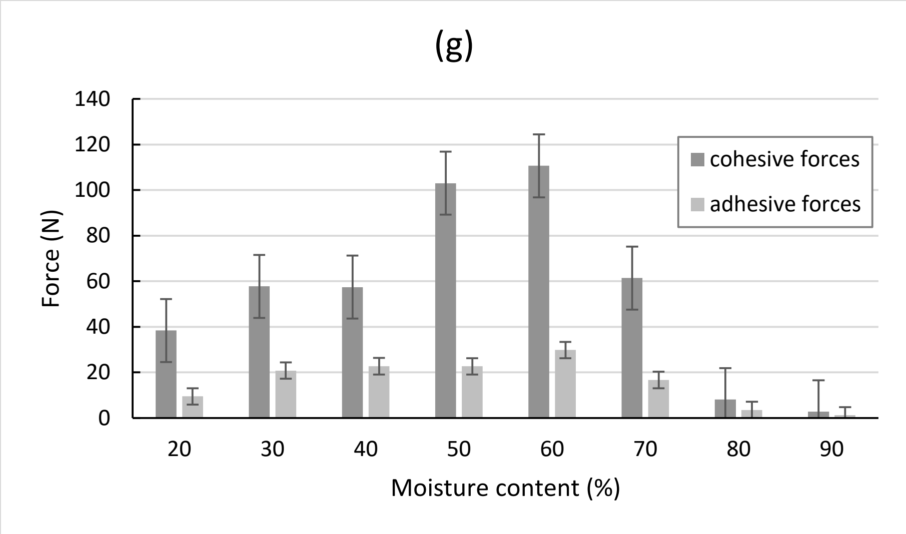

(a)
cohesive force
adhesive force
Force (N)
Moisture Content (%)
0
20
40
60
80
100
120
140
20
30
40
50
60
70
80
90
(b)
cohesive force
adhesive force
Force (N)
Moisture Content (%)
(c)
cohesive forces
adhesive forces
Force (N)
Moisture content (%)
(d)
cohesive forces
adhesive forces
Force (N)
Moisture content (%)



(e)
140
120
100
80
60
40
20
0
Force (N)
cohesive forces
adhesive forces
20
30
40
50
60
70
80
90
Moisture content (%)



(f)
140
120
100
80
60
40
20
0
Force (N)
cohesive forces
adhesive forces
20
30
40
50
60
70
80
90
Moisture content (%)



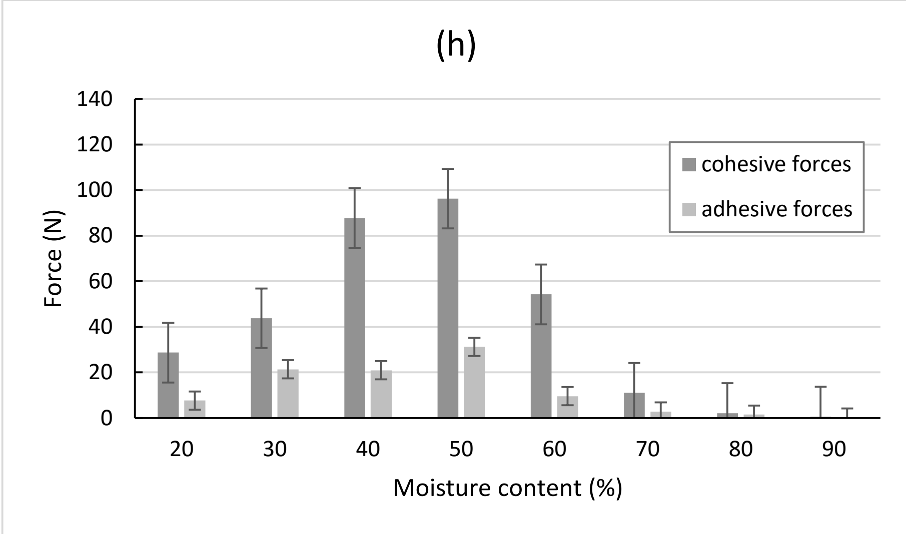


Figure 4-1 Cohesive/adhesive force against moisture content as a function of temperature (a) VIP sludge at temperature 25°C , (b)UDDT sludge at temperature 25°C , (c) VIP sludge at temperature 40°C , (d) UDDT sludge at temperature 40°C , (e) VIP sludge at temperature 60°C , (f) UDDT sludge at temperature 60°C , (g) VIP sludge at temperature 80°C , (h) UDDT sludge at temperature 80°C

4.1.2 Effect of temperature on the stickiness of faecal sludge

The trend of cohesive forces being higher than the adhesive forces is observed at all temperatures as shown in figure 4.1 and was also reported in literature for sewage sludge at ambient temperature (Deng et al., 2017). The factor by which the cohesive forces were stronger than the adhesive forces increased as the temperature increased, reaching a maximum at the highest temperature at which the cohesive forces were almost three (3) times as higher as the adhesive forces in the sticky region. This observation implies that as the temperature increased, the cohesive forces became stronger in comparison to the adhesive forces. This result has been supported by literature that shows high torque values were recorded and associated with increased temperature during the agitation of sewage sludge in the sticky region as the stirring is hindered by the presence of strong cohesive forces (Peeters et al., 2013, Bennamoun et al., 2013). The cohesive and adhesive forces increase with an increase in temperature for the temperatures tested in the research. The sticky peak of both the UDDT an VIP sludge did not vary significantly when the temperature was increased and thus it was taken that the sticky peak of the sludge was not affected by the variations in the temperature, for the temperatures tested in this research. The effect of temperature on the adhesive and cohesive forces on the different moisture contents of the VIP and UDDT sludge is illustrated in **Appendix A4.**

4.1.3 Comparison of the stickiness of UDDT sludge against VIP sludge

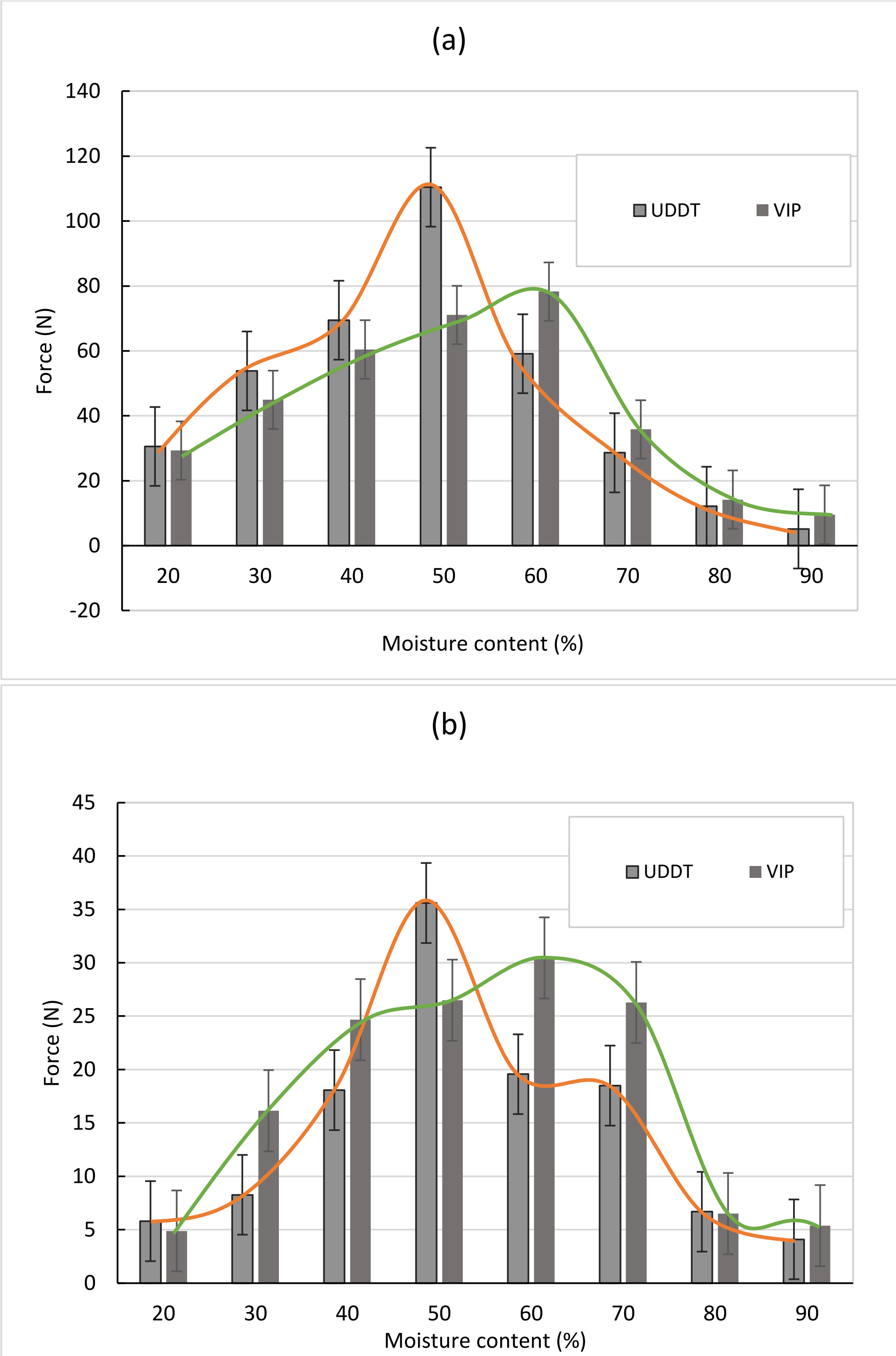


Figure 4-2 Force as a function of moisture content at ambient temperature a) Cohesive forces b) Adhesive forces

Figure 4-2 shows the comparison of UDDT and VIP sludge cohesive and adhesive forces against moisture content at ambient temperature as the other temperatures also followed the same trend as that illustrated for ambient temperature. The other temperatures are given in **Appendix A5.** The stickiness of VIP and UDDT sludge was quite comparable with a difference clearly only visible at the sticky peak.

Comparing graphs in Figure 4-1 and 4-2, the stickiness of UDDT and VIP sludges at all temperatures follows the same trend with only visible difference at the sticky peak. The sticky region for both sludge falls within the same range from 40% to 70% wt moisture content. The stickiness peak for the VIP and UDDT sludge was at different moisture content, with 60%wt for VIP and 50%wt for UDDT. The increase in temperature led to the increase of the stickiness parameters (cohesive and adhesive forces), indicating a decrease in sludge plasticity and flowabilty as reported as well for sewage sludge (Deng et al., 2019b). Analysing data presented in figure 4-1, the pattern of both cohesive and adhesive forces for both VIP and UDDT sludge at all moisture contents did not change as temperature increased from ambient to 60ºC, with only a decrease at 80 and 90%wt moisture content values.

The results showed that the effect of moisture content was more significant than the effect of the temperature on the cohesive and adhesive forces. As has been reported for sewage sludge, the significance of the factors affecting stickiness was in the order moisture content greater than sludge temperature (Deng et al., 2019b).

4.1.4 Stickiness as a function of cohesive and adhesive forces

The texture analyser gave the cohesive and adhesive forces of the faecal sludge at different moisture contents. The stickiness of the faecal sludge was given by the amount of force that is required to compress into/ penetrate the sludge and to peel off the faecal sludge from a surface (which is stainless steel in this instance) would thus be calculated according to the earlier in the methods section and calculated using equation 3-3. The relative stickiness is defined as the stickiness calculated with respect to a particular surface material, herein stainless steel. The area of the faecal sludge during experimentation at any temperature was constant, as the vials used in the experiments were all the same and standardised. The probe surface area was also standard and constant for all experiments, and thus the area component of the adhesive force was regarded as a constant. Figure 4-3 shows the force required to penetrate and to remove the faecal sludge at varying temperatures from a stainless steel surface.

The stickiness of UDDT was almost similar to that of VIP sludge at ambient temperature. Both the adhesive and cohesive forces of the sludges increased until reaching a peak and then decreased as was also observed for the relative stickiness of the sludges. The stickiness for each sludge was not significantly affected by increasing temperature at all moisture contents. The overall stickiness region of the sludges was comparable to the results reported for sewage sludge in section 2.3.2.2 with the stickiness peak at 50%wt for UDDT sludge and 60%wt for VIP. Both sludges were within the range of 30-70%wt.

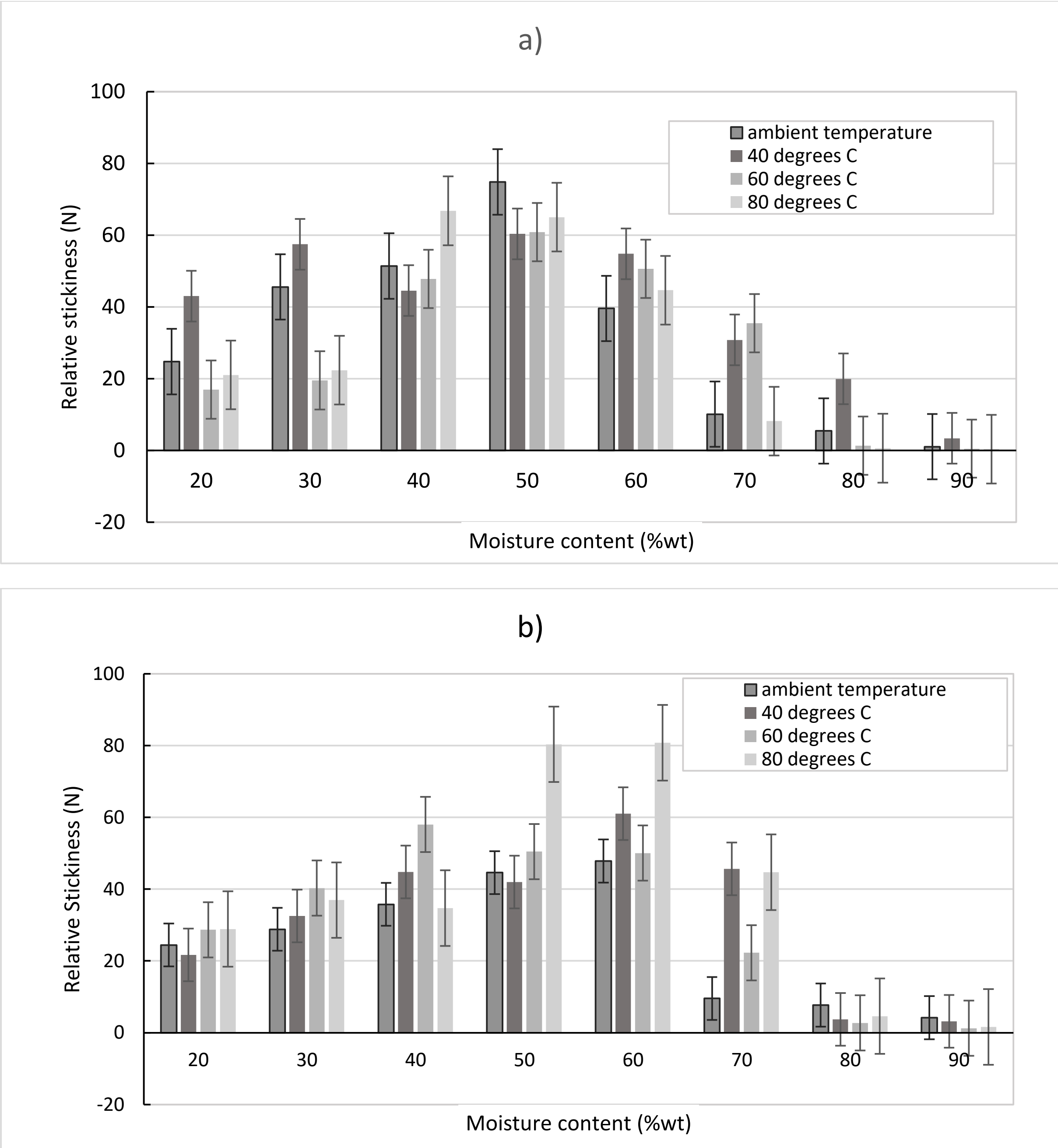
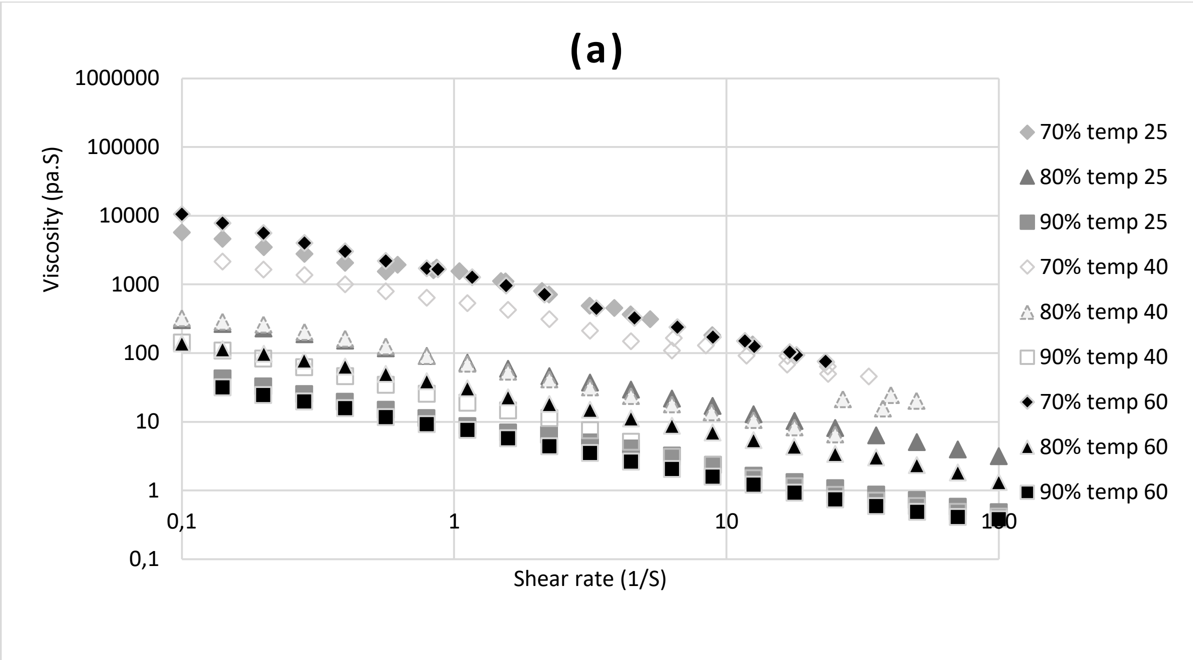


Figure 4-3 Stickiness of a) UDDT, b) VIP sludge

4.2 Rheology

4.2.1 Effect of moisture content and temperature on the rheology of faecal sludge

The effect of moisture content on rheology was investigated on samples of 70, 80 and 90%wt moisture content at different temperatures (25, 40 and 60^{o}C). As indicated in the methods section, the rheological properties of the samples with a moisture contents below 70%wt were not investigated as the material shows an inability to flow therefore indicating a loss of the viscous behaviour of the sludge due to change of consistency and thus beyond the operational limit of the rheometer. Figure 4-4 illustrates the relationship between viscosity and shear rate at the different moisture contents and temperatures. Both the VIP and UDDT sludge showed shear thinning behaviour, which corresponds to a decrease in viscosity and increase of shear stress by increasing the shear rate. This behaviour corresponded to what has been seen in the literature for faecal sludge (Septien et al., 2018). The results also showed that the shear stress and viscosity decreased at higher moisture contents.



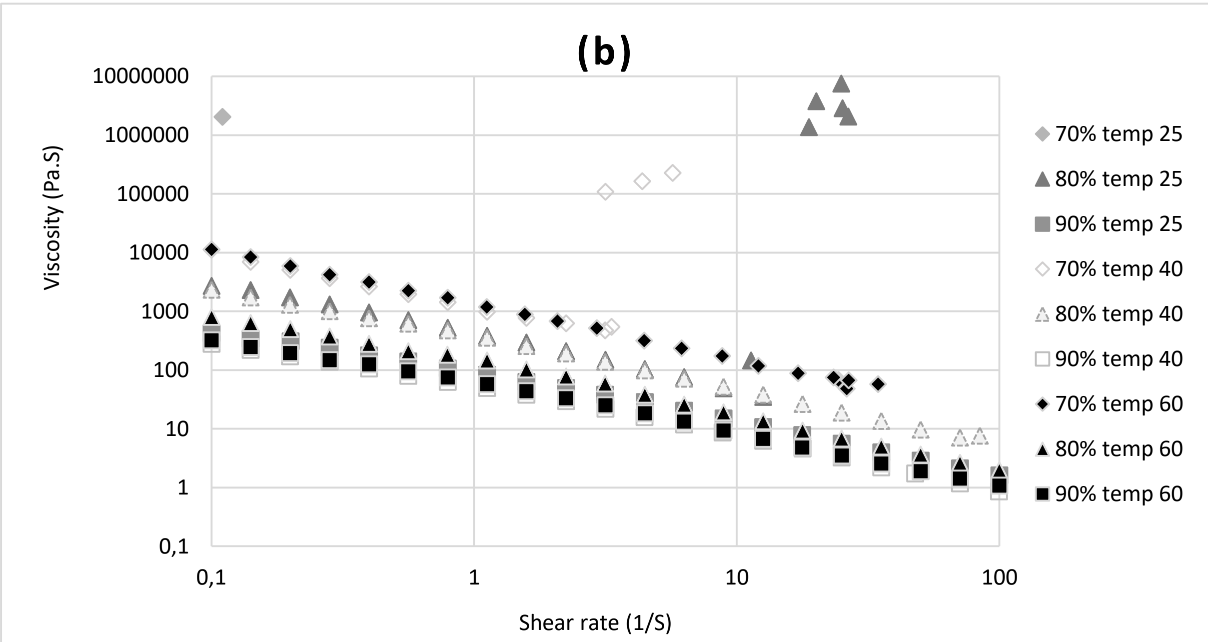


Figure 4-4: Viscosity versus shear rate as a function of moisture content and temperature (a) UDDT (b) VIP

The results showed that at any shear rate, the viscosity of the 70%wt moisture content samples was highest for all temperatures. This behaviour of higher viscosity at lower moisture content was also observed for fresh faeces (Woolley et al., 2014a). Figure 4-5 illustrates the viscosity of the sludge as a function of moisture content at a shear rate of $0.1s^{-1}$ at ambient temperature.

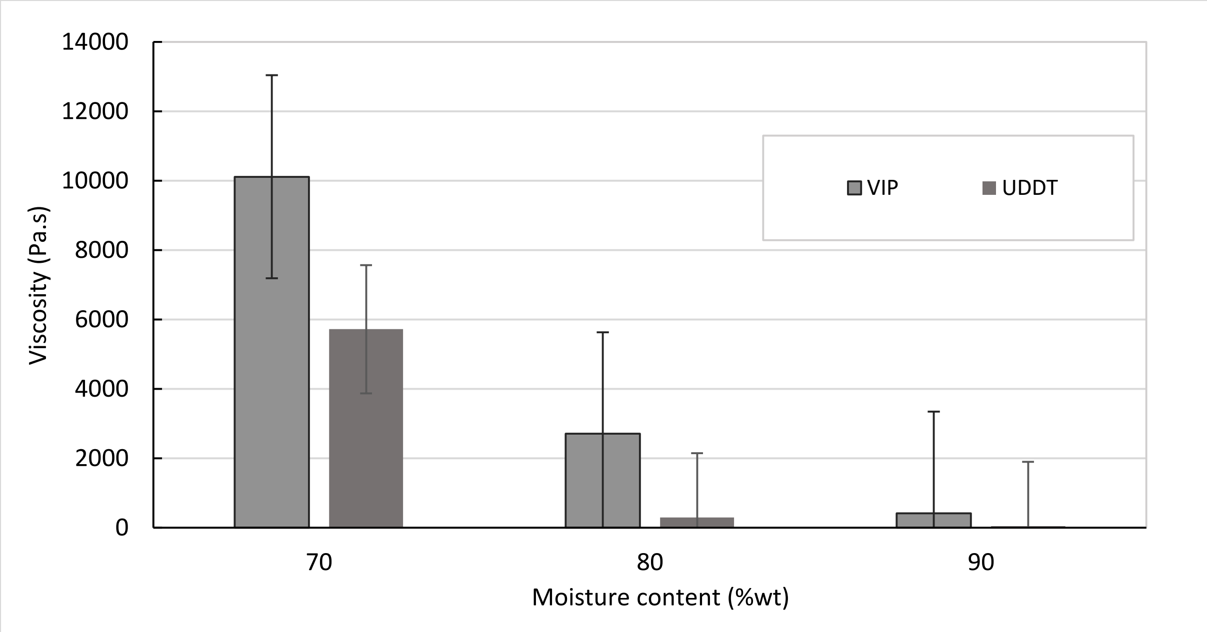


Figure 4-5: Viscosity as a function of moisture content at a shear rate 0.1s^{-1} at ambient temperature

The results in figure 4-5 show that viscosity at a shear rate of 0.1s^{-1} and at ambient temperature was higher for the VIP samples than for the UDDT sludge at the same moisture content. The results also show that the viscosity increased by a factor of 1.3 as the moisture content decreased by 10%. This result was almost the same as reported by Septien et al,. (2018a) who found that as moisture content decreased by ≈ 4%, the increase in viscosity was of one order of magnitude. Indeed, the decrease of the moisture content led to the increase of the solids content, making more difficult the sludge to flow, hence increasing viscosity. This resulted in an increase of the binding strength of the concentrated sludge particles, thus leading to a higher cohesion of the sludge. It, therefore, followed that an increase of moisture content enabled to lower the viscosity of the sludge by lowering the cohesiveness of the material. The cohesive forces increased with the same magnitude as the viscosity and these viscosity variations within the sludge can be an indication of the variations in stickiness of the sludge within the same moisture content region.

The results in figure 4-4 show that at the same moisture content, there was no significant changes as temperature increased. There are different results as a function of temperature at a given moisture content. However, the differences do not follow a clear trend, thus an observation on the effect of temperature on the rheological properties of the sludge is not given. The unclear trend could have been because the analytical instrument that was used in this experiment could not detect the small changes on the effect of temperature on the faecal sludge. This result was not expected as according to studies in sewage sludge and as confirmed through investigations with faecal sludge that the increase in temperature would have led to a decrease in viscosity (Deng et al., 2019b). The highest moisture content at the highest temperature showed similarities through the uncertainty bars with the viscosity at the lowest temperature for both the UDDT and VIP sludge.

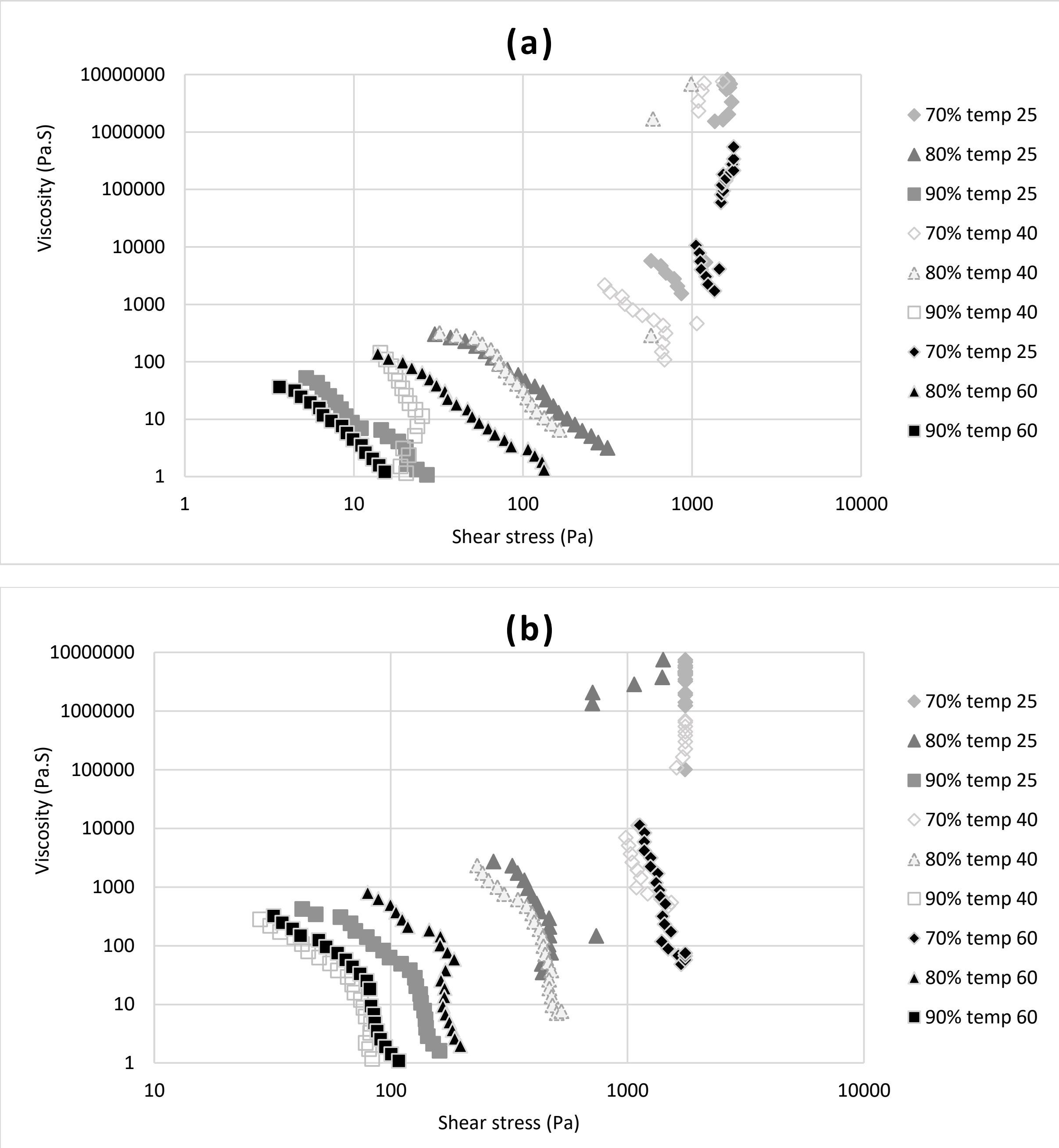


Figure 4-6: Viscosity versus shear stress as a function of moisture content and temperature (a) UDDT (b) VIP

Figure 4-6 displays the graph of viscosity versus shear stress. The viscosity decreased as shear stress increased until a point at which it drops drastically. This point corresponds to the yield stress of the sludge. At this point, the sludge starts to deform and flow, behaving in a plastic way. Below the yield stress, the sludge deforms elastically, such that after removing the strain on the sludge it reverts to its initial state. As discussed earlier (section 2.3.4.1), the yield stress value corresponds to the minimal shear stress to apply for the material to flow. The curves show a similar shape as reported in literature (Septien et al., 2018).

The rheological behaviour of sludge states that sewage sludge may show different adhesive and cohesive properties under different shear rates (Ratkovich et al., 2013). The shear rate increased the shear stress slightly increased as given by the results in **Appendix A6**. The lower the moisture content, the higher the shear stress experienced for any of the shear rates investigated and this agreed with what has been reported in literature (Woolley et al., 2014a, Woolley et al., 2014b).

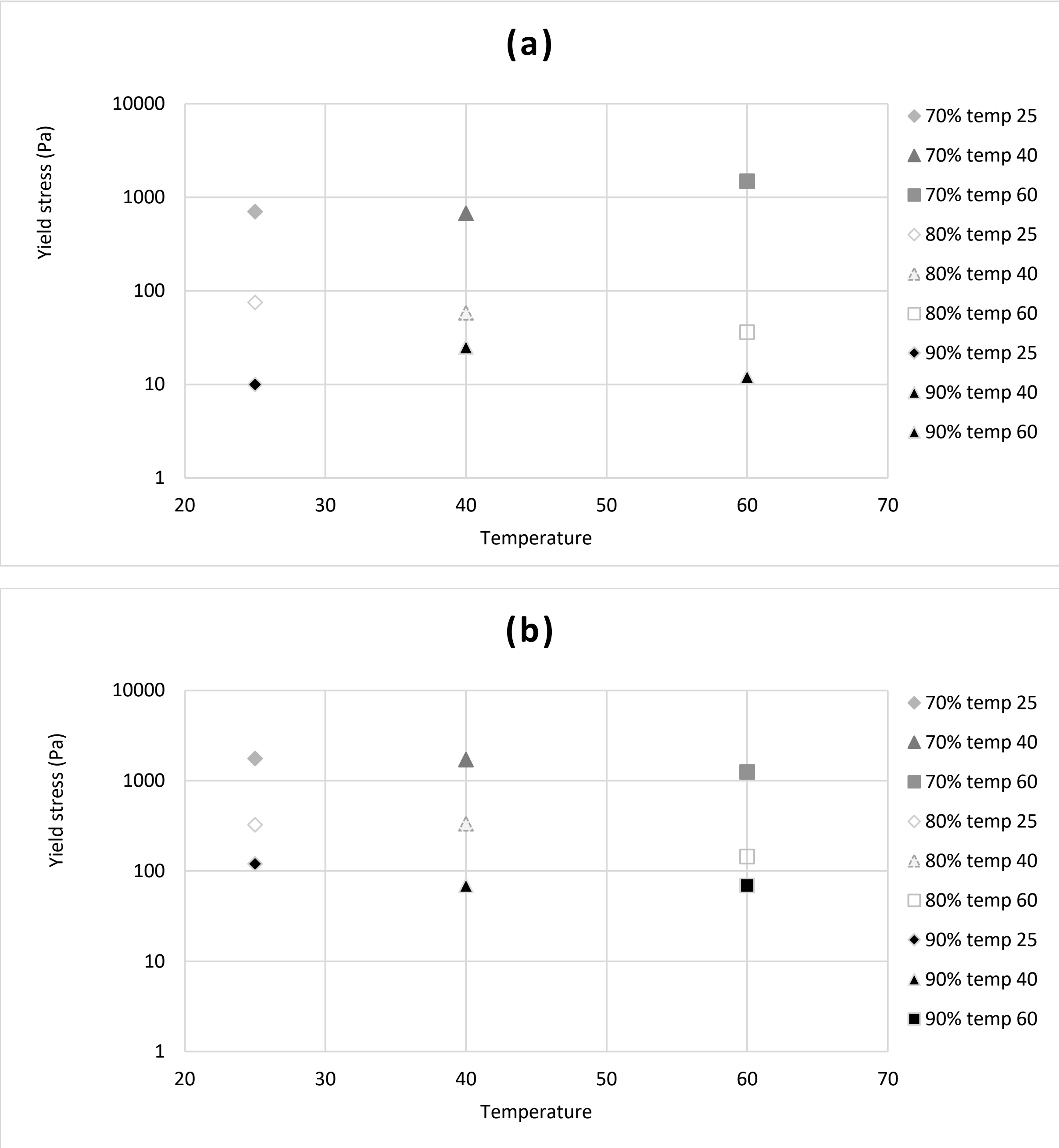


Figure 4-7: Yield stress as a function of temperature and moisture content a) UDDT, b) VIP

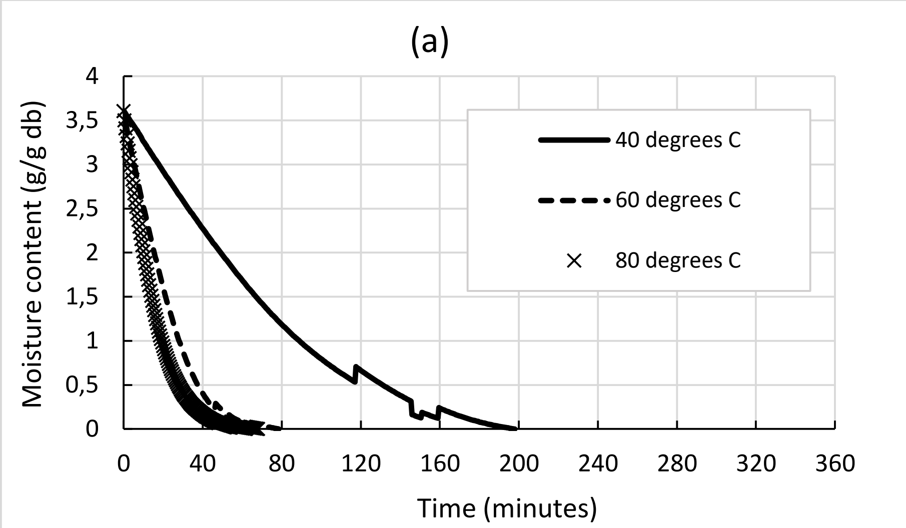
Figure 4-7 shows the yield stress as a function of temperature and moisture content. The yield stress decreased as the moisture content of the sludge increased. At higher yield stress values indicate that there was higher interaction between particles and thus stronger bonding of the faecal sludge particles. It followed that the consistency of the faecal sludge at higher values of yield stress was more viscous and cohesive forces were more pronounced. The stickiness of the faecal sludge was expected to be higher at higher yield stress values. There was no significant change in yield stress as the temperature increased for samples of the same moisture content.

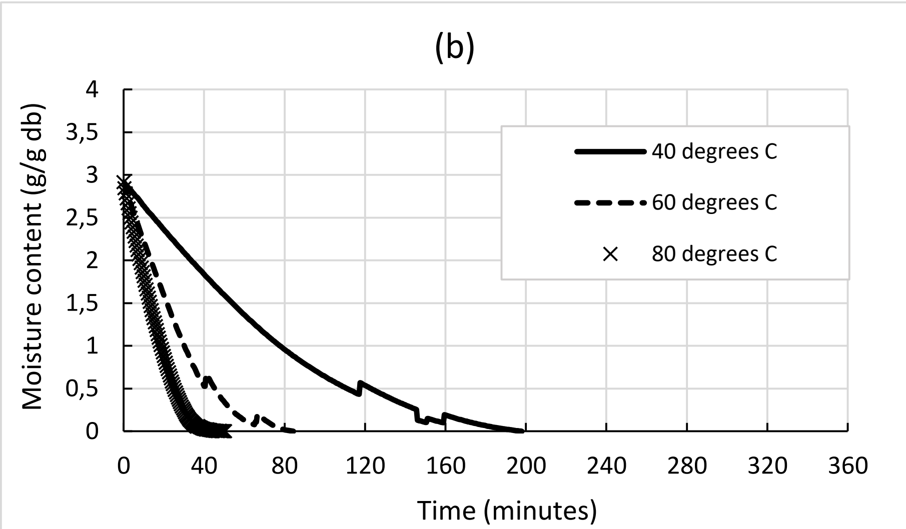
The stickiness and the viscosity of both VIP and UDDT sludge increased by a factor of approximately 1.5 for every 10% decrease in moisture content until achieving the sticky region of the sludge. This result suggested that the stickiness and viscosity of faecal sludge were related. The cohesiveness of the sludge increased with a decrease in moisture content for the moisture content 70-90%wt analysed as depicted by the increased viscosity and yield stress. The adhesiveness of the sludge decreased with an increase in moisture content for the moisture content range 70-90%wt analysed by the rheometer. This was in collaboration with the texture analyser results discussed in section 4.1 earlier and further giving a suggestion of the relationship between the stickiness and the viscosity of the sludge.

4.3 Drying kinetics and relationship with stickiness

The investigation on drying kinetics of the sludge was to ascertain how the kinetics vary within the sticky region that was determined earlier (section 2.3.7). Figure 4-8 shows the drying curves of UDDT and VIP samples as a function of time and their corresponding drying rate curves. The moisture content in Figure 4-8 was expressed on a dry basis as this is usually the basis used for drying kinetic analysis. Figure 4-8 depicts that the drying rate was at the fastest at 80°C. This result is expected because it is well known that the drying kinetics increase with temperature. It can be noted there was an increased difference in the drying rates between 40and 60°C as compared to the difference between 60 and 80°C. This suggested that the drying time for the sludge was reduced with an increase in the temperature.

From the results shown in Figure 4-8, the constant rate period on the drying curves for VIP was from the initial moisture content of 2.9g/g dry basis to ≈1.2g/g dry basis and for UDDT, the constant rate period was from initial moisture content to 3.5 ≈ 1.8g/g dry basis. The end of the constant rate period marks the start of the first falling rate period. The transition between the constant rate period and the falling rate period occurs within the sticky region for both the VIP and the UDDT sludge. The stickiness peak of VIP sludge was 1.5g/g dry basis and that of UDDT sludge was 1.0g/g dry basis. The sticky peak values for both the sludges were almost the same as the transition moisture content for the sludges from constant rate period to the falling rate period. This was taken to suggest that highest stickiness value is when the moisture from the sludge transitions from surface moisture and instigates movement of moisture from within the sludge as explained in Section 2.2.1.


(a)
Moisture content (g/g db)
Time (minutes)
40 degrees C
60 degrees C
80 degrees C
0
0,5
1
1,5
2
2,5
3
3,5
4
0
40
80
120
160
200
240
280
320
360


(b)
Moisture content (g/g db)
Time (minutes)
40 degrees C
60 degrees C
80 degrees C
0
0,5
1
1,5
2
2,5
3
3,5
4
0
40
80
120
160
200
240
280
320
360

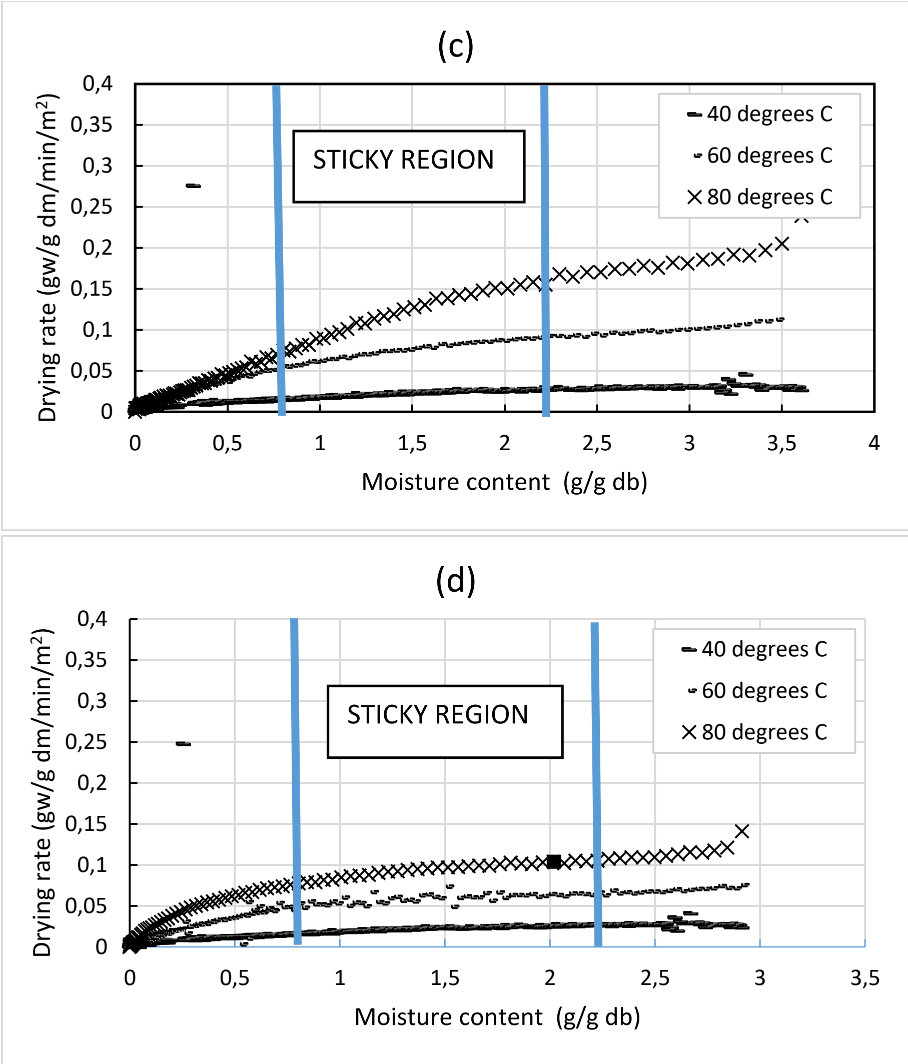


Figure 4-8:Moisture content versus time as a function of temperature (a)UDDT (b) VIP; drying rate versus moisture content as a function of temperature (c) UDDT (d) VIP

During the drying process, the drying rate can be related to the moisture content. The drying rate seemed to drop during the sticky phase as defined from the texture analyser (section 4.1). The drying rate depends on the moisture content of the material and the humidity in the surroundings (the driving force for drying is the difference in water concentration between the air and material). The distinct phases (constant rate period and the falling rate period) are illustrated by Figure 4-8c for VIP, and Figure 4-8d for UDDT, these phases were also seen in sewage sludge drying (Deng et al., 2017, Bennamoun et al., 2013). The sticky region as depicted in Figure 4-8 is between 0.7g/g (40%wt) and 2.3g/g (70%wt) for both the VIP sludge UDDT sludge. The boundaries defining the sticky region were taken from the results reported from the texture analyser. Comparing the UDDT and VIP sludge, the results as shown in figure 4-8, the drying rate of UDDT was slightly more than of VIP at 60 and 80°C and this is expected as the UDDT sludge has a stickiness that is comparable to that of the VIP sludge.

It has been suggested for sewage sludge that adjusting the temperature and moisture content can reduce the effect of stickiness (Ferrasse et al., 2006). Figure 4-8 also illustrates the effect of the sticky region on the time taken during the drying process. The duration of the sticky region is the longest for both sludges. This was also recorded in literature for sewage sludge (Ferrasse et al., 2006).

4.4 The Atterberg limits of faecal sludge

The shear strength of the VIP and UDDT sludge at different moisture contents was reported in Figure 4-9. The results showed that the shear strength of the faecal sludge decreased with an increase in moisture content. The shear strength gives an expression of the cohesiveness of the material and thus the shear strength evolves similarly to the cohesive measure of the material. As discussed earlier, (Section 4.2.1) the cohesiveness of the sludge and hence the shear strength increases with a decrease in the moisture content. These results corroborate with the findings from literature with sewage sludge and soils. The observation of lower penetration at higher strength could also be translated to faecal sludge (Vardanega and Haigh, 2014, O'Kelly, 2005).

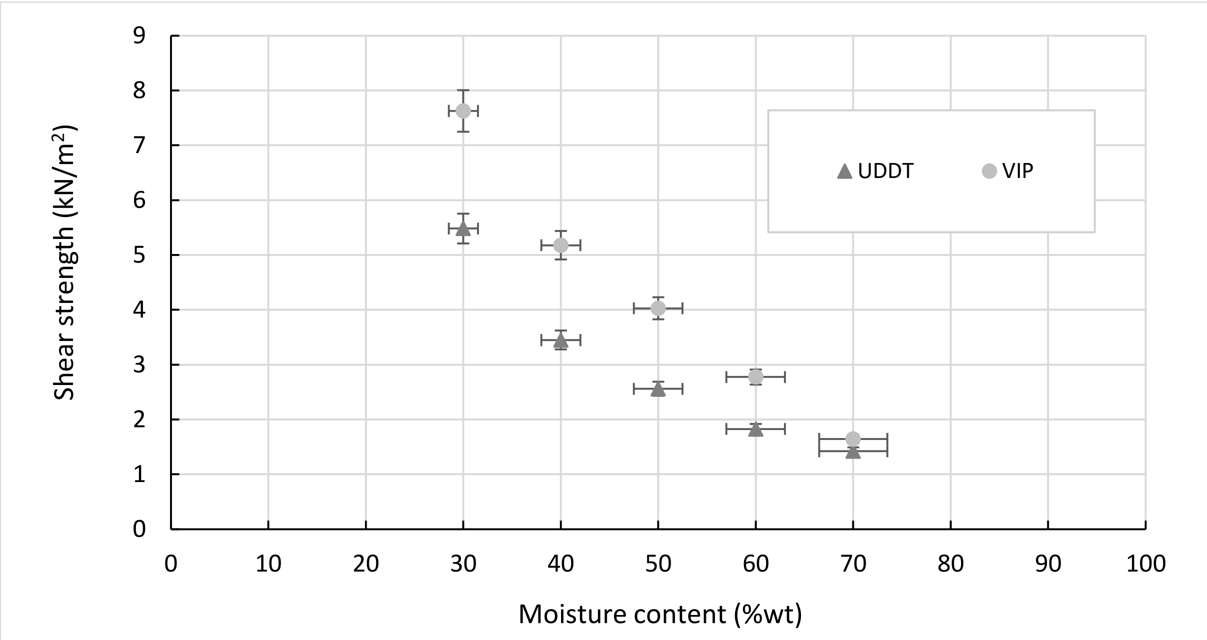


Figure 4-9: Shear strength as a function of moisture content

Table 4-1 shows the Atterberg limits for the VIP and UDDT sludge as investigated from the experiments using the cone penetrometer (section 3.4). The Atterberg limits for the VIP sludge gave the plastic limit as 57.9%wt, and liquid limit as 77.5%wt, and 48.6%wt as plastic limit and 67.2%wt as liquid limit for the UDDT sample. These plastic and liquid limits were close to the results reported by Septien et al., (2018b), and the differences were regarded to be from the variation of the characteristics of the faecal sludge. The liquid limit, as explained in earlier sections, indicates the moisture content above which the sludge can flow, and the plastic limit the moisture content below which the sludge becomes a solid. The plastic and liquid limits were respectively within the range of 55 to 80%wt for the VIP samples and 45 to 70%wt for UDDT. The moisture content range between the liquid and plastic limit is when the sludge behaves in a plastic way. These values were partially in agreement with the sticky region that has been reported in this study after the texture analyser tests. The correspondence between the sticky region and the Atterberg limits for the UDDT sludge was significant, however, for the VIP sludge, there is an overlapping between the sticky region and the Atterberg limits but the liquid limit and the plastic limits are too high for a good match. It can therefore be generalised that there is a correspondence between stickiness and plasticity as given in literature (Radford et al., 2015). The results showed that the plastic behaviour of the sludge corresponded to when the material was at its highest stickiness. The sticky peak for both the sludge was also recorded when the sludge is plastic. The use of Atterberg limits to confirm the sticky region of the faecal sludge has been reported in the literature; however, the results were not conclusive as the repeatability of the results was questionable (Radford et al., 2015). The cone penetrometer results from which the limits were obtained are attached in **Appendix C**.

It has been established that the plasticity index is a measure of the cohesiveness of sludge. The indices for both VIP and UDDT are relatively similar and thus imply that the cohesive forces within the different sludges were almost similar, with UDDT cohesive forces slightly higher. This result corresponds to what was measured in the texture analyser, as explained in section 4.1. 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 limits (plastic and liquid). For the UDDT and VIP, the liquidity index is close to 1, implying that the sludge was almost at its liquid limit at its initial moisture content and this was in agreement with the liquid limit values that were measured.

The sludge activity of both VIP and UDDT was relatively high, and thus the capacity to retain water in the sludge was high. The high capacity to retain water of the sludge indicates that there is more unbound water trapped in the sludge and thus the more difficult the dewatering process or more prolonged the drying process becomes. The swelling and shrinkage of sludge depend on the activity of the sludge. High activity soils (> 150%) show large variations in volume (Haigh, 2012). As has been observed in other studies, faecal sludge shows variations in volume, noted mostly as shrinkage (Makununika, 2016). The shrinkage of sewage sludge has been found to be in the range of 40-70% (Li et al., 2014, Leonard et al., 2008, Bennamoun et al., 2013).

Table 4-1 Atterberg limits for VIP and UDDT sludge

	Faecal sludge	
	VIP	**UDDT**
Liquid limit (%)	77.49	67.21
Plastic limit (%)	57.90	48.55
Plasticity index	19.59	18.65
Liquidity index	0.82	1.20
Sludge Activity (%)	275.72	285.60

4.5 Sorption Isotherms

The changes in moisture content of a faecal sludge sample affect both the osmotic properties and binding strength of water that is the available water for hydration in the faecal sludge as discussed in Section 2.3.1.2.1. Figure 4-10 shows the sorption isotherms (graph of water activity against moisture content) of the VIP and UDDT sludge at ambient temperature and 40°C.

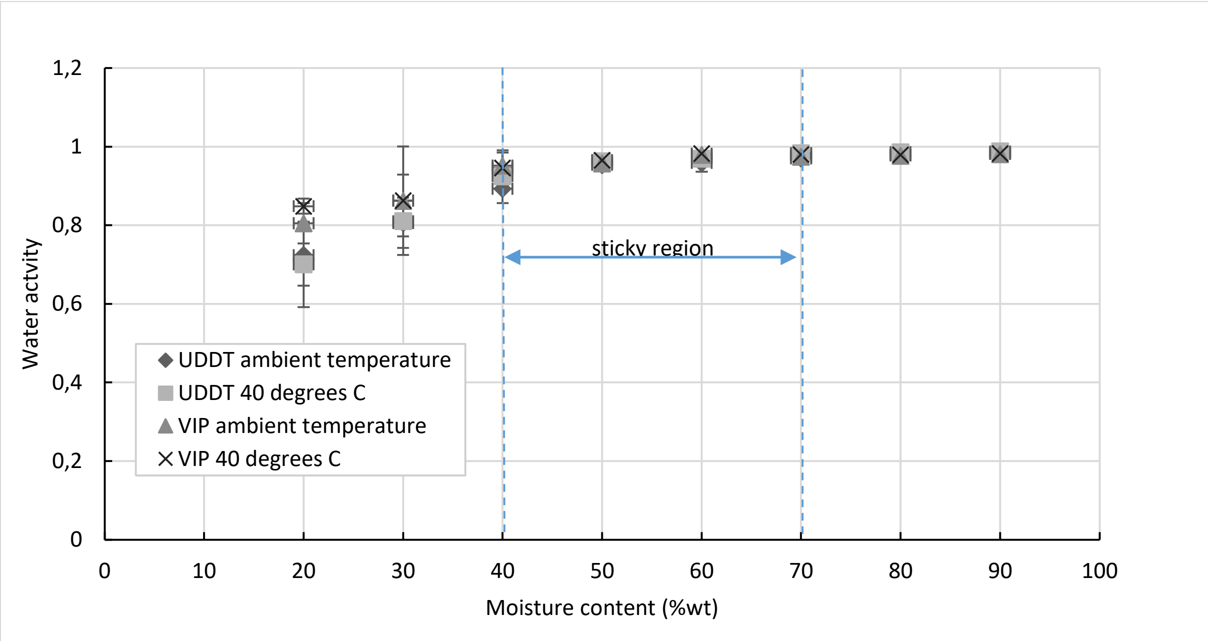


Figure 4-10: Sorption isotherms for UDDT and VIP sludge at varying temperature

The results in Figure 4-11 show that the water activity values were the same from 70%wt to 90%wt moisture content, for the UDDT sludge and VIP sludge. The results on water activity did not show any significant difference with an increase in temperature for all the moisture contents analysed. The moisture in the initial sludge was considered to be majorly free (or unbound) water, as the water activity values were around 1. The water activity decreased by decreasing the moisture content as drying proceeded. A significant drop in water activity was noticed for the moisture content 60%wt and 40%wt for both VIP and UDDT sludge. In this moisture content range, most of the moisture in the sludge could be supposed to be the more likely interstitial and surface water. There was no more significant unbound moisture when the water activity started to decrease at around 60%wt moisture. These results agreed with the results of water activity as a function of moisture content reported from Getahun et al., (2020). This means that the moisture became more bounded as drying proceeded. For the moisture contents below 40%wt, the water within the sludge was more bound water and intracellular water.

Increased moisture boundedness would imply that during the drying process there is more of the difficult moisture to be removed and this lowers the drying rate. Water activity was similar for UDDT sludge than the VIP sludge, as there was an overlap of uncertainity bars. This suggested that there is the same moisture boundedness for both VIP and UDDT sludge even at different temperatures. This implies that under the same drying conditions the sludges would have approximately close drying rates.

The results on water activity agreed with the graph discussed in section 2.2.2, and thus, the drying showed in the previous sections also support the water activity results. From figure 4-10, it could be identified the region for the unbound moisture (water activity = 1) and bound moisture (water activity < 1), but the types of bound moisture cannot be clearly distinguished. However, it could be assumed that the moisture removed during the sticky phase was interstitial (because it was the one ensuring the cohesiveness of the flocs of the sludge). Figure 4-11 illustrates the relationship of water activity and stickiness. The water activity gave the type of moisture that is present at each moisture content and it could be established that the sticky region was located when the boundedness of moisture in the sludge was between surface water and interstitial water. This was deduced, as the water activity started to decrease at the beginning of the sticky phase. Thus the sticky phase seemed to appear when there was less or no unbound moisture in the sludge.

From figure 4-10 and 4-11, the unbound and capillary water in the sludge leads to water activity approximately equal to 1. After removing this type of moisture, the sludge attains its sticky peak, and water activity starts to decrease because the remaining moisture is bound. Therefore, the maximum adhesiveness and cohesiveness in the sludge is achieved after removing the interstitial moisture. The sticky region started after the unbound moisture was removed. Then it could be assumed that the capillary moisture was removed during the sticky phase until loss of cohesiveness of the material (marking the end of the sticky phase and the transition to a granular solid). The moisture left in the granular solid could be assumed to be as surface and intracellular. The stickiness curve was adopted from the results of UDDT stickiness at ambient temperature.

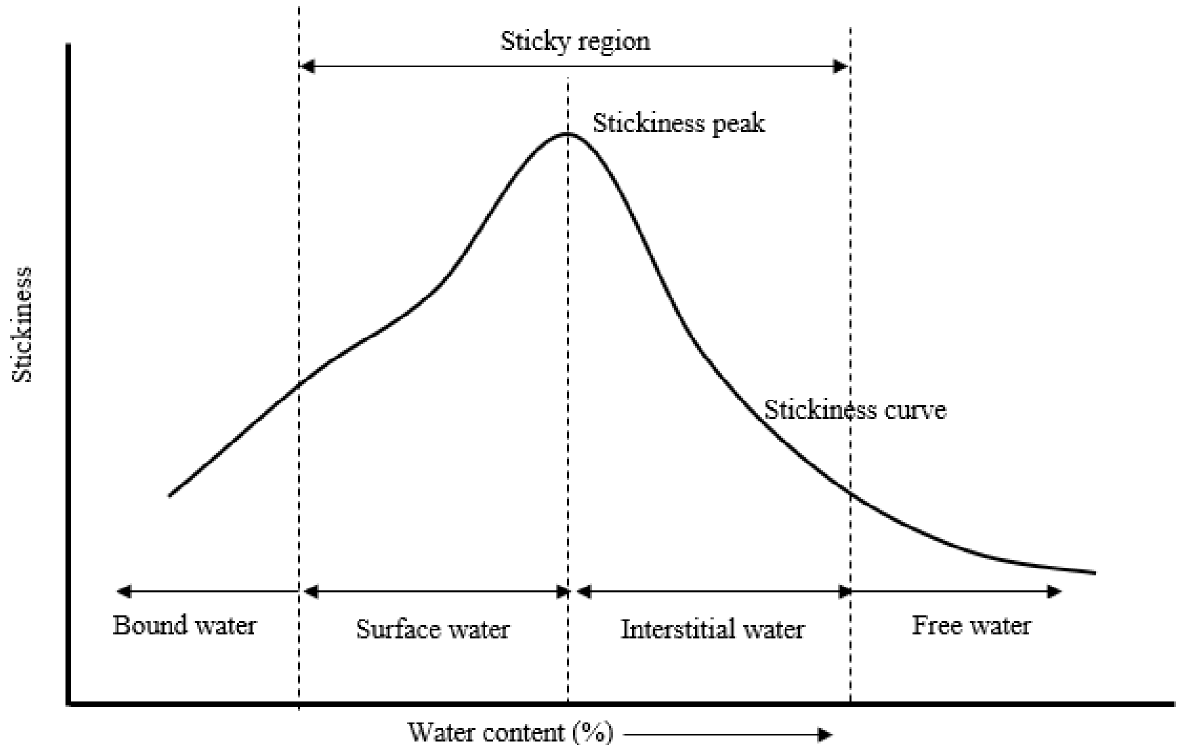
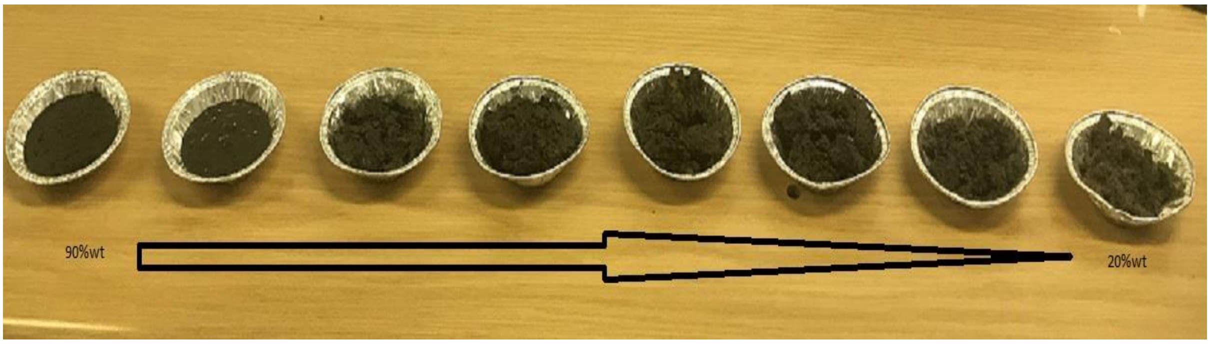


Figure 4-11: Relationship of stickiness and boundedness of moisture

4.6 Qualitative results

During the preparation of the samples (drying to the different moisture contents), it was observed that the material passed through several physical stages and experienced extensive shrinkage and formation of lumps. Figure 4-12 also shows the shrinkage and lump formation as from the sludge samples were dried from 90 to 20%wt moisture content. The shrinkage of the sludge was observed in this study, but not quantified. It equals to approximately 50-60% of the initial volume of sludge as mentioned in studies with sewage sludge (Leonard et al., 2008, Bennamoun et al., 2013). The shrinkage observed is as expected from the sludge activity results in section 4.4. A sludge activity greater than 150% was observed to cause high volume variations, while the VIP and UDDT sludge samples exhibited values of 275.7% and 285.6% respectively. Taking the ration of the sludge activities and the sludge activity indicator (150%), it is approximately 0.5 (Haigh, 2012). This value could be considered as a rough approximation of shrinkage that could be expected. The size of the lumps became smaller granules as the moisture content decreased from moisture content of 50%wt, as reported for agitated sewage sludge drying (Deng et al., 2017). The smaller granules observed were attributed to the shrinkage of the sludge.

(a)



(b)

Figure 4-12 Photographs of the sludge at different moisture content (a) VIP (b)UDDT

Figure 4-12 also shows that initially, the sludge was a watery paste then passed to a soft paste-like consistency and into granular as moisture content lowered. The sludge exhibited a watery consistency when the amount of unbound moisture was higher and water activity closer to 1. In the pasty phase, the sludge could form intermolecular forces as the wet contact surface forms molecular contact with the surface. The liquid bridges would be able to be formed and contribute to the adhesive forces of the sludge (Adhikari et al., 2001, Deng et al., 2017). Higher crosslinking of the polymers in the sludge and the mineral materials in the lumpy phase contribute greatly to the cohesive forces of the sludge as has been reported for sewage sludge (Deng et al., 2019a). It can be assumed that the capillary moisture was depleted during the transition of a paste to a granular solid due to the loss of cohesiveness (supposing the capillary moisture ensured the cohesiveness). In the granular solid state with water activity less than 1 (aw < 1), the remaining moisture can be assumed to be surface, chemically bound or intracellular. The liquid bridges in this phase will reduce significantly and the mechanical interlocking of the particles will be more pronounced contributing to the minimal cohesive forces of the sludge that exists in the granular phase (Deng et al., 2017). With a lumpy or solid consistency, there is less unbound moisture was present in the sludge (water activity less than 1).

5 CONCLUSIONS

This study aimed to understand the stickiness property of faecal sludge from two types of onsite sanitation facilities, namely VIP latrines and UDDT. The effect of moisture content and temperature on the sticky parameters, i.e. the cohesive and adhesive forces, were studied.

The following main findings from this study are:

- The adhesive and cohesive stresses were significantly influenced by the moisture content for both sludges, showing a peak in the moisture range 40 to 70%wt for VIP sludge and 40 to 60%wt for UDDT sludge and indicating the existence of the sticky region in this range.
- The cohesive forces were dominant over the adhesive forces.
- The increase in temperature led to an increase in the stickiness parameters (cohesive and adhesive forces), indicating a decrease in sludge rigidity by the increase in temperature.
- The stickiness of faecal sludge was affected by the moisture content considerably more than it was with temperature changes. The effect of temperature on the sticky region is not significant as the sticky region does not shift at any temperature.
- The overall stickiness of UDDT sludge was higher than the VIP sludge at all temperatures.
- Faecal sludge showed shear thinning behaviour. As the shear rate increased, the viscosity of the faecal sludge decreases.
- The faecal sludge exhibited lower shear stress and lower viscosity at high moisture contents.
- The yield stress for both sludge decreased as the moisture content increased.
- The stickiness and the viscosity of both VIP and UDDT sludge increased by a factor of ≈1.5 for every 10%wt decrease in moisture content; thus, the stickiness and viscosity of faecal sludge are directly proportional within the sticky region. The rheology of faecal sludge has been given as having the viscosity of sludge directly proportional to the stickiness of the sludge.
- The VIP sludge showed higher values of viscosity than the UDDT sludge at all temperatures and moisture contents.
- The sticky region can be observed from the drying kinetics data to be between 0.8g/g (45%wt) and 2.5g/g (71%wt) for the VIP sludge and the sticky region for UDDT being given to be between 1.0g/g (50%wt) and 3.0 g/g (75%wt) as can be evidenced by the drop in drying rates in these regions.
- The drying rate of the sludge decreased more sharply during the period defined as the sticky region. The drying rate decreased due to the changes in the type of moisture removed at the different stages.
- The plastic and liquid limits were respectively 57.9 and 77.5%wt for the VIP sludge, and 48.6 and 67.2%wt for the UDDT sludge. The limits correspond with the sticky region as determined

by the texture analyser. The sticky region therefore falls between the plastic and liquid limit, which is the region in which the faecal sludge behaves in a plastic manner. The stickiness peak is also found in this region.

- The sticky region of the sludge falls in the range at which the moisture being removed is capillary moisture until there is loss of cohesiveness, marking the end of the sticky region and transition to a granular phase.
- The water activity values as moisture content decrease significantly from 60 to 40%, which is the sticky region. The moisture removed during the sticky phase is assumed to be interstitial since it is the one that ensures the cohesiveness of the flocs of the sludge. The effect of temperature on the water activity was found to be minimal at temperature 40°C.
- The sludge moved from being watery and shiny to lumpy and pasty-like to granular as the moisture content decreased.

The stickiness of faecal sludge is affected by moisture content, temperature and the faecal sludge characteristics significantly. The variations in these factors affect the location of the sticky region and the sticky peak. The study has shown that water activity of sludge being affected by the moisture content, has a significant influence on the stickiness of the sludge as the boundedness of water can be an indication of the stickiness that can be expected in the sludge.

The stickiness phenomenon during drying of faecal sludge is an issue affecting the daily operations in industry. This study proposes a procedure for determining of the sticky region based on the texture analyser procedures adapted from the food industry. This allows for easy determination of sticky region by noting the increased cohesive and adhesive forces in the region. The procedure described in the study is simple and repeatable and can be used for daily management in the drying industry. The results from this study provide to the practitioners in the sanitation field and designers information on the relationship of stickiness with the rheological properties, kinetics, water activity and consistency of faecal sludge as a function of moisture content and temperature during the drying process. This knowledge can be applied to design systems that can avert the problem of clogging and equipment failure resulting from the stickiness of faecal sludge.

6 RECOMMENDATIONS

The future studies to complement the knowledge and understanding of the stickiness phenomenon could provide more information on the following issues and lead to further optimisation of drying systems.

- Analysis of stickiness in motion/ with agitation
  As the samples were prepared, the sludge was mixed at 20-minute intervals (section 3.1.3). During this preparation, the sludge underwent the same drying process as may be described for agitated drying systems, and thus further studies should be done to understand the impact of the agitation on the overall stickiness phenomenon. As previously mentioned, the shear rate affects the viscosity of the sludge. Thus an in-depth analysis of the effect of agitation on stickiness would be necessary. The studies could also further quantify the transition from lumpy sludge to granular sludge.
- Further investigation on how the sludge constituents affect the stickiness of the sludge needs to be done. The polymers and organic matter of the sludge have been identified to affect the sludge. However, this has not been studied in-depth, and thus a study on this topic would be suitable.
- The surface geometry and orientation of materials have been determined as factors that affect the stickiness, and thus the further characterization of this factor to the overall stickiness would be interesting.
- The study of stickiness of sludge on different types of material can also be further investigated. This could be done by the use of different materials for the texture analyser probe. Studying the effect of the inclination and smoothness of the surface could also be explored.
- Further experimental data can be obtained that can be developed to create hydro-structural diagram in which all limits can be determined.
- Further studies will be essential to give a better understanding of the stickiness causes and how the characteristics of the faecal sludge can be manipulated to minimise stickiness.

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APPENDIX A: Poster presentation

The poster was presented at the 6TH South African Young Water Professionals Biennial Conference (October 2019) and University of KwaZulu-Natal (October) 2019 Post Graduate Research and Innovation Symposium.

UNIVERSITY OF KWAZULU-NATAL INYUVESI YAKWAZULU-NATALI

An investigation into the stickiness of faecal sludge

PRG pollution research group

R. T. Mupinga*, S. S. Septien, J. Pocock, C. A. Buckley
Pollution Research Group, University of KwaZulu-Natal, Howard College,4001, Durban, South Africa

Introduction

- Stickiness leads to sludge buildup on dryer surfaces causing equipment damage.
- Stickiness in the pipework of sewers, requiring the pipes to be cleaned often due to the sludge build up on equipment as in the food industry (Goode et al., 2010).
- The stickiness phenomenon of faecal sludge reduces the efficiency of the drying systems.
- Faecal sludge has cohesion and adhesion properties that affect its overall stickiness property (Woolley et al., 2014, Li et al., 2014).
- The cohesion property of the faecal sludge can be investigated from the rheological properties of the faecal sludge. The literature has little information on the stickiness of the faecal sludge.
- Rheology is also influenced by moisture content (Septien et al., 2018, Tietze et al., 2016).
- Stickiness of the faecal sludge is characterised by the torque of agitation as this is strongly influenced by moisture content (Leonard et al., 2008, Peeters, 2011).
- Cohesive stress is expressed as the main origin of the torque hence contribute to the stickiness and also the torque of agitation (Deng et al., 2019a, Deng et al., 2019b).

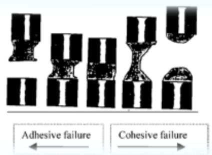


Figure 1.1 presentation of failure mechanism between adhesive and adherent surfaces(Kilcast and Roberts, 1998)

Figure 1.2 Sludge drying system (Tietze et al., 2016)

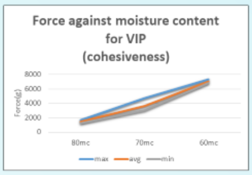
Objectives

- To understand stickiness and determine methods to mitigate fouling caused by stickiness of faecal sludge.
- To characterize stickiness of faecal sludge as a function of moisture content.
- To determine the relationship of rheological measurements with corresponding values from stickiness.
- To bring the understanding of the water activity on stickiness.

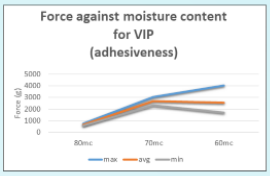
Materials and Methods

- The samples were faecal sludge from Ventilated Improved Pit Latrines (VIP) and Urine Diversion Dry Toilets (UDDT).
- The overall stickiness profiles were evaluated by the use of a texture analyser.
- The viscoelastic properties and shear rate of the faecal sludge with varied moisture content from 80% moisture content to 60% moisture content was determined using a rheometer. The higher moisture content was achieved by adding distilled water. The lower moisture content was achieved by evaporating unbound water from the sample in an oven at 150ºC, manually mixing the sample for 5 minutes with a stainless steel rod after every 25 minutes and testing with a thermal balance.
- The water binding capacity of the samples were analysed using a water activity analyser.

Results

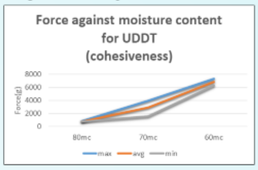


a.)

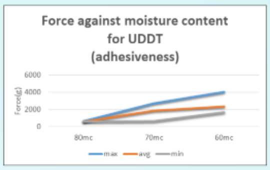


b.)

Figure 1.3 force against moisture content for VIP sludge a.)cohesiveness b.) adhesiveness



a.)



b.)

Figure 1.4 force against moisture content for UDDT sludge a.) cohesiveness b.) adhesiveness

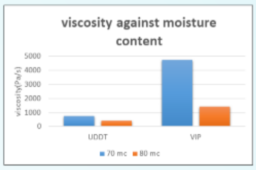


Figure 1.5 viscosity against moisture content (Shear rate =1/s)

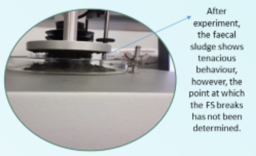


Figure 1.6 pulling back of the Texture analyser probe from a faecal sludge sample

- The water activity of both sludge was between the range 0.95-0.98 for the investigated range

Conclusion

- Stickiness of both VIP and UDDT sludge increases by a factor of ≈1.5 for every 10% decrease in moisture content for the range investigated.
- The adhesive forces are significantly lower than the cohesive forces in both types of sludge.
- Viscosity of the sludge increase by a factor of ≈ 2 as the moisture content decreases for every 10%.
- Stickiness and viscosity are therefore directly proportional.
- Stickiness and viscosity of VIP sludge is greater than UDDT sludge at any given moisture content for the investigated range.
- Stickiness decreases with a decrease in the water activity of the sludge.

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APPENDIX B: Ethics Approval letter

UNIVERSITY OF
KWAZULU-NATAL

INYUVESI
YAKWAZULU-NATALI

07 October 2019

Miss Ratidzaishe Tracy Mupinga (218087128)
School of Engineering
Howard College Campus
Dear Miss Ratidzaishe Tracy Mupinga,

Protocol reference number: BREC/00000204/2019
Project title: An investigation into the stickiness of faecal sludge.
Degree: Masters of Science in Engineering

EXPEDITED APPLICATION: APPROVAL LETTER

A sub-committee of the Biomedical Research Ethics Committee has considered and noted your application.

The conditions have been met and the study is given **full ethics approval** and may begin as from 07 October 2019. **Please ensure that outstanding site permissions are obtained and forwarded to BREC for approval before commencing research at a site.**

This approval is valid for one year from **07 October 2019.** To ensure uninterrupted approval of this study beyond the approval expiry date, an application for recertification must be submitted to BREC on the appropriate BREC form 2-3 months before the expiry date.

Any amendments to this study, unless urgently required to ensure safety of participants, must be approved by BREC prior to implementation.

Your acceptance of this approval denotes your compliance with South African National Research Ethics Guidelines (2015), South African National Good Clinical Practice Guidelines (2006) (if applicable) and with UKZN BREC ethics requirements as contained in the UKZN BREC Terms of Reference and Standard Operating Procedures, all available at http://research.ukzn.ac.za/Research-Ethics/Biomedical-Research-Ethics.aspx.

BREC is registered with the South African National Health Research Ethics Council (REC-290408-009). BREC has US Office for Human Research Protections (OHRP) Federal-wide Assurance (FWA 678).

The sub-committee's decision will be **noted** by a full Committee at its next meeting taking place on **12 November 2019.**

Yours sincerely

[redacted]

Prof V Rambiritch (Chair)

Biomedical Research Ethics Committee
Prof V Rambiritch (Chair)
UKZN Research Ethics Office Westville Campus, Govan Mbeki Building
Postal Address: Private Bag X54001, Durban 4000
Website: http://research.ukzn.ac.za/Research-Ethics/

APPENDIX A1: Effect of mass on the stickiness of faecal sludge

Figure A-1 shows the positive force required for the analyser probe to penetrate the UDDT faecal sludge sample and the opposing force required to pull out the probe from the sludge as a function of sample mass, as presented from the texture analyser software. The general trend observed showed a peak for compression. It has been described earlier that stickiness of material is affected by the volume of the material being investigated. The surface area of the experiment was kept constant and thus variations in the volume of the sludge would thus be a source of error if not maintained constant. Resulting from the rapid stress increase within the material and the even faster stress relaxation afterwards the separation of the probe tests. The positive values correspond to the compression and the negative values correspond to the pulling out of the probe (adhesion). The mass of the samples has a significant effect on the value of the stickiness, as shown in figure A-1. The stickiness of masses that were below 50 g had significantly high standard deviation values of the maximum forces, ranging between 60 and 82% as compared to the high mass samples of 80g and 100g that gave standard deviation values of the maximum forces, ranging below 25%. The variations in lower masses were because of the less the amount of sludge did not cover the surface area of the 80 mm vial, thus the actual volume of the sludge tested would vary depending on how the sludge is placed in the vial. For this research, a mass of 100g was chosen to allow for experiments to be easily replicable and minimal variations in volume as the sample would cover the base of the vials.

Figure A-2 shows the deformation of sludge after the compression using the stainless steel probe. The photograph shows that the flow of the sludge exhibits insistent behaviour as its particles show a tendency not to easily part (cling together). The more mass that was in the vial, the more of the phenomenon (cohesion/adhesion) could be observed and thus could be quantified more accurately. However, the exact point at which the faecal sludge reaches a breaking point has not been determined.

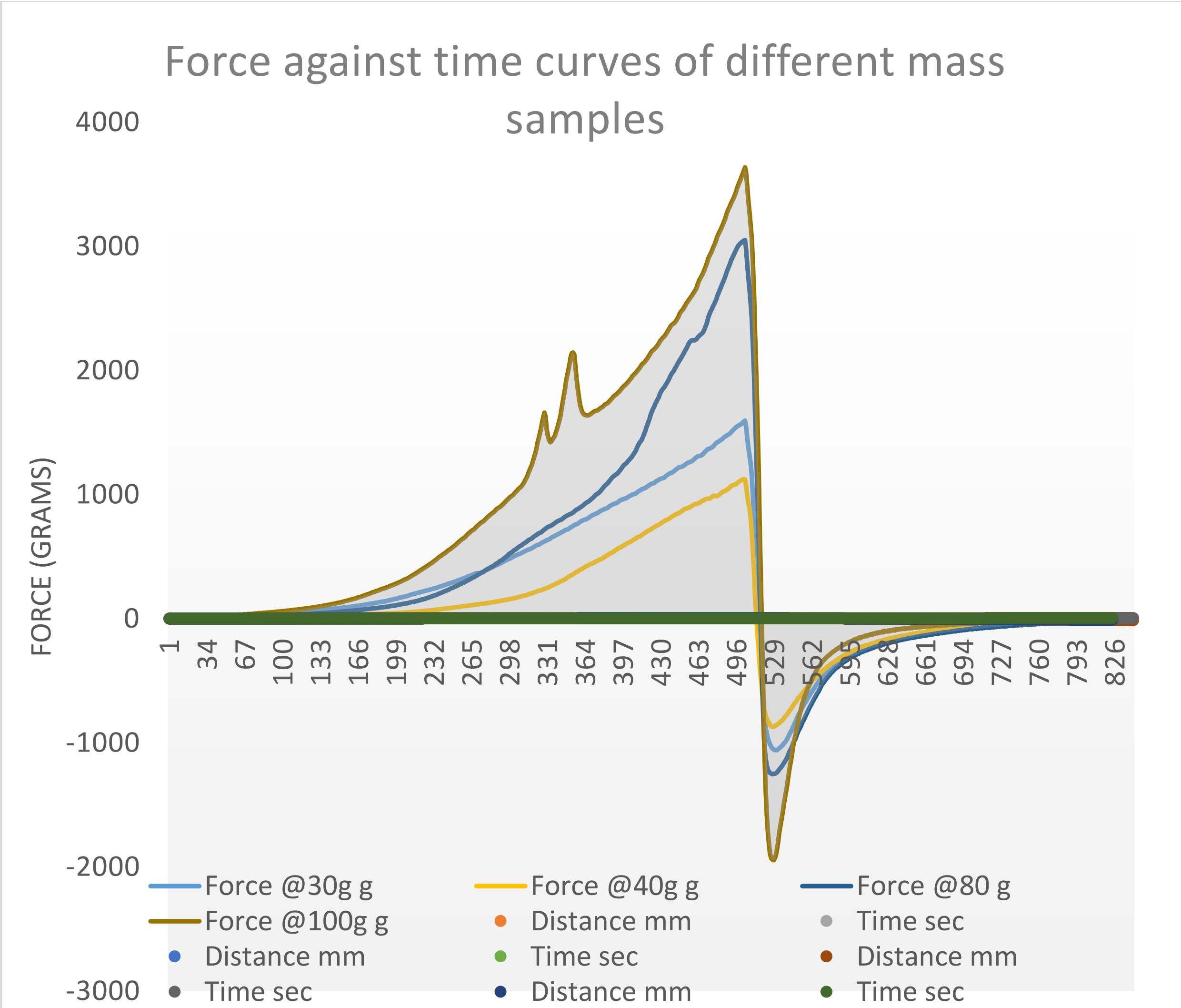


Figure A-0-1 Force against time curves of different mass samples

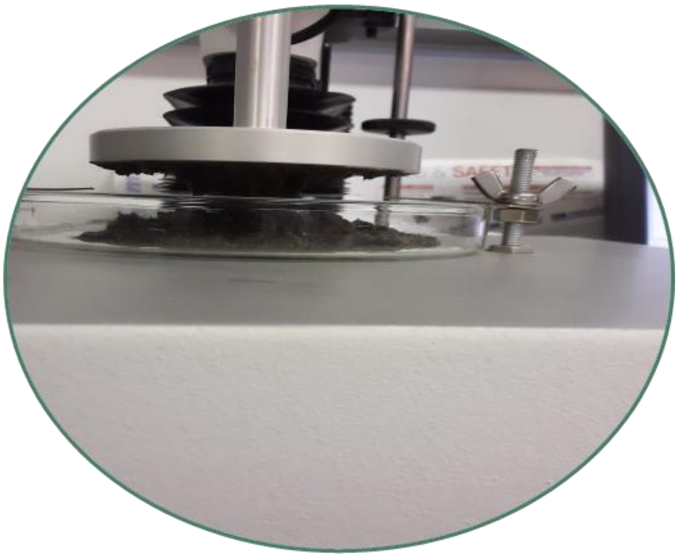


Figure A-0-2 Sludge flow after compression

APPENDIX A2: Texture analyser comparison of the compression mode and tension modes

	Cohesive forces		Adhesives forces	
	Compression mode	**Tension mode**	**Compression mode**	**Tension mode**
Test 1	8727.43	-2430.21	-2430.21	-2746.24
Test 2	9192.96	-2859.65	-2859.65	-2577.31
Test 3	9841.51	-2510.50	-3510.50	-2724.30
Test 4	12021.66	-2525.40	-4525.40	-2345.88
Test 5	9969.78	-2568.63	-3568.63	-2429.82
Average	**9950.67**	**-2578.88**	**-3378.88**	**-2564.71**
Standard deviation	1262.11	164.76	796.46	176.53
Coefficient of variation	12.68	-6.39	-23.57	-6.88

Anova: Single Factor (COHESIVE FORCES)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	**5**	**49753.33**	**9950.667**	**1592932**
Column 2	**5**	**49167.92**	**9833.584**	**615490.7**

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	**34270.96**	**1**	**34270.96**	**0.031037**	**0.864537**	**5.317655**
Within Groups	**8833692**	**8**	**1104211**			
Total	**8867963**	**9**				

Anova: Single Factor (ADHESIVE FORCES)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	**5**	**-12894.4**	**-2578.88**	**27144.2**
Column 2	**5**	**-12823.6**	**-2564.71**	**31164.36**

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	**501.7437**	**1**	**501.7437**	**0.01721**	**0.898867**	**5.317655**
Within Groups	**233234.2**	**8**	**29154.28**			
Total	**233736**	**9**				

APPENDIX A3: Volume increase in water bath

Both types of sludge (VIP and UDDT) show a slight increase in volume when the samples are heated in the water bath whilst covered with foil paper. The increased volume is consistent with the prediction of the sludge activity (>300%), as shown in table 4-4. This increase in volume is experienced at a more significant margin as the sample temperature increases from ambient temperature to 80^{o}C. The actual values for the volume increase were recorded. Table A-1 gives the corresponding volume variations and changes as the samples were warmed to different temperatures. This phenomenon was only investigated at sludge moisture content 80%wt for both UDDT and VIP.

The volume of the sludge was calculated as $Volume = \pi \times (radius)^2 \times height$

The diameter of the sample holders was constant at 80mm, and thus the only variable in the volume calculation was the height of the sludge in the sample container.

Table A-1 Volume changes in the faecal sludge at different temperatures

VIP				
	25^{o}C	**40^{o}C**	**60^{o}C**	**80^{o}C**
Mean Height	40.80	43.40	45.80	52
Standard Deviation	2.17	1.14	1.92	1.58
% Volume Increase		6.37	12.25	27.45
UDDT				
	25^{o}C	**40^{o}C**	**60^{o}C**	**80^{o}C**
Mean Height	39.80	42.60	44.20	50.40
Standard Deviation	1.92	1.82	0.84	3.36
% Volume Increase		7.04	11.06	26.63

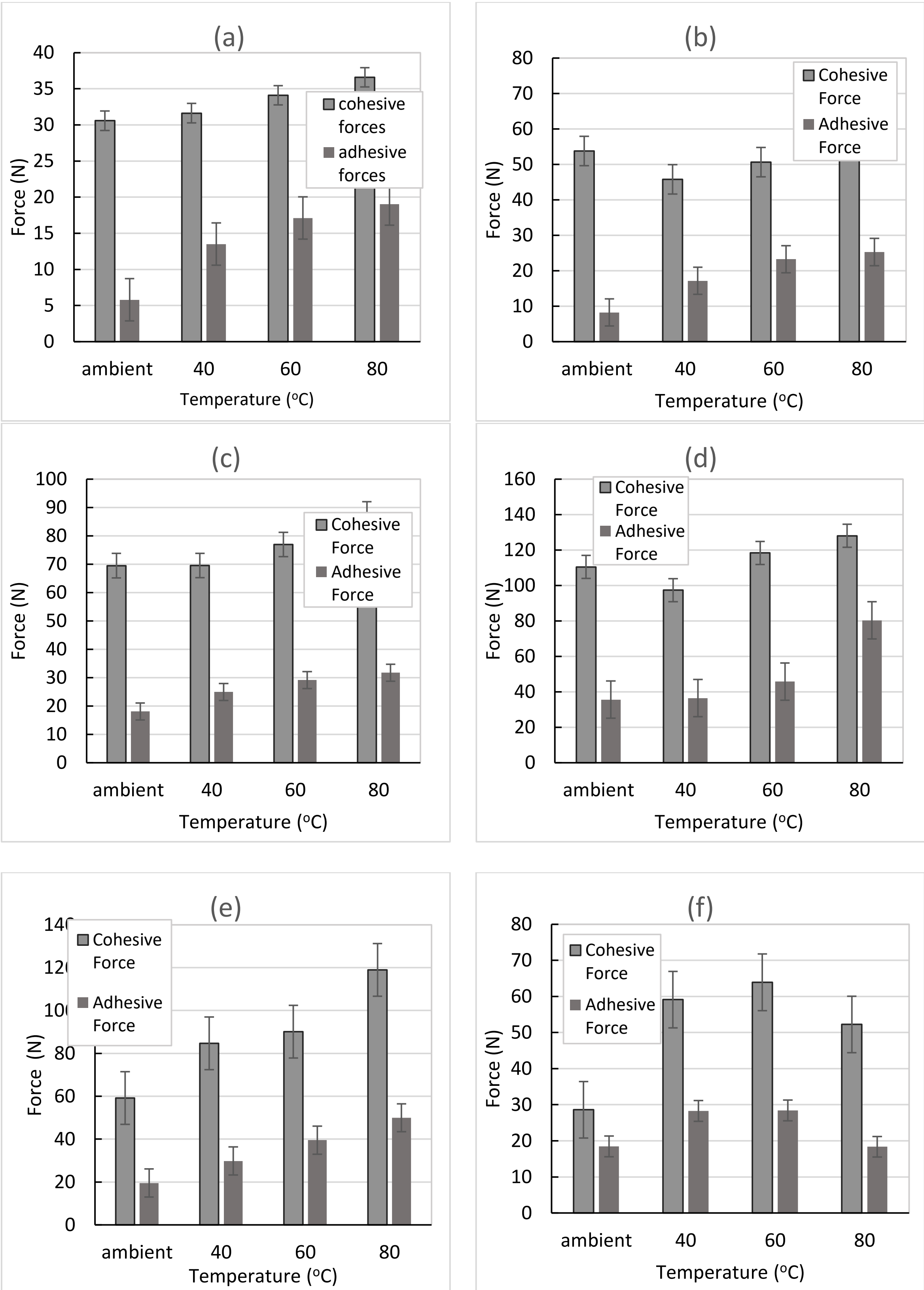
The volume increase at elevated temperature can be assumed to be caused by:

- increase in volume at elevated temperature can be due to the expansion of matter and the gases present in the faecal sludge,
- the increase in volume may also be attributed to water vapour from the samples as temperature reach 80^{o}C.

The volume change can be used to explain the increased drop in both adhesive and cohesive forces at moisture content values 80%wt and 90%wt. These moisture contents, as explained in the Methods section, were achieved by adding distilled water to the samples. Thus water may readily be converted to water vapour unlike in lower moisture contents as has been explained by the water activity of the sludge at these moisture contents. The less the free water available the less likely the water vapour is expected.

APPENDIX A4: Cohesive and adhesive forces as a function of moisture content and temperature

UDDT sludge



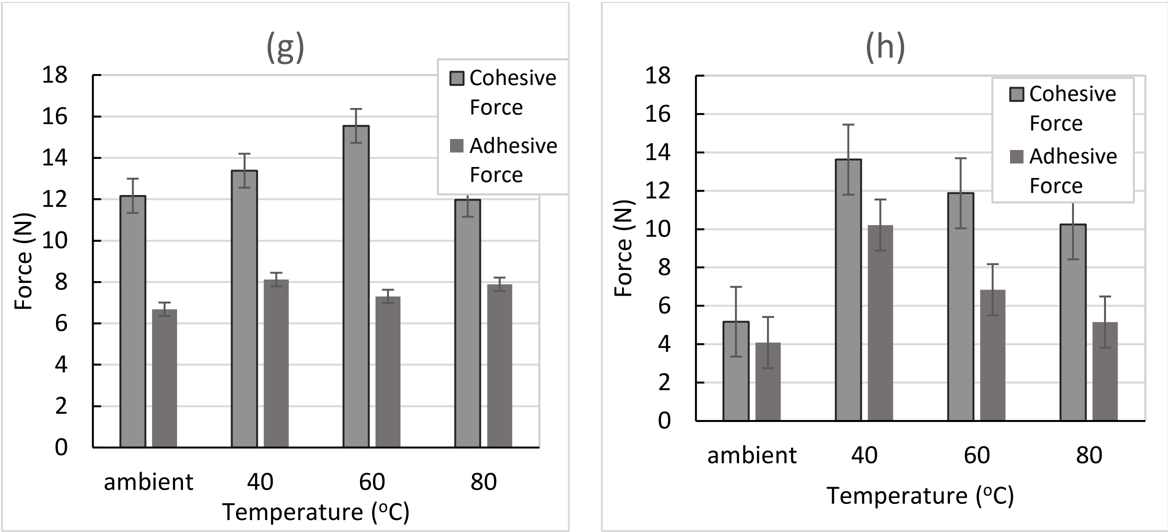
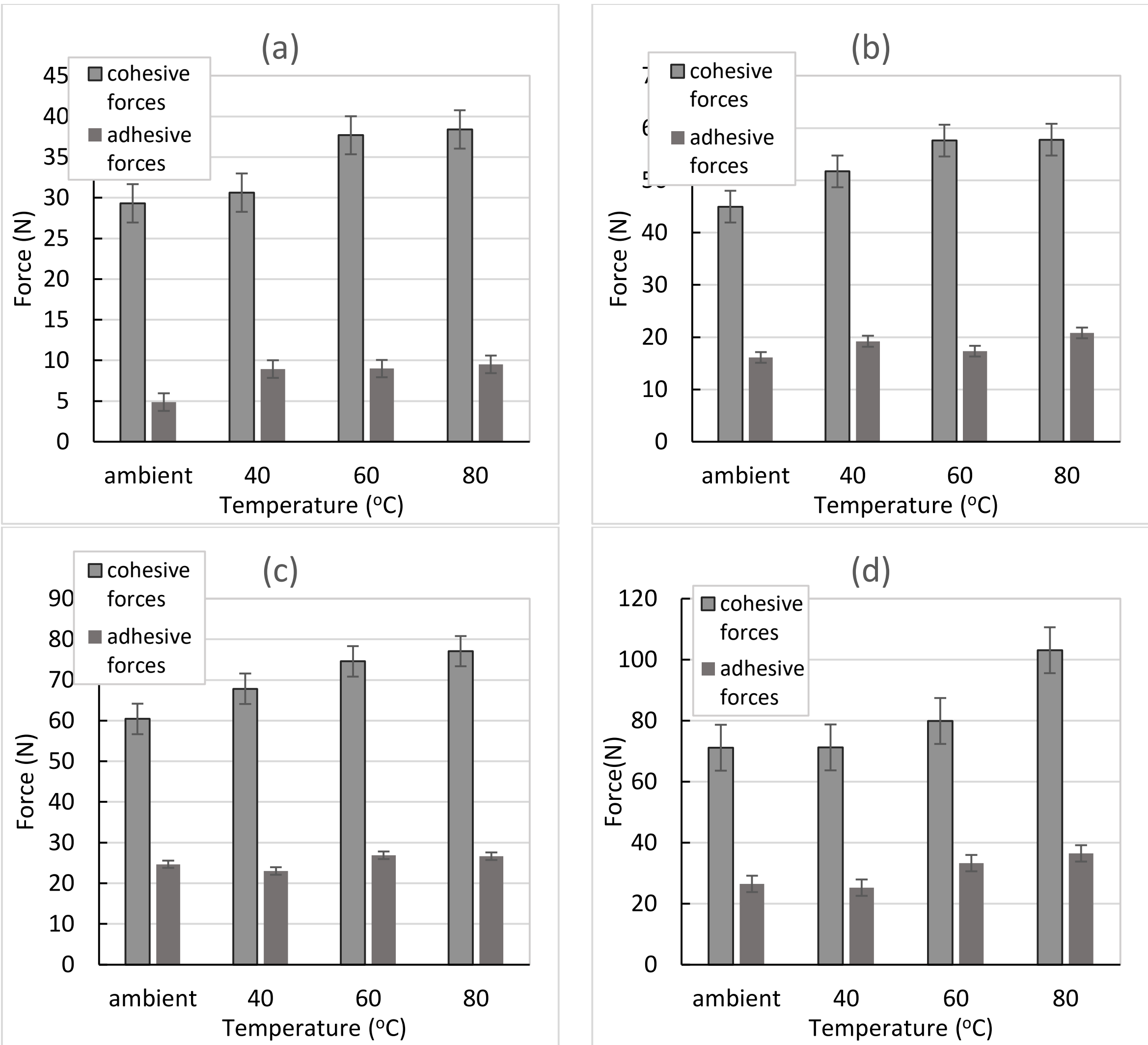


Figure A-2 UDDT Cohesive and adhesive forces as function of temperature and moisture content at: (a) 20%wt, (b) 30%wt, (c) 40%wt, (d) 50%wt, (e) 60%wt, (f) 70%wt, (g) 80%wt, (h) 90%wt.

VIP sludge



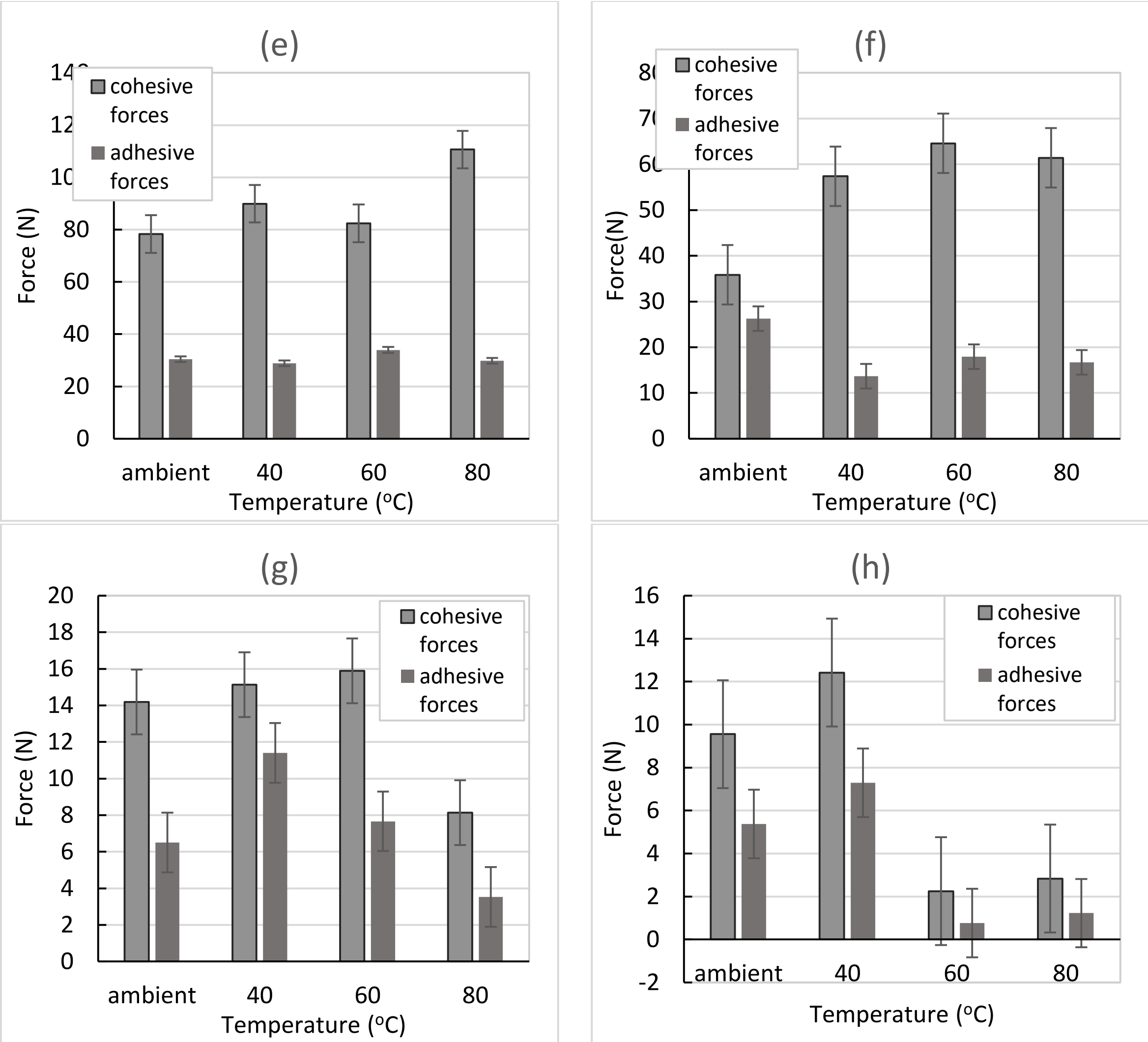


Figure A 0-3VIP Cohesive and adhesive forces as function of temperature and moisture content at: (a) 20%wt, (b) 30%wt, (c) 40%wt, (d) 50%wt, (e) 60%wt, (f) 70%wt, (g) 80%wt, (h) 90%wt.

APPENDIX A5: Force as a function of moisture content at varying temperature

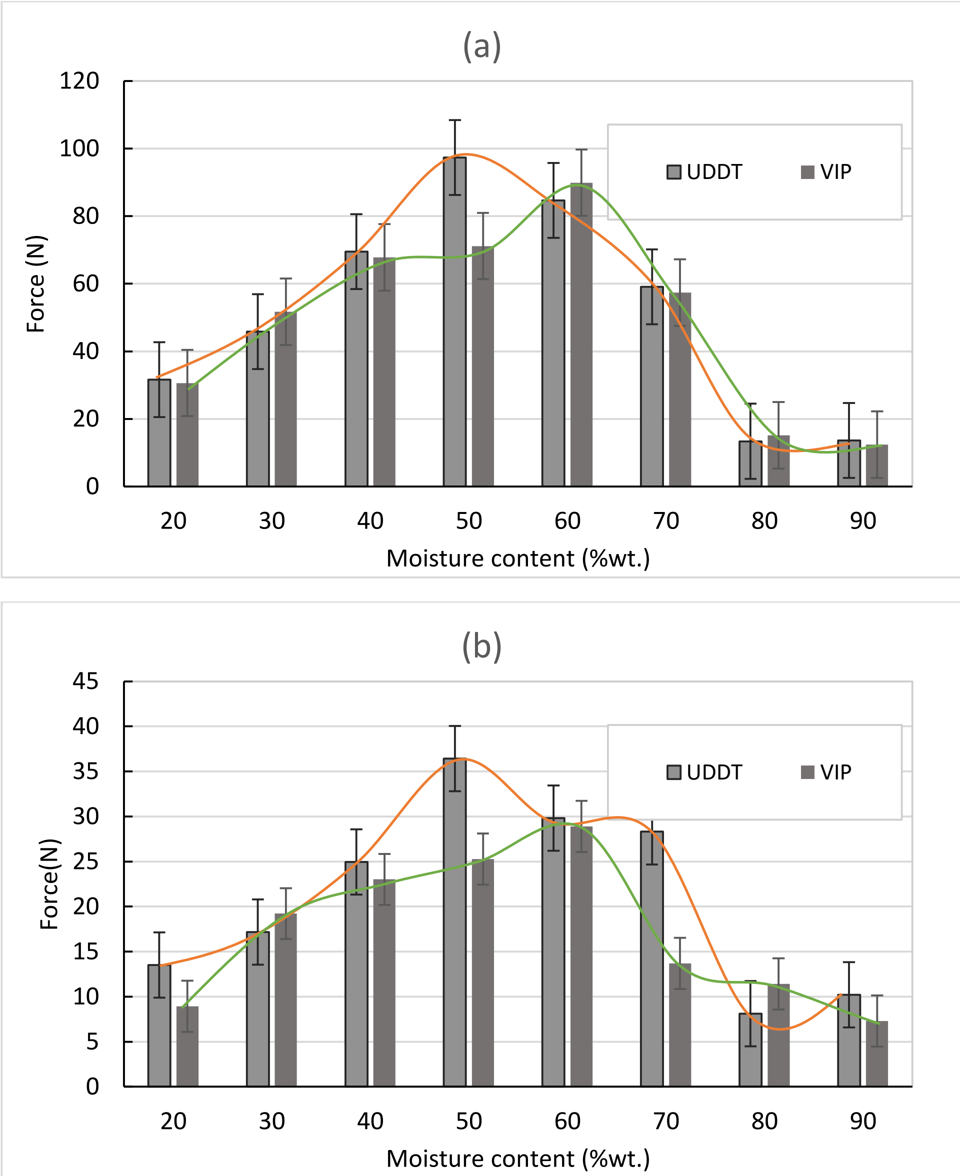


Figure 0-1Force as a function of moisture content at temperature 40 degrees C; a) Cohesive forces b) Adhesive forces

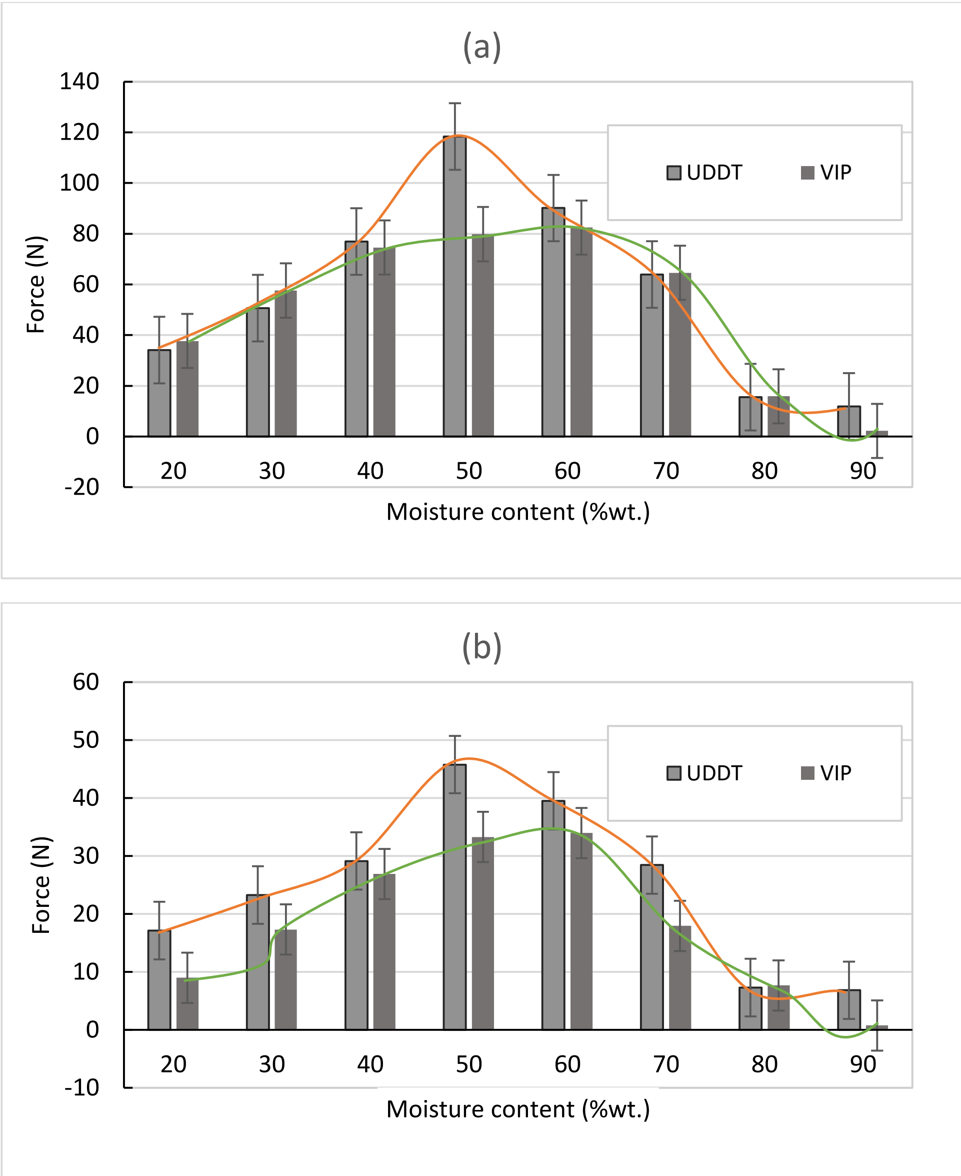


Figure 0-2 Force as a function of moisture content at temperature 60 degrees C a) Cohesive forces b) Adhesive forces

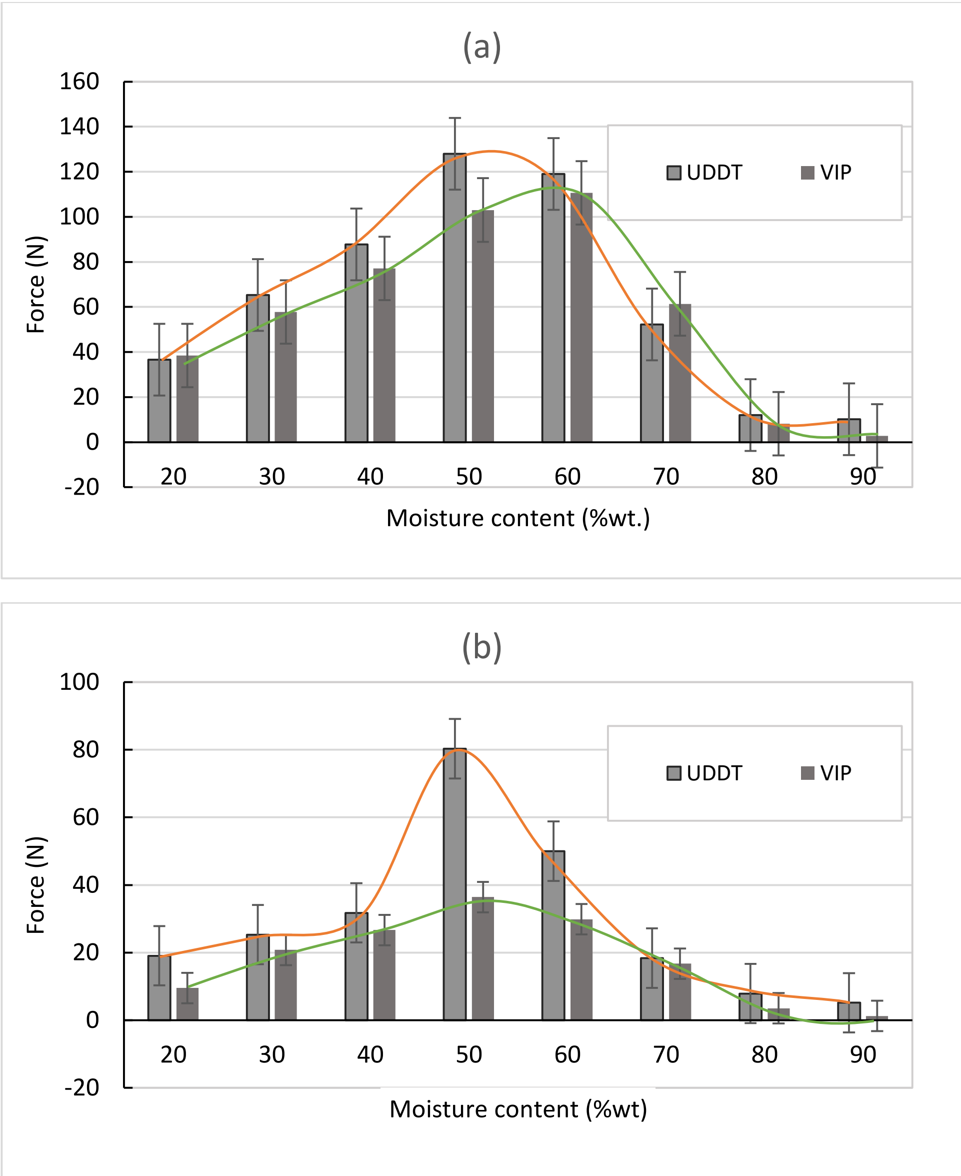
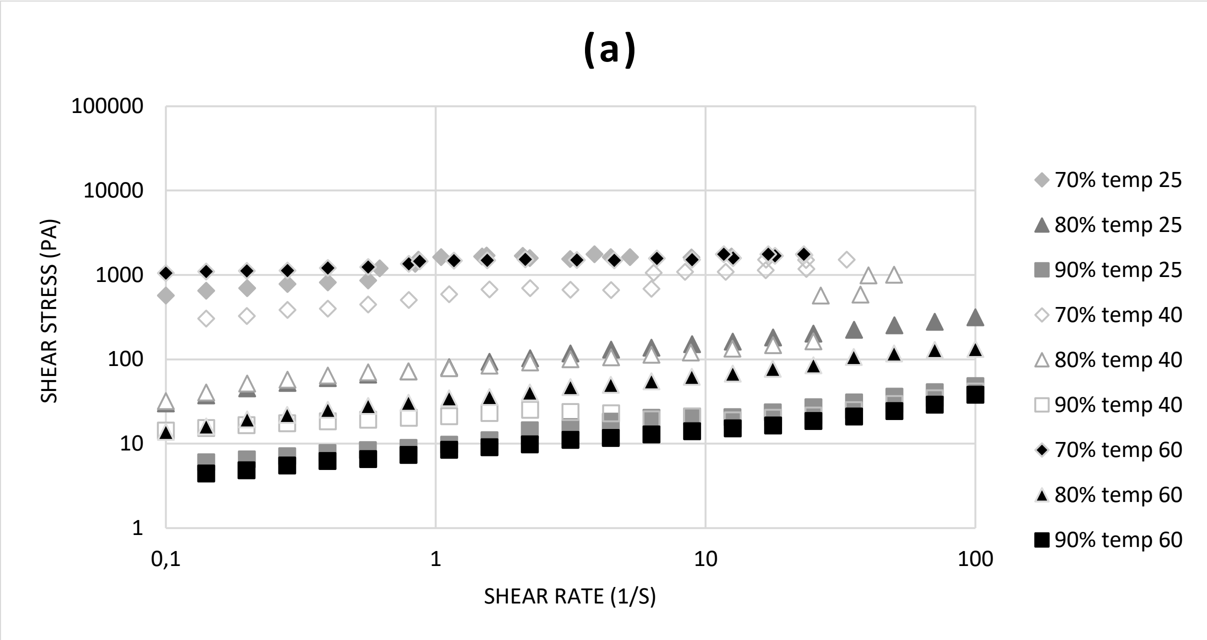


Figure 0-3 Force as a function of moisture content at temperature 80 degrees C; a) Cohesive forces b) Adhesive forces

APPENDIX A6: Shear stress versus shear rate as a function of moisture content and temperature



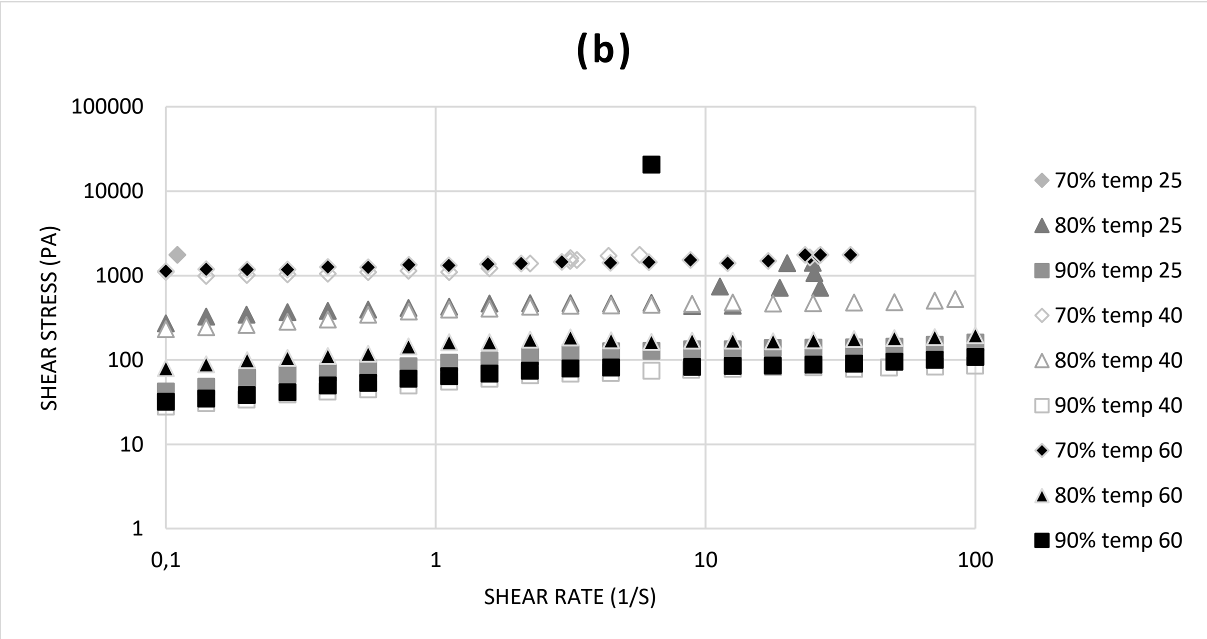


Figure 0-1: Shear stress versus shear rate as a function of moisture content and temperature (a) UDDT (b) VIP

APPENDIX C: Cone penetrometer results

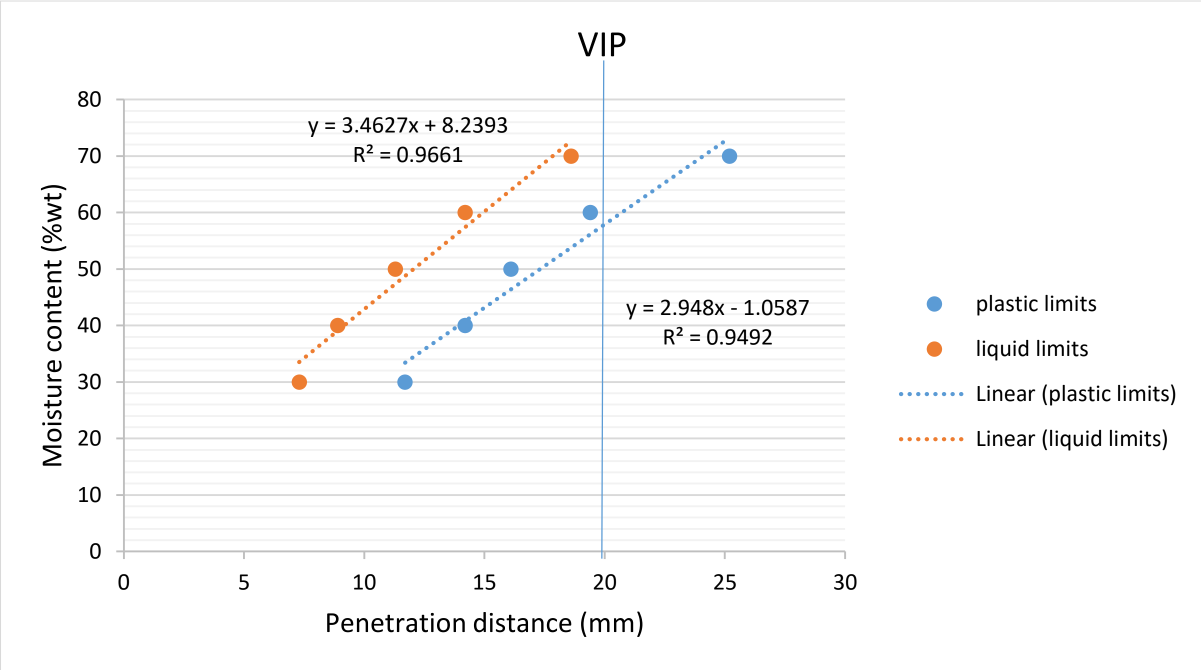


Figure B 1 Moisture content versus penetration distance for VIP sludge

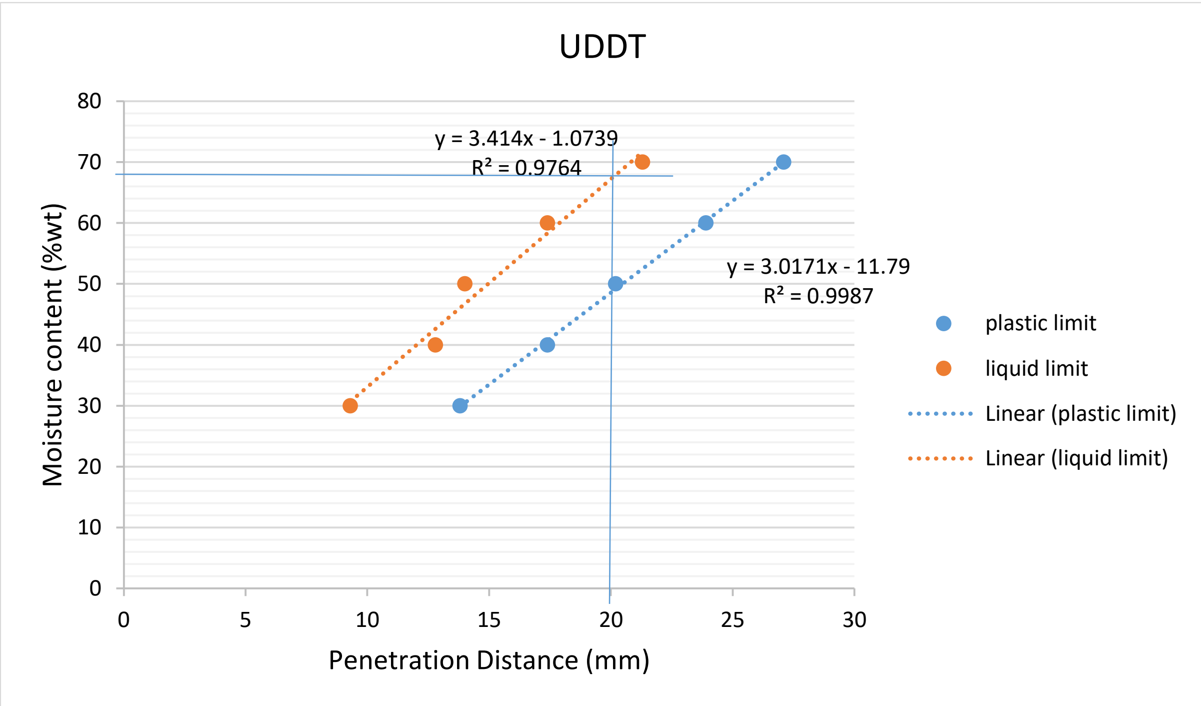


Figure B 2 moisture content versus penetration distance for UDDT