EFFECT OF AGEING ON THE PHYSICOCHEMICAL PROPERTIES OF FRESH FAECES

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This dissertation is submitted in fulfilment of the requirements for the degree

MSc Eng. Chemical Engineering

In the school of Engineering, College of Agriculture, Engineering and Science

University of KwaZulu-Natal

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March 2021

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ACKNOWLEDGEMENTS

I would like to appreciate and acknowledge God; without Him, my existence and that of this research would be a tale.

I want to extend my gratitude to Prof Chris Buckley and the PRG family for awarding me the opportunity to embark on this MSc journey of growth, hard work and personal fulfilment.

Many thanks to The Bill and Melinda Gates Foundation for funding this project.

My supervisors, Dr Santiago Stringel and Dr Jon Pocock, your guidance, correction and approachability are second to none. Thank you!

I am very appreciative of Kerry Philp and Merlien Reddy who were instrumental in ensuring the successful completion of this programme.

I am thankful to the lab personnel, particularly Thabiso Zikalala, for providing training in all the laboratory techniques and analyses.

I am grateful to my family and friends for their support through the duration of my programme. Mom, you have been an unlimited supply of strength, support and encouragement, my gratitude is eternal.

ABSTRACT

Conventional onsite sanitation facilities, like pit latrines and urine diversion toilets, and innovative reinvented toilets with in-situ excreta treatment involve onsite storage of faecal matter for a certain period, where biological and physicochemical degradation, drying and dewatering processes may occur. The study was conducted from an improved sanitation perspective and investigated how faeces transformed from when they are generated and deposited in a repository. Fresh human faeces were left to age for sixteen weeks under ambient conditions (temperature ~20°C and ~60% relative humidity) This was experimentally determined by how the moisture content, drying rate, dewaterability, rheological, physicochemical, and thermal properties were affected as the faeces aged.

Fresh faeces samples, collected from voluntary donations from healthy individuals at the University of KwaZulu-Natal, were aged in a ventilated environment under ambient conditions. The previously mentioned characteristics were evaluated weekly for sixteen weeks. Faeces dried with time since moisture content decreased from 79.1 to 26.9% (wet basis). Faeces could not be dewatered to enhance dehydration to reduce sample volume. The drying curves generated indicated a uniform rate of drying uninfluenced by the sample age and initial moisture content. Moisture-dependent characteristics such as rheological and thermal properties were mainly affected during storage and water activity. Despite an unexpected decrease in the first week, possibly due to biodegradation, the waste exhibited increased viscosity and yield stress due to the sample drying. The particle size did not change during the storage and did not influence the rheological properties. Also, the faeces' thermal conductivity and heat capacity significantly reduced with storage time as the sample was dried and showed a fair dependence on the sample water activity, which decreased during the process, suggesting an increase of the moisture boundedness along with the faeces dehydration. The minor variation in volatile solids, COD, carbon, nitrogen, ammonium and nitrates indicated that faecal matter remained rich in organic and nutrient content without undergoing considerable biodegradation. The dried samples maintained a calorific value of around 22 MJ/kg regardless of age.

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LIST OF ABBREVIATIONS

NSS	Non-Sewered Sanitation
BMGF	Bill and Melinda Gates Foundation
RTTC	Reinvent the Toilet Challenge
VIP	Ventilated Improved Pit
UDDT	Urine Diversion Dry Toilet
LOFLOS	Low Flush Onsite Sanitation Systems
DST	Dry Sanitation Technology
CBS	Container-Based Sanitation
OSS	Onsite Sanitation Systems
COD	Chemical Oxygen Demand
TS	Total Solids
VS	Volatile Solids
VFA	Volatile Fatty Acid
BOD	Biochemical Oxygen Demand
TKN	Total Kjeldahl Nitrogen
UKZN	University of KwaZulu Natal
BREC	Biomedical Research Ethics Committee
SOP	Standard Operating Procedure
WASH	Water, Sanitation and Hygiene
MC	Moisture Content
PSD	Particle Size Distribution
TN	Total Nitrogen

NOMENCLATURE

W	weight
%wt	wet basis % moisture content of the wet sample
MR	moisture ratio
M_f	final moisture
M_o	initial moisture
M_t	instantaneous moisture
a_w	water activity
db	dry basis

1 INTRODUCTION

Statistics predict that by 2030, human faeces produced worldwide will reach a staggering 4.6×10^{12} kg per annum from 3.9×10^{12} kg in 2014 (Berendes et al., 2018). The existing substantial gap in sanitation service provision will be consequently broadened, especially in impoverished communities. Over 30% of the global population currently has no access to improved sanitation facilities, with the southern hemisphere being affected more. Roughly 12% rely on open defaecation (95×10^{8} kg of faeces annually) because they either have no toilets at all (Berendes et al., 2018) or their toilets are in such poor or dilapidated conditions that they prefer to defaecate in the open air. Such situations inevitably strain and compromise water resources and the environment in underserved areas affecting the inhabitants' health (WHO, 2017).

Expanding centralised sewerage systems as a stand-alone solution in providing decent sanitation for everyone is costly and water-intensive in construction, operation and maintenance (Singh et al., 2015). Decentralised systems can be developed and implemented to serve the same function as centralised systems (Singh et al., 2015). For this reason, non-sewered facilities with onsite containment have proved to be a leading solution in curbing these challenges (Magri and Sï, 2013), with onsite sanitation segregating faeces totalling 456×10^{9} kg yearly from 56% of households in the world (Berendes et al., 2018). Conventional and reinvented toilets and waste treatment facilities that restrict their operations onsite meet these requirements.

Traditional toilets like septic tanks and ventilated improved pit latrines include confinement and treatment of human solid waste on-site (WHO, 2019). These systems are structured with a lined or unlined underground storage area to receive faeces upon excretion (Nwaneri et al., 2008, Strande and Brdjanovic, 2014), where they are stored long term. Human waste is primarily treated by effective containment for an extended time in-situ (WHO, 2019). The waste can be stored up to years onsite, but it depends on the toilet user count and the waste volume deposited with each excretion ‘event’ (Strande and Brdjanovic, 2014).

The typical non-sewered sanitation (NSS) systems mentioned above are prone to damage due to poor design or flooding. Conventional NSS encompass water shortages, unavailable space for building new pit toilets and poor management of ever-increasing wastewater volumes (BMGF, 2012). This prompted the Bill and Melinda Gates Foundation (BMGF) to start the Reinvent The Toilet Challenge (RTTC) in 2011 by designing innovative toilets and improving existing designs. These revamped facilities involved onsite storage but on a short-term basis and in-situ treatment systems. It was required that they function off-grid, not connected to any external water source or electricity supply. These technologies should be low maintenance, requiring under US$ 0.05 for daily operations and servicing, making them affordable to implement in impoverished and well-to-do nations alike. Reinvented toilets were intended to do away with challenges presented by conventional NSS (BMGF, 2012).

In both conventional NSS systems and reinvented toilets, excreta is typically contained in-situ at or close to the household, before or during processing. Many of these systems allow dehydration (dewatering and drying), vital in removing water weight, the main contributor to faecal mass. The faecal waste is periodically removed for end-use, further treatment, or disposal off-site. Therefore it is more desirable to deal with dehydrated waste since it is less voluminous, costs incurred to ferry it off-site are lessened (Strande and Brdjanovic, 2014). The moisture loss increases viscosity (Woolley et al., 2014b), yield stress (Woolley et al., 2014a), and concentrates the solids (total and volatile) (Chen et al., 2002, Flaga, 2005). Other factors of interest are particle size and particle size distribution since they also influence rheological properties (Mangesana et al., 2008).

Sometimes chemical and biochemical reactions take place during the process of drying (Mujumdar, 2014). These reactions may involve the biological breakdown of organic content in faeces by natural faecal bacteria (Buckley et al., 2008) and the deactivation of microorganisms as moisture is removed (Sagar and Kumar, 2010, Cairns-Smith et al., 2014, Strande and Brdjanovic, 2014). The processes described above may compromise or enhance specific solid product properties (Mujumdar, 2014). The amount of free water in the faeces available to the microbes facilitates these biological reactions (indicated by water activity). Previous researchers used COD, TS, VS, ammonium, and nitrates as markers of faecal organic content (Almeida et al., 1999, Nwaneri, 2009, ZAVALA et al., 2002, Woolley et al., 2014b, Onabanjo et al., 2016a), where decreases indicate biodegradation (Bakare, 2014, Zuma, 2016).

Therefore, faeces ageing under containment may undergo modifications to physical properties and composition with storage. The processes described above may compromise or enhance specific solid product properties (Mujumdar, 2014). Generally, fresh faeces have not been well-characterised from the perspective of improved sanitation, waste treatment, and resource recovery, technological development and service provision. Although the properties of faeces are known, there is an observed lack of available literature on how the faeces evolve with time, which is critical information for on-site sanitation facilities, particularly dry sanitation systems.

This research focused on characterising the evolution of fresh human faeces at ambient conditions (temperature ~20°C and ~60% relative humidity) for 16 weeks. This period was used as a representative timeframe of how long faeces are stored in onsite toilets on a short-term basis. Typically, pit latrines can store waste long-term for up to five years (Zuma, 2016). The findings will provide a better understanding of how faecal matter characteristics evolve from time of generation to stabilisation, during storage, prior to treatment. This study caters to dry onsite sanitation systems that are well-ventilated and employ source separation of urine and faeces in their design, treating the solid waste as an individual stream. The experimental work covered how fresh faeces properties changed over time, so urine and flush water were excluded.

1.1 AIM

This thesis aims to understand the effect of ageing of faeces on their physical and chemical properties at ambient conditions.

1.2 OBJECTIVES

The objectives listed below guided activities of the research to achieve the intent of this project:

- To determine how the physical structure of faeces is transformed as the process of ageing progresses.
- To determine the impact of ageing on the amount of organic and inorganic matter content in faecal matter.
- To investigate how ageing influences dewaterability, drying ability, rheology, particle size distribution and thermal properties of faeces.
- To ascertain how bound and unbound moisture content in faeces change with age.

1.3 SCOPE OF PROJECT

This research focused on characterising the evolution of fresh human faeces at ambient conditions for 16 weeks. This period was used as a representative timeframe of how long faeces are stored in onsite toilets on a short-term basis. Fresh human faeces donated by healthy volunteers, involving mainly students and staff from the University of KwaZulu Natal, were used in this research. Using fresh faeces was central in the study to investigate the path of evolution followed by fresh faeces as they transformed into faecal sludge. Laboratory analysis was conducted on the faeces during their storage in order to monitor the evolution of their physiochemical properties, following the Standard Operating Procedures of the Pollution Research Group.

The results obtained from this study provide further clarity on what transpires to cause changes in the early stages of deposition of faeces in long term storage conventional toilet systems. Knowledge gained may be extended to innovative toilets that contain faeces on a short-term basis and in-situ treatment. Findings can also shed more light on how fresh faeces are modified in an open environment in populations that still practice open defaecation.

The effect of ageing of fresh faeces on the microbial count and pathogen kill-off was outside this research scope.

This study was conducted according to the Ethics Committee's guidelines and assigned the ethics clearance number BREC/00000524/2019 as in the ethics clearance certificate in Appendix A.

1.4 INITIAL HYPOTHESES

- Fresh faeces undergo biological degradation as they age during storage.

- Unbound water is released into the atmosphere when fresh faeces age under in-situ containment.
- The process of ageing affects the physical and chemical properties of the material.
- Ageing influences rheological properties of faeces.

1.5 THESIS OUTLINE

- INTRODUCTION

This chapter contextualises the background that motivated to conduct the current study and a clear indication of the goals the project intended to achieve.

- LITERATURE REVIEW

This segment contains three major subsections. Sub-section 2.1 introduces the concept of on-site sanitation and the different types of facilities. Section 2.2 details the composition of excreta input into these facilities, narrowing its focus on faecal matter. The differences in characteristics between faeces and faecal sludge are highlighted, and evidence of the evolution of faecal matter (specifically, faecal sludge) during in-situ storage from past studies is provided. Section 2.3 describes the processes that occur in different dry on-site storage systems that lead to a transformation of faecal matter and how they may impact its disposal and end-use.

- MATERIALS AND METHODS

This section describes the experimental work methodology and the different equipment types utilised in this project. The techniques used to analyse the data are also described here.

- RESULTS AND DISCUSSION

This chapter describes and discusses the results obtained in this study, the trends deduced from the data analysis and comparison with literature.

- CONCLUSIONS AND RECOMMENDATIONS

The outcomes from the experimental work and data analysis are summarised, and inferences are drawn on their impact on non-sewage sanitation systems.

2 LITERATURE REVIEW

2.1 Onsite Sanitation

Sanitation embodies disposing of wastes such as human excreta, solid domestic and medical waste wastewater (and its reuse) and drainage of surface rainwater (Brikké et al., 2003). The focus of this project is on human excreta. Toilet facilities are principally onsite or off-site (Sharp, 2010).

Off-site sanitation deals with waste carried away to a treatment plant through the sewage grid and treated before disposal. Onsite sanitation contains human excreta for some time in the proximity of the toilet. It is not transferred to an off-site location for primary treatment (Fourie and Van Ryneveld, 1995, Torondel, 2010). In this method, the waste undergoes onsite degradation to an extent (Lawrence et al., 2001). The accumulation of faecal material eventually leads to the facilities filling up and requiring emptying on a periodical basis or building new ones. The residue may be treated and reused or disposed of off-site (Fourie and Van Ryneveld, 1995).

Forms of onsite sanitation systems include septic tanks, pit latrines, among others. Those used in South Africa include VIPs (Ventilated Improved Pit latrines), UDDTs (Urine Diversion Dry Toilets), LOFLOS (Low Flush Onsite Sanitation Systems), also known as aqua privies, and septic tanks. VIPs, UDDTs and LOFLOS, receive human excreta and sometimes greywater, whereas septic tanks are designed to accept both (Fourie and Van Ryneveld, 1995).

Based on water usage, dry and water-based sanitation systems form subclasses of onsite sanitation (Tilley, 2014, Lawrence et al., 2001, Brikké et al., 2003).

2.1.1 Dry sanitation

Dry sanitation technology (DST) involves discarding human liquid and solid excreta in the toilet without flushing water. This system eliminates the expense of using water to dispose of urine and faeces (Gounden et al., 2006). DST best suits communities with no sewerage network coverage and/or where water is sparingly available. Dry sanitation involving reuse of the waste is reportedly a reasonable substitute for water-based sanitation (Peasey, 2000). By design, some DSTs allow reuse of waste end-products for agricultural purposes. However, pathogens need to be deactivated so that the end-product can be handled safely. Faecal bacteria reduces depending on storage time, pH conditions and humidity (Peasey, 2000). Pathogen-die off occurs during storage and the length of the storage period required to ensure this is dependent on the type of technology utilised. Final products from toilets can then be safely handled and used as soil conditioners and plant fertilisers (Peasey, 2000). The most popular forms of low-cost on-site DSTs include pit latrines, VIPs (Peasey, 2000) and UDDTs (Gounden et al., 2006).

2.1.2 Water-based Sanitation

Typically, water-based systems use more resources, have higher costs and are less sustainable in comparison to dry systems, although they may produce reusable products as well (Green and Ho, 2005). They require a consistent supply of water to operate correctly. A constant amount of flush water is necessary to carry the excreta away from the toilet bowl so that the toilet stays functional (Tilley, 2014). Water-based toilets include pour-flush, cistern flush and urine diversion flush toilets. For facilities that require flushing water, such as LOFLOS and pour-flush toilets, water is a definite faecal sludge constituent (Green and Ho, 2005, Tilley, 2014).

2.1.3 Container-Based Sanitation (CBS)

Containerised systems are being developed to do away with problems associated with traditional onsite sanitation systems (Saxena et al., 2019, Hawkins et al., 2017b). These include wastewater management challenges caused by over-increasing domestic water consumption resulting from growing population densities and space constraints to construct new pit latrines when old ones fill up (Hawkins et al., 2017b). Inadequate regulation of onsite sanitation systems (OSS) such as pit latrines and septic tanks inevitably lead to groundwater pollution, thus compromising water quality. These shortcomings led to the consideration of CBS as a potential alternative (Saxena et al., 2019).

CBS uses containers where human waste accumulates and is stored temporarily at household level. Once the containers are full, they can be tightly closed and transported to an off-site location for treatment or disposal of the content and cleaning of the containers (Hawkins et al., 2017b, Saxena et al., 2019). Compared to OSS, CBS offers faecal sludge in-situ containment with easy disposal and, generally, a more uncomplicated management strategy for faeces (Saxena et al., 2019).

2.1.4 Reinvented Toilets

The Reinvent the Toilet Challenge (RTTC), sponsored by the Bill and Melinda Gates Foundation (BMGF), has supported the development of low-cost, sustainable and innovative sanitation technologies. This initiative aims to accelerate the process of providing improved sanitation for 4.5 billion people lacking primary or safe sanitation (BMGF, 2012, Hawkins et al., 2017b). Technology developers ingeniously revamped toilets and waste treatment systems to become not connected to the sewerage network, to the electrical grid and water sources. These ablution facilities are designed to forgo using flush water (BMGF, 2012) and feature human waste in situ treatment (BMGF, 2014). The toilets incorporate different treatment processes, e.g. dehydration, biodegradation, thermochemical conversion and electrochemical disinfection, to facilitate efficient recovery of nutrients, energy and clean water (BMGF, 2012). Table 2.1 cites examples of reinvented toilets associated with the BMGF, with the features mentioned above, along with how much it costs to operate and maintain them per day (BMGF, 2014).

Table 2.1 Reinvented off-grid sanitation systems featuring dehydration and degradation processes (BMGF, 2014)

Prototype	How it works	Daily cost per user
Biofil Toilet System	A digester is connected to an already installed toilet in a household. Deposited waste gets dewatered using sieve-like media. The remaining solid excreta is retained in the aerated digester box, where it is subjected to decomposition by macro- and microorganisms.	US$0.00 – 0.01 No operation and minimal maintenance costs.
Miniwaste Processor (MWP)	The waste is deposited in a waterless lavatory chamber. This chamber links to the MWP, which receives the waste and thermally dries and sterilises the faeces for later use as a fertiliser.	US$0.01 (daily operations cost is 0, some savings as maintenance costs)
The Earth Auger: Urine Diverting Dry Toilet	A dry toilet model that does not require any water or energy input. It solely relies on a mechanical auger and gears to mix and cover faecal matter. Compost bacteria perform biodegradation of organic matter in-situ to yield soil conditioner beneficial for agricultural purposes.	US$0.02-0.05
Aerosan	The system hauls air into the repository, setting off passive ventilation, which dries the faecal waste. Another option, passive solar heating, dewaters this waste. These processes reduce the foul smell and excreta volume. Complete treatment can be conducted on-site or transferred to an off-site facility to produce a pathogen-free compost suitable for agricultural use.	US$0.035 - $0.14
Cranfield Nano Membrane Toilet	Faeces and urine are flushed as a single stream using a revolving device powered by a hand crank or bicycle generator. The rotating action also works to separate the two waste types. Free water is recaptured for laundry or irrigation purposes. The solid fraction is left to degrade in short-term storage and ultimately produces power for low-voltage domestic use and fertiliser.	$0.05 – 0.10

2.2 Characteristics of faecal matter

If appropriately utilised, dry sanitation toilet content should comprise human excreta and anal cleansing water or other cleansing material (Foxon et al., 2011). The nature and type of food consumed significantly affect the composition and quantity of faecal excreta (Niwagaba, 2009, Rose et al., 2015). Dissimilarities in diets cause variations in physical and chemical structure of faeces, even on an individual basis (Still et al., 2012).

2.2.1 Constituents of fresh faeces

The solid human excreta is essentially water and solids (Rose et al., 2015). The solid composition includes lipids, protein, carbohydrates, undigested food fragments and bacteria (Torondel, 2010, Rose et al., 2015). On an elemental level, fresh faeces principally contain carbon 51±2%, hydrogen 7±0%, oxygen 21±3% (Onabanjo et al., 2016b) and 5-7% nitrogen (Feachem and Cairncross, 1978), all on a dry basis. Other noteworthy elements in the dried solid portion are phosphorus 3-5.4%, potassium 1-2.5% and calcium 4.5% (Feachem and Cairncross, 1978). Carbon is the main constituting element at around 45-55% on a dry basis (Rose et al., 2015, Septien et al., 2020), which is expected since faeces are organic material (Septien et al., 2020). Degradable organic matter constitutes about 80-90% of human solid waste on a dry mass basis (Buckley et al., 2008, Still et al., 2012). The degradable organic matter in the faeces (on a dry mass basis) can be further classified as listed below (Still et al., 2012):

- Undigested elements (Rose et al., 2015): 30%
- Bacteria (the majority is non-viable): 30% (Torondel, 2010, Rose et al., 2015)
- Fats: 10-20%
- Protein: 2-3%
- Shed intestinal linings

Additionally, pathogens populate faeces in numbers contingent on the health status of individuals (Still et al., 2012). Harmless E-coli strains and bacteria are also present (Torondel et al., 2016). These bacteria in the excreta aid the post-defaecation biodegradation of the stool in onsite containment (Still et al., 2012). Most faecal bacteria survive between one week and two months only (Strande and Brdjanovic, 2014) based on their ability to adapt to the external environment (Torondel et al., 2016). In unlined conventional onsite sanitation facilities, fungi, maggots, and other microorganisms migrate from the external environment to assist biodegradation (Buckley et al., 2008).

2.2.2 Characterisation of faecal matter during storage

It is essential to determine the rates of the degradation reactions for the organic material. Constituents of faeces need to be known as they affect the design and performance of the waste treatment system (ZAVALA et al., 2002).

Parameters such as COD, TS and VS indicate how biodegradable organic waste is (ZAVALA et al., 2002). Collectively, all organic material may be measured as total COD. Faecal waste consists of ash (~20%) and biodegradables (~80%) (Nwaneri et al., 2008). Studies done by different researchers to characterise fresh faeces are summarised below in Table 2.2.

Table 2.2 Characterisation data of fresh faeces

Parameter (Unit)	Almeida et al. (1999)	ZAVALA et al. (2002)	Nwaneri et al. (2008)	Remington (2019)	Onabanjo et al. (2016a)	Woolley et al. (2014b)
COD (mg/mg db)	1.38	1.45	1.13	1.366±0.106	-	-
Moisture content (%wt)	79.2	81.8	78	76±5	-	77.1±7.6
TS (% wt**)**	20.8	18.2	22	-	-	-
Volatile solids (% db)	-	84.4	84	-	85.39	87.6±3.1
Ash (% db**)**	-	-	16	-	14.56	-
NH_3-N (mg/mg db**)**	7.2	3.4	-	-	-	-
T-N (mg/mg db**)**	-	60.1	-	-	-	-
NO_3-N (mg/mg db**)**	0.14	0.03	-	-	-	-

The variances in organic and chemical composition shown in the different studies in Table 2.2 arose because of the diverse food consumed by the target groups (Tilley, 2014, ZAVALA et al., 2002, Rose et al., 2015).

Gaining better insight into the transformation behaviour of fresh faeces as they undergo ageing in in-situ containment can improve the current ways excreta is managed in dry NSS technologies. Substantial work has been done on how faecal sludge properties are transformed by ageing by prolonged containment in-situ, pending emptying and/or subsequent treatment. Be that as it may, not much literature is available on how ageing impacts the properties of fresh faeces.

Nwaneri (2009) provided evidence that human waste (fresh faeces and urine) does experience biodegradation when deposited in an onsite sanitation containment facility. This was demonstrated through a comparative study on fresh excreta and faecal sludge from a VIP latrine. Newly produced waste showed higher values of Biochemical Oxygen Demand (BOD), Total Solids (TS) and Total Kjeldahl Nitrogen (TKN) than those of faecal sludge, as seen in Table 2.3.

Table 2.3 Difference in characteristics between fresh faeces and faecal matter in containment (Nwaneri, 2009)

Parameter	Units	Fresh excreta (faeces and urine)	Pit latrine Sludge
BOD	g/cap.day	45	8
TS	g/cap.day	110	90
TKN	g/cap.day	10	5
COD	mg/L	-	20 000 – 50 000

Characteristics of human waste are highly variable depending on the length of the residence time in containment (Andriessen et al., 2019). Bakare (2014) characterised faecal sludge samples from a conventional on-site sanitation facility, namely VIP latrines (*n*=16). Samples were taken from the surface layer and 0.5, 1.0 and 1.5 m deep. The parameters tested and outcomes are shown in Table 2.4. Faecal sludge from different layers underwent varying degrees of ageing while in storage. Deeper layers with longer residence time would have had more time to degrade (Zuma et al., 2015).

Table 2.4 Characterisation of differently aged faecal sludge from a conventional OSS facility

		Depth from the surface top			
Parameter	Units	**Surface**	**0.5 m**	**1 m**	**1.5 m**
Moisture	%	76.88±1.22	71.63±2.58	64.60±2.98	67.22±3.07
COD	g/g db	0.603±0.060	0.382±0.034	0.251±0.030	0.244±0.032
VS	% db	57.89±3.37	47.74±3.90	33.95±4.04	36.57±4.32
Biodegradability	%	52.46±10.92	41.35±9.38	24.08±7.73	16.55±6.25

* mean ±stdev

Different studies (Zuma, 2016, Bakare, 2014, Wood and Buckley, 2013) investigated the faecal sludge properties from the surface of pit contents, and 0.5, 1 and 1.5 m depths shown in Table 2.4. Properties analysed included moisture content, volatile solids, COD, ammonia, TKN, pH, calorific value and thermal conductivity. They found a general decrease in characteristic values with increasing depth. Hence, the value of these properties decreased with increasing age in storage. Results mentioned above reveal that faecal sludge dries out in storage while the organic matter undergoes decomposition in conventional on-site sanitation facilities.

2.3 Transformations under storage

The implementation of dry sanitation with the intention of reusing end-products employs either of two fundamental processes, dehydration or decomposition (Peasey, 2000).

2.3.1 Dehydration

As stated in Section 2.2, researchers' studies evidenced a general trend of moisture reduction with ageing and prolonged storage of the faecal waste onsite (Wood and Buckley, 2013, Bakare, 2014, Zuma,

2016). This section focuses on onsite dehydration sanitation facilities and how moisture reduction occurs either through dewatering or drying, or both. Drying can lead to physical properties changes (Mowla et al., 2013, Mujumdar, 2014). This segment covers ways in which physical properties of faeces conceivably are transformed during containment on site.

Urine and faeces are separated and collected as different streams in UDDTs. The collection facility for stool has two chambers, where they are used one at a time. Faeces accumulate in the section below the pedestal and undergo drying (Peasey, 2000, Gounden et al., 2006). A dry, well-ventilated and high-temperature environment best promotes waste drying (Tilley, 2014). If there is sufficient aeration, faeces can generate enough heat to kill some pathogens (Peasey, 2000). Commonly, waste is sprinkled with absorbents (lime, ash or earth) onto the excrement after defaecating to aid dehydration and minimise flies and odour. Cesspools are used rotationally; users seal off one when it fills up and utilise the second one. The latter also meets the same fate once full, and then people revert to using the first chamber after emptying its contents (Peasey, 2000, Gounden et al., 2006).

Stool kept in situ loses a significant 75% of its volume to become dried and crumbly due to dehydration. However, faeces experience minimal biodegradation in the process (Tilley, 2014), leaving a product still rich in carbon and other organic material (volatiles) (Tilley, 2014, Harder et al., 2019). There remains a risk of reactivation of some pathogens in conducive environments (Tilley, 2014). Emptied contents can be buried, composted or used as a soil conditioner (Peasey, 2000).

2.3.1.1 Drying and dewatering

Drying is a crucial procedure in managing faeces and faecal sludge that sterilises faecal material, making it relatively safer for handling. Sterilisation is achieved when water activity of the faecal material drops below the pathogen water activity present in the faeces as they cannot survive below this value (Remington, 2019, Bourgault et al., 2019).

Drying and dewatering eliminate water weight constituting the bulk of faecal mass and volume, thereby reducing transport costs. Depending on the intended end-use, drying may simplify the next treatment steps (Strande and Brdjanovic, 2014, Mujumdar and Devahastin, 2000) and enhance desirable properties such as the heating value of faeces as a solid fuel (Onabanjo et al., 2016a, Mujumdar and Devahastin, 2000). Drying is when a substance loses moisture through evaporation. However, when moisture removal is performed using mechanical separation processes, it is termed dewatering. Dewatering is inclusive of methods such as filtration, centrifugation and sedimentation. Moisture is lost in vapour form for drying, whereas dewatering the moisture remains in its liquid phase. Drying is facilitated by a moisture, temperature or humidity gradient whereas dewatering requires applying a mechanical force to effect separation of the liquid and solid phases (Mujumdar 2000).

The drying technique utilised to remove moisture depends on its location, whether inside the solid or on its surface (Seader et al., 1998). There are three moisture classes, bound, unbound and free (Mujumdar and Devahastin, 2000, Vaxelaire and Cézac, 2004). Free water is partially or wholly extractable by mechanical dewatering, e.g. subjection to compression, gravitational settling or centrifugal force (Ekechukwu, 1999, Strande and Brdjanovic, 2014). Bound water content is physically, biologically or chemically bonded to faeces (Chen et al., 2002). Applying thermal energy removes the bound moisture from a solid (Chen et al., 2002, Elsaesser et al., 2009, Vaxelaire and Cézac, 2004) though the physically bound type can be removed by mechanical dewatering. Figure 2.1 illustrates the relationship between bound and unbound moisture.

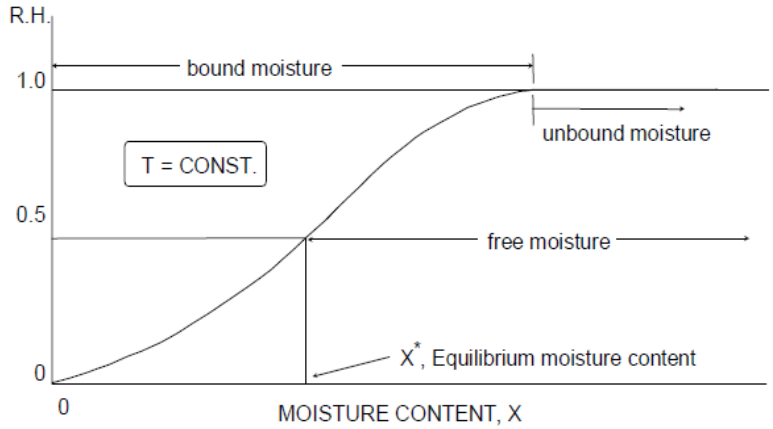

Figure 2.1 A relationship between types of moisture in a solid (Mujumdar and Devahastin, 2000)

The drying process is through evaporation of free water from the exposed surface or interior of faecal waste under storage. Introducing hot air from an external heat source is one way of effecting moisture removal (thermal drying). Alternatively, drying may be passive, relying on natural mechanisms of evaporation such as the sun or wind convection (Andriessen et al., 2019). Passive drying is facilitated by sturdy continual air circulation from outside, contacting surface contents in the storage area. For traditional OSS, ventilation can be through the squat hole and up the vent pipe (Mara, 1984, Buckley et al., 2008). In on-site storage, moisture contained in solid human waste can be released into the surrounding air in the form of vapour (Franceys et al., 1992, Strande and Brdjanovic, 2014). The evaporative action of moisture leads to faecal material drying (Strande and Brdjanovic, 2014). This form of low-temperature drying utilises constant ventilation until moisture content and drying air reach equilibrium. It is a principle that preserves targeted nutrients typically applied in bulk drying or long term storage of crops (Ekechukwu, 1999).

Dewatering in OSS may be in the form of physical screening, filtration or gravity settling. The process of dewatering may occur while solid excreta fill up storage due to compaction, causing faecal contents to be denser at the bottom. In semi-lined or unlined conventional toilets, the water is forced out and seeps into the surrounding underground environment (Franceys et al., 1992, Strande and Brdjanovic,

2014). Some systems employ physical screening or mechanical forces to attain separation of the liquid and solid waste fractions (Strande and Brdjanovic, 2014). One example is the onsite waste treatment system for toilets developed by Duke University (under the RTTC) that uses a conveyor made of several rubber bands that sift blackwater. Liquids seep through the bands while solids remain on the bands and are conveyed to an extruder (Hawkins et al., 2017a). Dewaterability of faecal contents depends on the storage period, where the fresh or raw faecal material is more challenging to dewater than the older, more stabilised waste (Strande and Brdjanovic, 2014). Studies suggest it is because fresh faeces have no free water, moisture is strongly bound to the dry bone structure (Remington, 2019). Moisture only starts being released when organics start being biologically broken down. The longer the storage period, the more water is freed up by biodegradation, if it takes place (Agoda-Tandjawa et al., 2013, Zuma, 2016). However, absence of biodegradation results in loss of loosely bound moisture through drying and material clumping up in the process (Agoda-Tandjawa et al., 2013), and as faeces get drier they cannot be dewatered.

2.3.1.2 Influencing factors of drying

Aspects like temperature, humidity, airflow, external environment pressure, surface area, moisture content and the physical nature of solids govern the rate at which drying occurs (Mujumdar, 2014). A further discussion of these factors is presented below.

Type of solid - Organic and inorganic wet solids respond differently to drying conditions. Inorganic ones retain moisture in pores between particles but remain unaffected as moisture is eliminated. As a result, the properties and appearance of the dried solid are independent of drying conditions. Organic solids can dissolve moisture or trap it in the tiny pores in the solid. They usually shrink in volume when drying and are, therefore, affected by moisture removal (Seader et al., 1998).

Moisture gradient - Moisture transfer during drying occurs because of a moisture gradient (Ekechukwu, 1999). When the surface dries faster than the solid interior, higher temperature and moisture gradients arise in the solid, leading to case hardening, or cracking. As time progresses, drying usually becomes slower in its advanced stages (Seader et al., 1998).

Temperature – When drying occurs at too low a temperature (and humidity is too high), drying takes place more slowly. Elevating drying temperatures promotes moisture evaporation, thus quickening the drying rate (Ilic and Turner, 1989, Iguaz et al., 2003, Elsaesser et al., 2009, Celma et al., 2012).

Speed of air - Increasing air flow rate promotes mass transfer from the surface. In this way, the moisture gradient is continually renewed and further promoting mass transfer of water to the air (Bergman et al., 2011). Iguaz et al. (2003) reported that air velocity mainly affects drying performed at low temperatures.

Surface area – The drying rate is proportional to the contact surface area. The rate of moisture evaporation from the free surface is slowed down, thus reducing the quantity of moisture lost. The drop

in drying rate occurs because the sludge surface is not saturated by moisture anymore, leading to the falling rate period (Léonard et al., 2004). A shrinkage in contact surface area lengthens the drying time, whereas granulation increases the contact surface area, making drying faster (Flaga, 2005). So, in essence, granulation and shrinkage of substances have opposing effects on the drying rate.

Thickness - The thickness of a substance influences the drying rate. Depending on the substance geometry, sometimes its shrinkage only affects the thickness and not the surface area. The thicker the material, the slower the mass transfer is, leading to a slower drying rate.

Relative humidity - This parameter affects the external mass transfer and, consequently, the drying rate, especially during the constant rate period. Increasing the air relative humidity reduces the moisture concentration transfer potential between the material's surface and the dry air, causing a reduction in external mass transfer.

Besides, drying gets driven by the concentration difference between water vapour in the atmosphere and water as moisture in the wet solid. The air humidity influences the equilibrium moisture content, affecting the maximum amount of moisture removable from a substance. As the atmosphere increases in humidity, less moisture is removed due to higher equilibrium moisture content.

2.3.1.3 Implications on physical properties of faecal matter

Moisture contained in faecal sludge has been shown in Section 2.2.2 to diminish over time in a repository. Moisture loss/removal effects physical changes in faecal matter (Mujumdar 2000). Physical properties that may be impacted include composition, solids concentration, particle size and rheological behaviour (Feng et al., 2014, Cheng and Li, 2015). However, characteristics of fresh faeces such as moisture content, ageing and degree of biodegradability are dissimilar to those of faecal sludge from pit toilets.

The following segment discusses the consequences of drying and dewatering on faecal matter physical properties.

2.3.1.3.1 Water Activity (a_w)

The ratio between water vapour pressures on faecal material and the pure water vapour pressure under similar conditions refers to the water activity (Strande and Brdjanovic, 2014). Water activity values approximating 1.0 reflect that water is free (Strande and Brdjanovic, 2014, Getahun et al., 2020) whereas, near 0, it is highly bound (Getahun et al., 2020). Remington (2019) indicated that moisture in fresh faeces was still firmly bound at a_w as high as 0.85 (~27-34%wt). Getahun et al. (2020) found that liquid in faecal sludge was unbound at a_w 0.85 (~ 30%wt), and more firmly bound moisture was present below 30%. The initial water activity value for fresh faeces samples ranged between 0.93 – 1 for the moisture contents of 63% - 86%wt (Remington, 2019).

Getahun et al. (2020) and Strande and Brdjanovic (2014) ascertained water activity to lessen due to declining moisture content regardless of the faecal sludge source. Inactivation of most faecal-borne pathogens occurs when water activity becomes less than 0.85 (Sagar and Kumar, 2010, Cairns-Smith et al., 2014), corresponding to a moisture content between 27%-34%wt for fresh faeces (Remington 2019). Yeast and mould cannot grow below 0.62 water activity (Sagar and Kumar, 2010). Therefore, no yeast, mould, nor pathogenic bacteria is expected to grow when a_w falls beneath 0.62. Thus, drying and dewatering can lead to a reduction in the microbial count. The longer faecal matter stays in storage, the more water activity is reduced, hindering microbial growth (Sagar and Kumar, 2010, Strande and Brdjanovic, 2014). Despite this, the product may not necessarily be sterile (Sagar and Kumar, 2010). If the water activity drops below the critical values shown in Table 2.5, growth is impeded.

Table 2.5 Critical water activity values for microorganisms

Microorganism	Cairns-Smith et al. (2014)	Sagar and Kumar (2010)	Strande and Brdjanovic (2014)
Faecal borne pathogens	0.85	0.85 – 0.86	0.90
Yeast	-	0.62	-

However, Agoda-Tandjawa et al. (2013) found water activity increasing as ageing time increased. It was presumed to be explicitly caused by volatile fatty acids (VFAs) generated by organic carbohydrate polymers being hydrolysed during storage. VFAs are amphiphilic and arrange themselves to restrict contact with water, making it less bound to the solids (Agoda-Tandjawa et al., 2013).

Water activity has an inversely linear relationship with the solids concentration. When the solids in a substance become more concentrated, the solid matrix becomes more strengthened as well. Therefore, the smaller the water activity, the stronger the solid form (Agoda-Tandjawa et al., 2013).

Thermal properties of water in a substrate are potentially controlled by how water is bound inside that substrate. It is not moisture content that affects biological reactions but water activity (Gavrila et al., 2008).

2.3.1.3.2 Rheology

Fresh faeces possess yield stress at low shear stress values, but when the yield point is exceeded, apparent viscosity decreases as shear rate increases (Woolley et al., 2014b). This particular behaviour of faecal matter past the breakpoint is termed shear-thinning (Woolley et al., 2014a, Septien et al., 2018). Although when undergoing fermentation, the structure weakens in that phase (Agoda-Tandjawa et al., 2013), thus reducing the faecal viscosity. Fresh faeces are thixotropic since the apparent viscosity decreases when exposed to shear and increases again while at rest. However, the apparent viscosity

cannot return to its initial magnitude, evidencing that faecal matter structure cannot recover completely (Woolley et al., 2014b).

- *Influence of moisture content*

Shear stress and apparent viscosity are affected by the quantity of moisture contained in a faecal sample (Woolley et al., 2014b). Moisture content does not solely determine the thickness of faecal matter but has the most significant influence (Woolley et al., 2014b, Septien et al., 2018). Fresh faecal material with higher moisture content has lower apparent viscosity. For any given shear rate, fresh faeces with low moisture contents possess high apparent viscosities. Viscosity decreases by increasing moisture content when shear rate is fixed (Woolley et al., 2014b).

The shear stress applied to cause movement of fresh faeces reduces in magnitude with increasing faecal moisture content (Woolley et al., 2014a). Apparent viscosity of fresh human faeces decreases smoothly with rising shear stress until the yield point. Fresh faeces experience elastic deformation before reaching the yield point, but the faeces start to flow when the yield point is exceeded. The yield stress represents the lowest shear stress value required to surpass the elastic resistance of faecal matter to start flowing (Woolley et al., 2014a, Septien et al., 2018). Increasing moisture lessens the yield stress of faecal material that needs to be surpassed to cause a flow in the faeces when emptied from onsite storage using a pump. As drying concentrates solids content in the sludge, more shear power is required to mix it (Flaga, 2005, Chen et al., 2002). Initiating flow can reach a point where it becomes non-viable due to low moisture content. The most aged faecal material can lose its ability to flow because it is too dry (Septien et al., 2018).

- *Influence of particle size and solids concentration*

Solid content significantly affects rheological properties. As drying removes moisture from sludge, the solids become more concentrated, resulting in a higher sludge viscosity (Feng et al., 2014, Cheng and Li, 2015). Apparent viscosity increases with the total solids concentration regardless of particle size (Mangesana et al., 2008).

As a substance is drying, individual particles tend to form clumps. The effect of clustering affects viscosity more than the size of individual particles. Consequentially, there is an obstruction to flow and rotation of individual particles causing increased flow resistance, inevitably increasing viscosity (Siri Harboe 2012). However, if there is microbial activity, and it involves hydrolysis, the colloidal macromolecules are destroyed as the organic content is hydrolysed. This brings about loss of natural shape and improved solid matter flow (Feng et al., 2014), thus lowering the viscosity.

2.3.2 Biodegradation

Chemical and biochemical reactions may occur during drying, causing a preferred or unpreferred shift in properties of a solid (Mowla et al., 2013, Mujumdar, 2014). The duration that waste spends in onsite

containment systems before processing also significantly affects properties due to organic matter digestion during storage (Strande and Brdjanovic, 2014). This section explains the possible reactions that take place in containment leading to changes in faecal matter qualities that were discussed in Section 2.2.

Biodegradation of faecal matter is performed by microbes (bacteria, worms and others). Designs of most decomposition toilets incorporate the use of certain organic additives to aid decomposition. The solid product of the toilet after storage is utilised as a soil conditioner. Liquid fractions may include urine or liquids produced because of faecal matter compaction or biodegradation. These liquids may be left to evaporate, redirected to a soak-pit (Peasey, 2000) or collected and treated for re-use in crop irrigation.

Bacteria break down complex organic material to a stable organic residue that is unlikely to transform further because of pronounced depletion of organic material in in-situ containment (Still et al., 2012). Faecal matter is broken down in different ways due to the diversity of present bacteria, principally aerobic or anaerobic (Franceys et al., 1992, Foxon et al., 2011).

2.3.2.1 Anaerobic and aerobic biodegradation

Biodegradation involves breaking down faecal organic matter with or without oxygen to facilitate the process. Aerobic breakdown uses oxygen, but the exclusion of oxygen from the process renders it anaerobic biodegradation (Still et al., 2012). Equation 2.1 describes the aerobic route, where organic material is consumed through oxidation and carbon dioxide is released, and new cells are synthesised.

$$0organic\ waste + O_2 + nutrients \xrightarrow{micro-organisms} CO_2 + H_2O + C_5H_7NO_2 + other\ products \quad (2.1)$$

- $C_5H_7NO_2$ are the new cells, and other products are heat and non-biodegradable residue.

Anaerobic degradation occurs in four key biochemical steps (Strande and Brdjanovic, 2014, Torondel, 2010):

- Hydrolysis – the breakdown of particulate matter to soluble substrates
- Fermentation of hydrolysis products to simple organic compounds, such as acids, alcohols, volatile fatty acids and gases (H_2, CO_2, H_2S and NH_3) (Bakare, 2014, Torondel, 2010).
- Acetogenesis – acetate is synthesised from organic acids and CO_2 that came from fermentation.
- Methanogenesis – microorganisms use CO_2, H_2, formate, acetate remaining from the first three steps to generate methane.

When faeces are deposited in well-ventilated containment, the faecal pile is exposed to a consistent oxygen supply. An aerobic environment is created (blue region in Figure 2.2), leading to faecal material being broken down aerobically by aerobes (Buckley et al., 2008). However, there may be zones where

oxygen diffusion through faecal material is hindered, causing conditions to become anaerobic (Mara, 1984, Still, 2002, Chaggu, 2004, Buckley et al., 2008). A high moisture content promotes anaerobic degradation because the presence of excess moisture obstructs oxygen movement (Nwaneri et al., 2008). The region of anaerobic activity is outlined in orange in Figure 2.2.

The extent to which the biodegradable organic fraction in faecal matter is transformed into bacteria, waste residue, and other degradation products determines the level of stabilisation. Product material is considered 'wholly stabilised' when the quantity of biodegradables becomes insignificant. Stabilised organic material cannot be biologically transformed further in storage (Buckley et al., 2008).

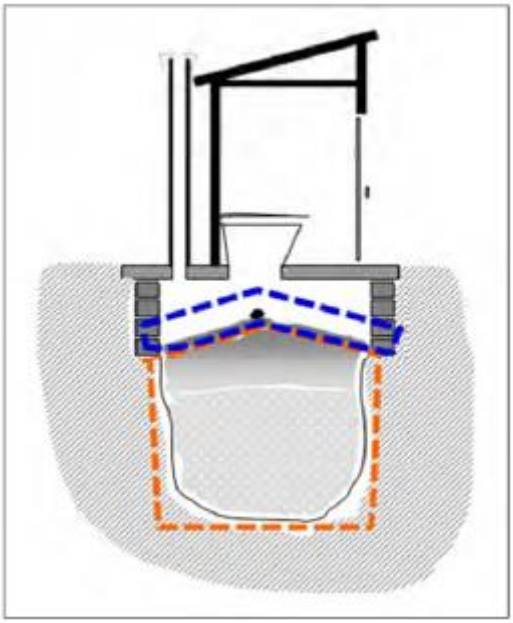

Figure 2.2 Regions of aerobic (blue) and anaerobic (orange) degradation of faecal matter during storage in on-site sanitation facilities (Still et al., 2012)

Microorganisms initiate biodegradation by disintegrating particulate matter and complex organic compounds (lipids, carbohydrates and proteins) into more soluble smaller substrates (fatty acids and glycerol, sugars, and amino acids). The smaller substrate-nutrients contained in faeces are further broken down for growth and respiration. Microbes can feed on biodegradable organic matter in the presence or absence of oxygen, depending on the conditions. Buckley et al. (2008) discovered that degradation could deplete as little as 10% of COD in fresh faeces in storage without aeration, but in a predominantly aerobic environment, even up to 50%. As this process progresses, part of the faecal matter is converted to biomass and energy. Some energy released during biodegradation is used to reproduce more bacteria, and the remainder converted to heat (Franceys et al., 1992, Kelleher et al., 2002). It follows that biodegradation is an exothermic process regardless of the route (Tchobanoglus et al., 2003, Taljaard et al., 2005, Strande and Brdjanovic, 2014). However, the aerobic produces much more heat and biomass than the anaerobic process (Buckley et al., 2008). The increase in biomass

caused by the growth and multiplication of present microbes inevitably increases COD (Buckley et al., 2008, Herlina et al., 2019).

Other faecal matter digestion products are gases that include biogas, ammonia and hydrogen sulphide (H_2S). Any nitrogenous organic compounds present transform into ammonia (Franceys et al., 1992), and under favourable conditions, some ammonia may be oxidised to nitrates and nitrites by microorganisms (Strande and Brdjanovic, 2014). Non-biodegradable material and phosphates are also end-products. Microorganisms cannot digest non-degradable material and some dead bacteria, which form the remaining stable sludge. Biodegradation ceases at this stage as biomass is considered fully biodegraded (Buckley et al., 2008).

One of the results of the breakdown of organic matter is volume reduction of the faecal matter. Anaerobic digestion is more effective in shrinking stool volume, yielding a mere 0.05-0.10 gCOD biomass/gCOD of substrate consumed, whereas the aerobic process forms 0.50-0.70gCOD biomass/gCOD of substrate consumed. Anaerobic digestion has much better potential to produce biogas, reducing volume and odours while stabilising faecal matter (Strande and Brdjanovic, 2014).

2.3.2.2 Nitrogen Cycle during faecal matter degradation

The biological nitrogen cycle is crucial to managing human waste since nitrogen can be a helpful nutrient or a possible pollutant if improperly disposed of in the environment (Strande and Brdjanovic, 2014). During biodegradation, nitrogen cycles between bound and mineral forms. Microbes feed on the mineral nitrogen to grow, and it becomes part of the organic cell components of the microorganisms in a process known as immobilisation, shown in Figure 2.3 (Strande and Brdjanovic, 2014). Bound nitrogen is trapped mainly in organic microbial cell structures, making up about 1-2% of the faecal mass (Wrong and Vince, 1984). Mineral nitrogen is present as ammonium, nitrite and nitrate in faecal matter (Strande and Brdjanovic, 2014).

Generation of ammonia occurs when microbes hydrolyse faecal urea and deaminate amino acid-nitrogen (Wrong and Vince, 1984). Ammoniacal nitrogen is present in low concentrations making up only 20% of the total nitrogen in faeces. A point to note is that faeces on their own contain low amounts of nitrogen because nitrogenous waste compounds mainly get expelled from the human body through urination (Strande and Brdjanovic, 2014). However, faeces can still produce high quantities of NH_4-N, even in cases where urea is absent because at least 12% of total nitrogen can be converted to ammonia when bacteria are thriving. A much higher conversion occurs when bacterial survival is compromised (Wrong and Vince, 1984). Hydrolysis and deamination of bacterial cell components can liberate a significant amount of ammonia since a substantial portion of the faeces' nitrogen is in these components (Wrong and Vince, 1984). However, ammonia generation from this process is dependent on the existence of bacterial enzymes rather than the bacterial count (Wrong and Vince, 1984).

Magri and Sï (2013) kept faeces in an open and uncovered environment for 19 weeks, where they predominantly got desiccated under storage. An aspect of note was the general increase in free ammonia concentration (on a wet basis), indicating a shift in nitrogen content while faecal matter was still stored. The rise was attributed to possible degradation and mineralisation of organic nitrogen in the stored faeces since there were no external sources of the free ammonia.

When NH_4-N is released in the process of mineralisation, a portion of it is converted to nitrites, then nitrates (Panuvatvanich et al., 2009, Strande and Brdjanovic, 2014). Nitrates usually experience two fates, conversion into nitrogen gas (Strande and Brdjanovic, 2014) or loss as percolate (Panuvatvanich et al., 2009). However, in systems that impound faeces for some time and disallow loss by percolation, nitrates tend to accumulate in storage (Panuvatvanich et al., 2009). Figure 2.3 depicts the process described above.

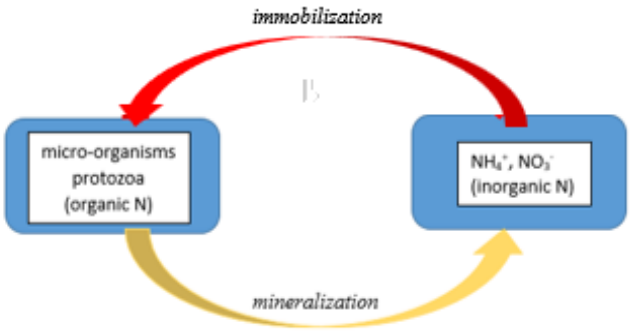

Figure 2.3 The process of mineralisation and immobilisation (Strande and Brdjanovic, 2014)

2.3.3 Impact of storage on disposal and end-use

End-products of faecal matter and their characteristics are determined by the treatment options employed to the faecal material (Strande and Brdjanovic, 2014). Modification of human waste properties owing to dehydration and biodegradation processes after storage has consequences on its disposal or end-use. In cases where the goal is to discharge the waste ultimately in the environment, it is vital to understand how the properties of the product change at different stages of storage. The processes that occur impact pathogen, nutrient, and COD presence in faecal waste, and it is essential to know at which stage, safe disposal into the environment is possible. Environmental pollution inevitably occurs when unstabilised human stool is discarded in an unregulated manner. This kind of mismanagement leads to the following problems (Strande and Brdjanovic, 2014):

- Leaching of nitrates into the ground and contaminating drinking water sources.
- Eutrophication, due to rapid algae reproduction, depletes oxygen in water resources, causing aquatic organisms' death. This growth of algae results from the high organic and nitrogen load from the uncontrolled disposal of faecal matter in water bodies.

- People contract various diseases due to direct or indirect exposure to untreated or insufficiently treated waste with high pathogen content.

Although reuse of faecal waste is considered an option after storage, there is usually a need to treat this waste post-storage to ensure pasteurisation. Alternatively, it can just be directed for reuse but with restrictions. Based on the characteristics of the faecal material product such as nutrient content, calorific value, among others, the final product can substitute conventional material used in specific industries.

2.3.3.1 Reuse in agriculture

Resource recovery from faecal sludge is mainly for land application purposes (Diener et al., 2014). Faecal sludge is favoured in agriculture as it is rich in organic matter with high nutrient content (macronutrients such as N, P and K) and also contains minimal heavy metal contaminants (Ingallinella et al., 2002). Mineral forms of nitrogen such as nitrates, nitrites and ammonium in faecal matter are already bioavailable and therefore quickly assimilated by plants (Anderson et al., 2003, Strande and Brdjanovic, 2014). Phosphorus is present in waste residue from biodegradation that cannot undergo further degradation and degraded microbes (Anderson et al., 2003). There is preservation of nutrients in a sample when drying happens at low temperatures (Sagar and Kumar, 2010). An element like nitrogen is firmly bound to the bone-dry structure of the stool and is difficult to remove. However, the nitrogen can be released slowly over time when incorporated into soil for agricultural purposes (Septien et al., 2020). Therefore, organic nutrient sources such as faecal matter have the advantage of continually supplying nutrients because they release nutrients gradually (Strande and Brdjanovic, 2014).

2.3.3.2 Reuse as biofuel

Solid fuel quality is assessed in volatile fraction, fixed carbon or using carbon, oxygen, hydrogen, nitrogen and sulphur content (ultimate analysis). Faecal matter contains both moisture and dried solids, where the latter is directly combustible (Andriessen et al., 2019). A certain degree of drying is necessary to exploit net energy because moisture delays fuel ignition, reduces the calorific value and hinders ensuing combustion processes (Onabanjo et al., 2016a). Drying that takes place at temperatures below 200 ºC was proven to conserve the calorific content. However, calorific values decrease significantly above 200 ºC due to substantial loss of volatile material from thermal degradation (Getahun et al., 2020).

Volatile matter is another determinant of energy density (Andriessen et al., 2019) because it quickly burns off from dried samples. Studies on faecal waste stored in conventional OSS toilets concluded that the longer it was kept contained onsite, the more it experienced biological degradation of volatile solids, causing a reduction in the calorific value (Zuma et al., 2015, Ostrem et al., 2004). The decline was linked to the depletion of readily available organic content (Gold et al., 2014, Andriessen et al., 2019, Zuma et al., 2015). In contrast, Muspratt et al. (2014) established a lack of correlation between calorific content and faecal material storage time.

Studies have confirmed that faecal sludge contains energy (11-19.1MJ/kg db) comparable to conventional biosolids, as shown in Figure 2.4 (Gold et al., 2014, Muspratt et al., 2014, Zuma et al., 2015, Getahun et al., 2020). Accordingly, dried faecal sludge was deemed a feasible industrial solid fuel (Gold et al., 2014, Muspratt et al., 2014). The mean calorific value of fresh human faeces at 24.73 MJ/kg db (Onabanjo et al., 2016a) is higher than all the other biosolids, including faecal sludge. This implies that fresh human faeces are a viable substitute energy source based on the high calorific content.

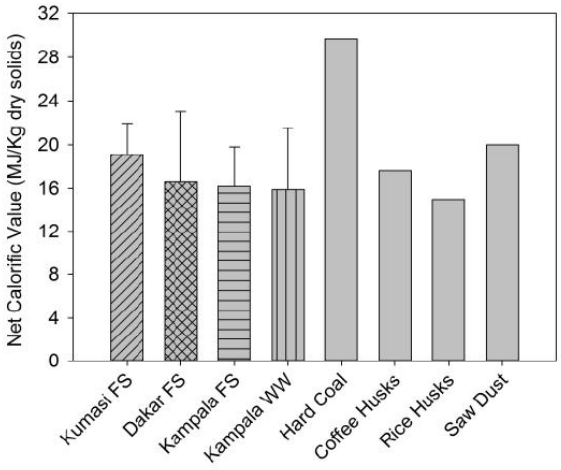

Figure 2.4 Calorific values for faecal and wastewater sludge and conventional biomass fuels (Muspratt et al., 2014)

2.3.3.3 Biogas production

Parties or industries interested in renewable fuel can harness biogas produced from human waste biodegradation to generate energy (Torondel, 2010, Strande and Brdjanovic, 2014, Buckley et al., 2008). Human faeces can produce 0.02 – 0.28 m^3 of biogas per kilogram of wet faeces (Porras and Gebresenbet, 2003). The fractions of the biogas constituents are affected by the COD fraction, stability and temperature of the faecal material (Bakare et al., 2012). It is advocated that sludge stored on a short-term basis be used for biogas purposes because of its high concentration in readily available organic material. Over time, ongoing biodegradation of faeces reduces carbon (Muspratt et al., 2014) and volatile solids and the biogas product escapes (Diener et al., 2014). The capability of faecal matter to produce biomethane diminishes as the containment period gets extended because faeces further stabilise with time (Bakare et al., 2012). So, older stool is undesirable to use in generating biogas. Production of biogas in sufficient quantities makes it a suitable option for cooking. It is, however, probably impractical to exploit biogas for electricity due to too elevated business start-up and operation costs (Semiyaga et al., 2015).

2.3.3.4 Raw material in construction

Dewatered, dried or incinerated sewage sludge sourced from wastewater treatment plants has replaced clay raw material in making Portland cement. The Japanese technology in Figure 2.5 uses over 20% of

resultant sludge diverted from the treatment facility (Taruya et al., 2002). This process could potentially be used incorporating faecal sludge instead. Dehydration alters thermal properties of human waste because they are controlled by moisture content. Low thermal conductivity makes dried solid waste an effective thermal insulator, a useful building material attribute (Septien et al., 2020). However, brick manufacturers (Kampala) have not wholly embraced faecal sludge as raw material, questioning its properties' consistency and citing the abundance and affordability of mainstream raw materials (Diener et al., 2014).

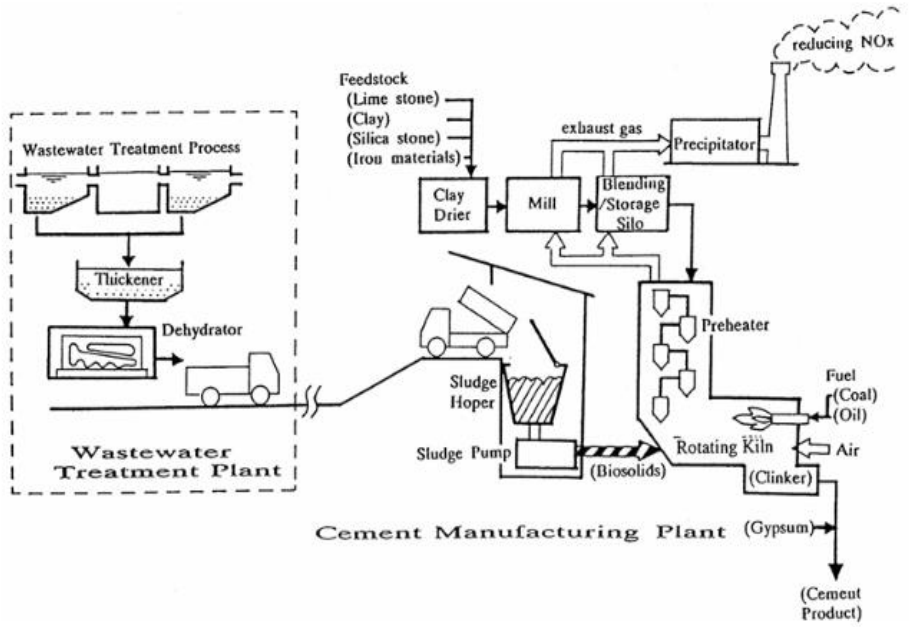

Figure 2.5: Overview of the cement manufacturing process using dewatered wastewater sludge (Taruya et al., 2002)

2.4 Summary

Faecal sludge containing urine, stored onsite, changes in physiochemical, thermal and rheological properties due to dehydration and biodegradation during storage. When it is resident in conventional onsite toilets, the composition and volume vary as the contents go through different extents of transformation in storage depending on the length of containment. It is essential to know the sludge's properties emanating from the systems to ensure it is safely, sustainably and efficiently managed. However, many rising sanitation innovations include toilets that source separate faeces and urine and store the faeces onsite on a short-term basis before treatment. In this scenario, the transformation path taken by fresh faeces from generation to containment is unknown. This knowledge gap poses a challenge in selecting emptying equipment, treatment and/or disposal technologies or end-use for the end-product, post-storage. It is imperative then to know how the properties of fresh faeces evolve. The available literature on faecal sludge transformation properties could be applied to assess fresh faecal matter evolution in the current project.

3 MATERIALS AND METHODS

This work investigated how fresh faeces stored onsite evolved with time under ambient and aerobic conditions. Experiments conducted characterised the fresh faeces to find out how the process of ageing affected degradation, the physical properties related to drying and dewatering, and the rheological properties of the faeces.

3.1 Sampling

In this study, fresh faeces were provided by healthy anonymous volunteers (*n*=73). Recruitment of volunteers took place at the University of KwaZulu Natal (UKZN) in Durban, South Africa, through a paid collection campaign. Samples of fresh faeces were collected from the donors irrespective of ethnicity, occupation and diet; however, they had to be aged 18 years and over. The Biomedical Research Ethics Committee (BREC) issued ethics approval referenced in Appendix A (Protocol reference number: BREC/00000524/2019) before engaging potential volunteers and procuring samples. The sampling, handling and testing of faecal matter were per the Standard Operating Procedures (SOPs) of WASH Research and Development Centre-UKZN, which can be accessed on http://prg.ukzn.ac.za/laboratory-facilities/standard-operating-procedures.

A 1-litre plastic bucket with a tight-fitting lid was available to every volunteer. Buckets were numbered and weighed prior to distribution. Donors were required to pass stool only (no urine or anal cleansing material) in the bucket and return it within 24 hours of defaecation. Each bucket of fresh faeces was then weighed to determine the sample mass, which was ~140 g on average. The airtight buckets containing the samples (Figure 3.1) were stored in the cold room at 4 °C until processing to avoid changes in the physicochemical properties of the material through biodegradation and dehydration. Samples were preserved in the cold room until there were enough faeces to make a composite sample to cater to all experimental work. Therefore, cold room storage time depended on when the fresh faeces were brought in and ranged from less than a day to one week. Using the Bristol Stool Chart, samples in the current study were identified as Type 1 to Type 6 (the Bristol Stool Chart provides imagery and descriptive text that classifies human faeces into seven different types). The faecal samples donated ranged in appearance from watery and fluffy to lumpy and sausage-like. Entirely liquid faeces, identified as Type 7, were not included in the current study. Figure 3.2 shows the high heterogeneity in the fresh faeces samples collected. As soon as the collection period ended, individual samples were all slowly and gently mixed (to avoid altering the structural properties) into one composite (Figure 3.2 and 3.3). The faeces were emptied into a 20 L bucket and manually mixed until the composite had attained a uniform colour and faeces were no longer in lump form (sign of homogeneity) using a long plastic axe handle as an improvised stirrer.

Figure 3.1 Individual samples of fresh faeces in 1L buckets prior to mixing

Figure 3.2 Different stool types collected

Figure 3.3 Composite sample of fresh faeces after mixing the individual contributions

3.2 Experimental setup and procedure

The well-mixed composite was divided into eleven equal weighed identical containers. Containers were labelled Day 0, Week 1 to Week 8, Week 12 and Week 16, as displayed in Figure 3.4. The containers were not sealed with their lids but were kept open to mimic aerated conditions in on-site sanitation facilities. They were covered by mesh fabric (Figure 3.5) to prevent flies and other insects from accessing the faeces inside.

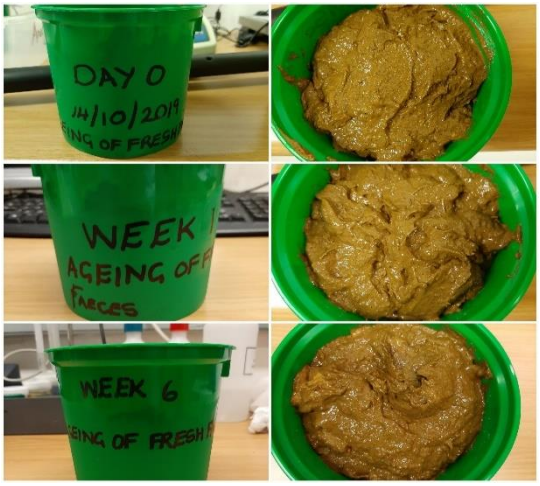

Figure 3.4 Containers in which the faecal samples were placed for the storage experiments

Figure 3.5 Container with sample covered with mesh that was held in place by a rubber band

These containers were placed in a fume cupboard to extract foul odours produced during the process of ageing (Figure 3.6). The fresh faecal matter samples, except Day 0 (initial sample), were left to age in a fume cupboard under ambient room conditions (temperature ~20°C and ~60% relative humidity) for varying time durations for a total period of 4 months. Day 0 sample was analysed before storage to establish the fresh faeces' initial characteristics before ageing commenced. Subsequently, each sample was analysed once it aged the number of weeks labelled on its container. After the samples aged for the desired timeframe, they were stored in the cold room to preserve their characteristics until testing.

Figure 3.6 Fresh faeces samples in the fume cupboard

In light of the qualitative observations and findings in the initial week of in-situ containment of Batch 1 samples, it was imperative to conduct another round of experiments with a sole focus on the first week only. Another phase of tests was then performed on the second batch of freshly collected faeces to establish if the results from the first week of Batch 1 were a random occurrence or an actual stage that faeces experience when contained onsite in dry toilets. The sampling and experimental set up were still

performed following the procedure as for Batch 1. For Batch 2, 3 L buckets were used in place of the 1 L buckets used initially to cater to possible sample swelling (as observed in Batch 1). The fresh faeces were stored for a week where they were analysed after 3, 5 and 7 days. The initial sample was analysed as well to establish characteristics prior to the influence of ageing.

3.3 Analysis of the faecal samples

All analyses followed the Standard Operating Procedures (SOPs) from the UKZN WASH centre. The impact of ageing on the physical and chemical properties of fresh faeces was determined by experimentally generating data in the laboratory on its variations in moisture content, drying kinetics, water activity, rheological properties, particle size distribution, organic matter content (VS, COD), carbon, nitrogen, NH_4^+, NO_3^-, calorific value and thermal properties (thermal conductivity and heat capacity).

The laboratory methods used in determining how properties of fresh faeces change over time in storage are detailed in this section. Table 3.1 summarises the analysed properties and the reasons for their analysis.

Table 3.1 Significance of the studied properties

Property	Importance to the study
Total Solids/Moisture Content	Fresh faeces consist mainly of moisture, making water the main contributor to mass and volume. Moisture is the component of faecal matter to remove through dewatering and drying.
Drying curve	Drying kinetics shows the rate at which fresh faeces can dry, and this parameter is essential for drying process design.
Free moisture	The amount of free moisture (or unbound moisture) reflects the extent of dewaterability.
Volatile solids/Ash	Volatile solids content estimates the organic material in fresh faeces and can determine the extent to which stabilisation has occurred. Ash is mainly composed of inorganic compounds left behind after combustion, after complete oxidation of all the organic matter.
Carbon and nitrogen	Change in these elements' chemical composition indicates the transformation of the organic and nitrogenous fractions. The C:N ratio indicates possible chemical transformation processes that the faecal material is undergoing.

Viscosity/ Shear stress	Viscosity indicates the thickness of the faecal material and its ability to be pumped.
Particle size distribution	Change in particle size is an indication of faecal matter breakdown or particle agglomeration. This influences the rheology of faecal material.
Water Activity	This parameter is an indicator of water availability for chemical and biochemical reactions. Below a given water activity, microbes cannot develop anymore, so this parameter is an indicator of microbial activity. Water activity reflects the binding strength between moisture and the dry skeleton of faecal material, i.e., if moisture is unbound, weakly bound or firmly bound.
COD	This parameter estimates the bulk organic content in fresh faeces and can establish the degree of stabilisation of faecal matter.
NH_4^+ and NO_3^-	The forms of nitrogen can determine microbial activity. It also assesses the stability of faecal matter and its potential end-use in agriculture.
Calorific value	This parameter ascertains the suitability of the end-use of fresh faeces as a fuel. Calorific value reflects the energy content of the material, and its variation can detect any eventual degradation of the faecal matter.
Thermal conductivity	Measures the ability of faecal matter to conduct heat and influences the thermal processes.
Heat Capacity	Heat capacity quantifies the amount of heat absorbed by faecal material to increase its temperature and, therefore, influences a material's behaviour in a thermal process of faecal matter.

3.3.1 Moisture Content

Moisture content (MC) tests were performed according to the standard methods used for water and wastewater analysis (APHA, 2017) used by the WASH Research and Development Centre. For this analysis, 10-20 g of samples were dried in the oven at 105°C for 24 hours. Calculations of the quantity of total solids were done using Equation 3.1.

$$Total\ solids\ in\ wet\ sample\ = \frac{(W_3 - W_1)}{(W_2 - W_1)} \tag{3.1}$$

The difference between wet and dry solid masses recorded in the TS analysis give the moisture content of the sample. Moisture content expressed on a wet basis (Equation 3.2)

$$Moisture\ content\ in\ wet\ sample\ = \frac{(W_2\ - W_3)}{(W_2\ - W_1)} \quad (3.2)$$

Where:

W_1 – Crucible mass (g)

W_2 – Wet sample mass + crucible mass before drying (g)

W_3 – Dry sample mass + crucible mass after drying (g)

3.3.2 Volatile solids content

The dried residue from the moisture content analysis was ignited in the furnace at 550 °C for 2 hours to determine the concentration of volatile solids present in the fresh faeces as they age in storage as adopted from the standard analysis methods for water and wastewater (APHA, 2017). Volatile solids (VS) volatilise when heated at 550 °C for 2 hours and correspond mainly to the organic content. Determination of the VS content on a dry basis was achieved using Equation 3.3.

$$Volatile\ solids\ in\ dry\ sample\ = \frac{(W_3\ - W_4\ )}{(W_3 - W_1)} \quad (3.3)$$

$$Ash\ in\ dry\ sample\ = \frac{(W_4 - W_1)}{(W_3 - W_1)} \quad (3.4)$$

Where:

W_1 – Crucible mass (g)

W_3 – Crucible mass + sample after drying (g)

W_4 – Crucible mass + sample after incinerating (g)

3.3.3 Chemical analysis

Properties that included COD, ammonium, nitrates, carbon and nitrogen content were analysed to establish how the chemical composition of fresh faeces evolved whilst undergoing ageing.

3.3.3.1 Photometric and Spectrophotometric tests

For the preparation of these tests, a mass between 1 and 2 g of faeces sample was liquefied in a blender using a known volume of distilled water. In some instances, subsequent dilutions were necessary to lower the COD, NH_4^+ and NO_3^- concentrations within the measuring range of their respective testing kits.

Samples of faecal matter solutions were added to *HACH* COD digestion vials (containing potassium dichromate) and heated in a digester block at 150 °C for 2 hours. The oxidisable organic compounds in the samples are oxidised during heating by potassium dichromate ($K_2Cr_2O_7$) and, in turn, $Cr_2O_7^{2-}$ is reduced to green Cr^{3+}. The measuring range of the COD LR test kit was 0-150 mg/L, and test results were determined using the *HACH* photometer. The LR is a colometric method that measures mg of O_2 consumed per litre of a sample by measuring the remaining quantity Cr^{6+}.

A similar method was applied in measuring the NH_4^+ and NO_3^- concentration in faeces that had undergone different periods of ageing. Spectrophotometric tests were conducted on sample solutions to determine the concentrations of NH_4^+ and NO_3^- using *Spectroquant Merck-100* equipment. Sample solutions were added to test tubes containing reagents and left to stand for 10 and 15 minutes for NH_4^+ and NO_3^- spec tests, respectively. Subsequently, each solution was transferred into a cuvette and inserted into the instrument. The instrument is pre-programmed with different stored test methods, and their corresponding concentrations and the desired one is selected. Readings are made in the device using classical photometry and displayed on the screen. The measuring kits ranges were 2.0 -75 mg NH_4^+-N/L and 0.1-25 mg NO_3^--N/L.

3.3.3.2 Carbon and Nitrogen tests

The chemical composition of samples in terms of total carbon (C) and nitrogen (N) was measured using a *CNS analyser* from *LECO TruMac*. Pre-weighed masses of ~ 0.1 g of well-mixed fresh faeces were placed in ceramic boats and loaded into the purge chamber of the instrument. The furnace contained pure oxygen that facilitated complete sample combustion at 1350°C. Resultant gases in the form of CO_2, NO_x and SO_x were separated by chromatography and measured in a thermal conductivity cell inside the instrument. Initial wet sample masses were an input parameter before analysis. The C and N sample results were generated as a percentage of the wet sample mass, which can be interpreted as the elemental mass fraction in the analysed wet sample.

3.3.4 Centrifugation

Centrifugation was used to determine the amount of moisture released from the faecal samples by mechanical means as they aged during storage. Free and partially bound water is separable from faecal matter through centrifugation (Strande and Brdjanovic, 2014). This was performed using the *HERMLE Z323* centrifuge. Four centrifuge tubes containing 40 ml of fresh faeces were placed inside the centrifuge and rotated at 5000 RPM for 60 minutes at 20-minute intervals. The centrifugal forces speed up sedimentation resulting in the solid particles accumulating and sticking to the walls at the bottom of the centrifuge tubes. The supernatant was then collected separately and weighed to estimate how much free water was present in the sample.

3.3.5 Water Activity

Water activity was determined using the *AquaLab Tunable Diode Laser-TDL* instrument. Samples were homogenised by slowly and gently mixing with a spatula before testing and put in sample cups up to the demarcated level. After sample preparation, each sample cup was closed with a tight-fitting lid to avoid moisture loss while awaiting measurement. The sample cup was placed in the measuring chamber in the water activity meter, where the sample slowly exchanged moisture with the air inside the chamber until equilibrium was reached. A hygroscopic polymer sensor in the device measured relative humidity of air in the headspace above the sample. The water activity is equal to the relative humidity measured

in the cell at the thermodynamic equilibrium. Experiments were conducted at a set temperature of 25 °C, which was maintained automatically by the instrument. The accuracy of the equipment was ±0.005 at 25 °C.

3.3.6 Rheological Properties

Characterisation tests for viscosity and shear stress of ageing faecal matter were performed at 25 °C using the *Anton Paar Rheometer MCR72* and the *Viscotherm 2* cooling tower (for temperature control). The rheometer has a built-in motor that provided measurements in rotational mode. Flow and deformation of samples were thus investigated using rotational tests, where samples were subjected to controlled shear rates.

Samples were gently mixed before the testing and a single test run required 100 - 150 g of faeces. The rheometer used a vane-in-cup geometry to subject every sample to shear rates ranging from 0.1 to 1 000 s^{-1} for approximately 15 minutes. Generally, each shear rate is maintained till the sample adapts itself to each measuring point. For shear rates greater than 1 s^{-1}, each shear step was maintained for at least one to two seconds. Data obtained from the rheometer was captured through the *Rheocompass* software™. For each test, rheograms were generated on a computer monitor to provide visuals of the shear strain-shear rate and viscosity-shear rate relationships on a logarithmic scale.

Yield stress is the lowest magnitude of shear stress that needs to be applied to faeces to cause them to start flowing. This property was indirectly determined by plotting a graph of viscosity against shear stress (Septien et al., 2018). The yield stress point corresponded to the value of shear stress when the faeces transitioned from elastic to viscous deformation. This point is characterised by a change of slope in the graph when the viscosity starts to drop. The smooth decline in viscosity with increasing shear stress prior to the yield stress corresponded to the elastic deformation, whereas the viscosity drop after the yield stress was due to viscous deformation. The yield stress values of the faecal material stored for different times were presented in a graph against their corresponding moisture contents.

3.3.7 Particle Size Analysis

Particle Size Distribution (PSD) analysis was used to determine the size and range of particles representative of the faecal matter samples aged at different storage times. The investigation was conducted using the *Malvern Mastersizer 3000* particle size analyser, which measures the size of particles using laser diffraction. The instrument executes this by measuring the intensity of light scattered as a laser beam passes through a dispersed particulate sample. The instrument used data obtained from the scattering pattern to calculate particle size (specifically particle diameter). Samples preparation involved dispersing a quarter of a 4 ml-spatula of faecal material in water to form a well-mixed paste in a crucible. In each test run, droplets of this paste were dispersed into 600 ml of water until the required obscuration range was reached (as determined by the instrument). A triplicate test took 15-20 minutes

on average. The *Malvern Mastersizer 3000* software generated results as a PSD curve graph of volume density (%) against particle size class (µm).

3.3.8 Thermal Properties Analysis

The *C-Therm TCI*™ Thermal conductivity Analyser was utilised to measure thermal conductivity and heat capacity. Homogenised faecal matter of a volume of 1.88 ml was measured using 0.63 ml and 1.25 ml spatulas and weighed. Sample density was calculated by dividing the total mass in the two spatulas by its volume and introduced as input in the software interface. The volume was spread as a thin layer to cover the sensor face, and a blotter placed on top to cover the sample during the test. Tests in triplicates took an average of 20 minutes. The apparatus provides values for the thermophysical properties using the *C-Therm TCi* Software by indirect calculation. Thermal conductivity was calculated by comparing the sensor response to the factory calibration. Heat capacity was calculated through the measured effusivity, thermal conductivity and density.

3.3.9 Calorific Value

The calorific value of the faecal matter was measured using a *Parr 6200 Calorimeter*™. Samples of fresh faeces were dried at 105°C in the oven and ground into pellet/powder form before measuring the calorific value. The calorific value was then measured by fully combusting the pre-weighed sample mass of between 0.5-0.7 g in the bomb calorimeter. The calorific energy of a dry sample is termed gross calorific value.

3.3.10 Drying curves

A thin film of homogenised fresh faeces weighing between 1.0 – 1.5 g was spread uniformly on an aluminium tray of diameter 90 mm and dried at 105 °C using the *Radwag Max 50* Thermal Moisture Analyser. The surface of the layer was not smooth and unmasticated food particles were present in the form of undigested tomato peels and were not included in the drying tests. The balance continuously weighed the subsequent sample mass changes until there is no change in mass or it is around 0.001 g (see Appendix B for the detailed test procedure). This balance was connected to a computer monitor that captured the sample weight every 30 seconds. The average mass of the three runs was used in calculations for moisture content at the measuring points. Moisture content was calculated on a dry mass basis using equation 3.6. The results were presented as drying curves for the different faecal samples to demonstrate how drying kinetics were affected during ageing. The drying curve is a plot of decreasing moisture ratio against drying time, assuming that mass loss is due to moisture evaporation. MR provides a baseline to compare the moisture loss for differently aged samples since they had different moisture contents and is calculated according to Equation 3.7.

$$M_t = \frac{W_t - W_f}{W_f}$$	(3.6)
$$MR = \frac{M_t}{M_o}$$	(3.7)

Where:

W_t and W_f – initial wet sample mass and final dry sample mass, respectively.

M_o and M_t – initial moisture content and instantaneous moisture content, respectively.

3.4 Statistical analysis

All tests were conducted in triplicates; however, some rheology tests were duplicated due to insufficient sample size for a third run. The plotted points represented the average values of results obtained in triplicates. The experimental errors in the measurements were determined by classical statistical analysis (i.e., performing the one-sample t-student test at a 95% confident interval). Regression analysis was used to establish goodness of fit between different parameters.

4 RESULTS AND DISCUSSION

In this chapter, experimental results from fresh faeces ageing over four months are presented and analysed. A second batch was tested to give a more detailed view of the results from batch 1 in the first week of storage. Batch 1 and 2 results were consistent and will be discussed together. Refer to Appendix F for a comparative graphical overview of the characteristics of the initial samples and week 1 samples from the two batches. The findings are presented in five sections, beginning with the visual changes that occur when new faeces age in a repository unit. The second section details how drying characteristics and dewaterability are affected by ageing. The third section covers the evolution of rheological properties (viscosity and yield stress) with age. The fourth section involves how ageing may transform the material in terms of biological or physiochemical degradation. The focal point of the final section is the effect of ageing on thermal properties, which contributes to the design of dryers and further thermal processes. The degree of stability of waste at various ageing stages determines the type of treatment post-storage, energy requirements for treatment (both mechanical and thermal) and disposal requirements.

4.1 Qualitative observations

The stored fresh faeces initially underwent some swelling, followed by volume shrinkage. Within 24 hours of being in a repository, the faeces began swelling up. It was assumed that the swelling was caused by gas due to anaerobic digestion, based on literature from Strande and Brdjanovic (2014) and Torondel (2010). Samples continued to expand in volume for about four days, to the extent where samples could no longer be entirely contained in the 1 L buckets. This increase in sample volume from the onset of storage is shown in Figure 4.1. All samples were transferred to buckets of a more substantial capacity of 3 L. The expansion of faeces in batch 2 did not look as pronounced as in the first phase because the same sample mass was placed in a bucket of larger capacity (see Appendix C for pictorial evidence).

Figure 4.1 Fresh faecal samples before and during swelling

Additionally, upon trying to remove the mesh fabric, the section in contact with the sample surface appeared to have melted and fused with the surface layer of fresh faeces. Biodegradation is known to be exothermic. Therefore, it was assumed that this heat emanated from the faecal waste samples and could have caused the mesh fabric's fusion with the faecal matter. Peasey (2000) gave a similar report of faeces heating up in dry and aerated sanitation facilities and how continual aeration promoted heat production. The heat and gas generated were not quantified because they were unforeseen occurrences. However, the fabric was a polyester material that melts at 47 °C and estimates the solid waste temperatures.

The samples stopped swelling, and the volume began to regress around the fifth day and shrank even more with increasing age. At the end of the experiments, there was a significant volume reduction compared to the initial faecal material (Figure 4.2). Crust formation on the surface accompanied this loss in volume from the second week, as shown in Figure 4.2. Drying of the sample was observed starting from the outside surface, going inward, and spotted by the dry crusty surface and moist faecal matter beneath that layer. Limitations of internal moisture transfer possibly cause this. If the internal moisture is not transported fast enough to the material surface, superficial desiccation occurs at the surface (Léonard et al., 2004). The crust layer in Figure 4.2 only got thicker with age. The volume reduction was not quantified in the current research.

Figure 4.2 Progression of crust formation over eight weeks

The consistent result of faeces swelling in both batches indicated that it might be typical in the early days of storage. Extending the storage duration caused the top outer exterior of the stool to form a crust which only got thicker with time.

4.2 Drying characteristics

4.2.1 Moisture content

Figure 4.3 relates the moisture in the samples to the length of storage time. Stool in the first batch lost moisture over sixteen weeks in storage, reducing the initial moisture content around 79.1 to ~26.9 %wt. Batch 2 confirmed the trend, with moisture decreasing from 78.2 to 75.8 %wt in that first week. Fresh faeces had initial moisture contents of 78.2 %wt and 79.1 %wt, which were conversant with the range of 77.1 – 81.8 %wt reported by Almeida et al. (1999), ZAVALA et al. (2002), Nwaneri et al. (2008),

Woolley et al. (2014b) and Remington (2019). The results revealed that faecal material dried naturally and gradually over time. The trend in the current study was supported by findings of faecal waste stored in conventional onsite toilets becoming increasingly dehydrated over time (Zuma, 2016, Bakare, 2014, Wood and Buckley, 2013). In essence, raw faeces experienced in-situ drying over sixteen weeks of storage.

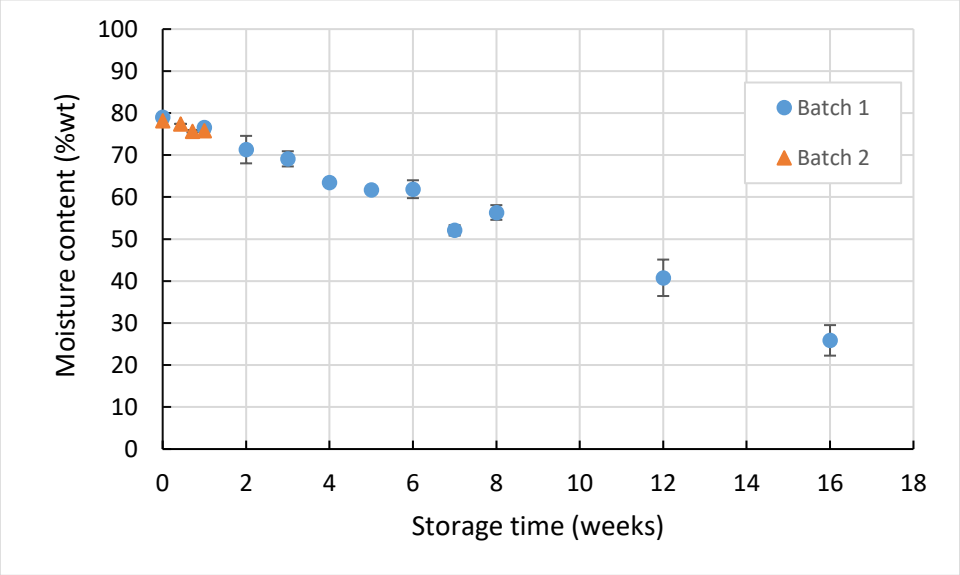

Figure 4.3 Moisture content of faecal matter as a function of storage time

4.2.2 Drying Curves

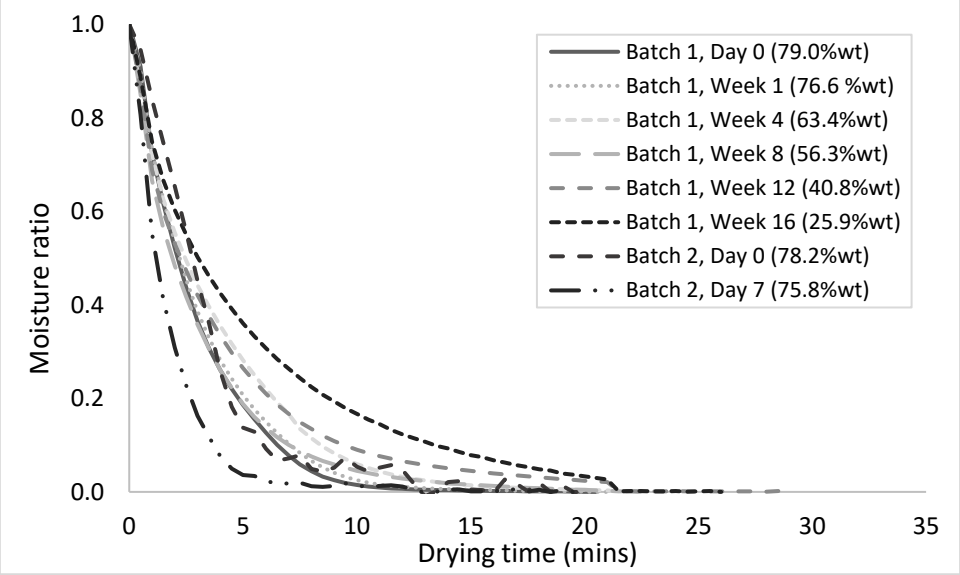

Figure 4.4 Comparison of drying ability of differently aged samples of faecal material

Drying tests were performed at 105 °C in the moisture analyser on the samples at different storage times to evaluate the drying ability of the faecal matter as it aged. Results were presented as drying curves of change in moisture ratio with the drying time, as illustrated in Figure 4.4. All faecal samples from batch

1 and 2 showed consistent drying behaviour (refer to Appendix E for the rest of the drying curves) and revealed that the initial moisture contents had no considerable effect on the drying kinetics. The drying curves showed that the different samples took approximately the same time to dry (about 15 – 20 minutes), despite having different initial moisture content caused by sample ageing. So, the storage time did not affect the drying ability of the faecal matter. Similar drying times implied that samples with higher moisture content dried faster than those with low moisture contents. This was because the samples with high moisture content had a higher amount of less bound moisture, which is easier to remove, compared to samples with low moisture content, which have more tightly bound moisture (supported in section 4.2.4).

4.2.3 Centrifugation

Centrifugation tests were conducted at 5 000 RPM to assess the dewaterability of faeces and how this evolved with extension in storage time. The evolution of the capability of faeces to be dewatered is displayed in Figure 4.5. The samples yielded no supernatant, meaning faeces could not be dewatered regardless of how long they were stored. Tests were not extended beyond the fourth week because faecal matter only got drier with increased age, as shown by the moisture results in Figure 4.4, and cannot be dewatered still. Failure to mechanically dewater faeces implied that faeces consist mainly of bound water. It was concluded from the results that stored faecal matter is not dewaterable even with advancing age, as also reported by Strande and Brdjanovic (2014). The authors stated that raw/fresh faecal waste is difficult to dewater.

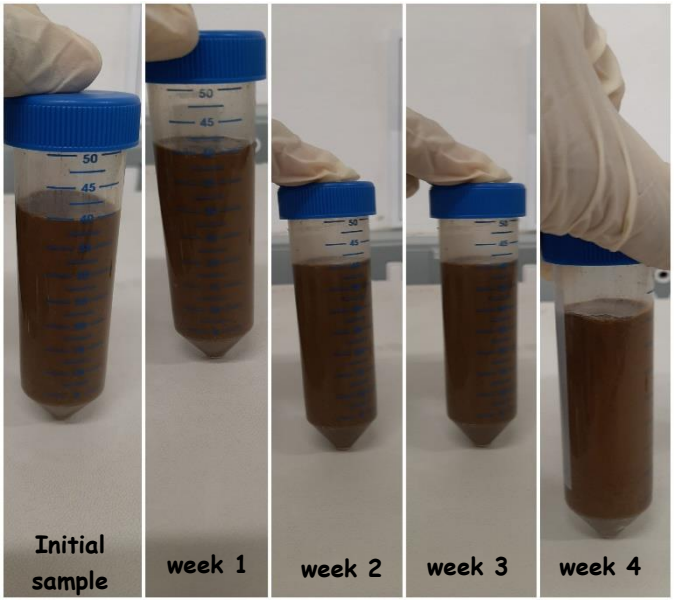

Figure 4.5 Photographs of the fresh faeces samples aged at different times after centrifugation

4.2.4 Water Activity

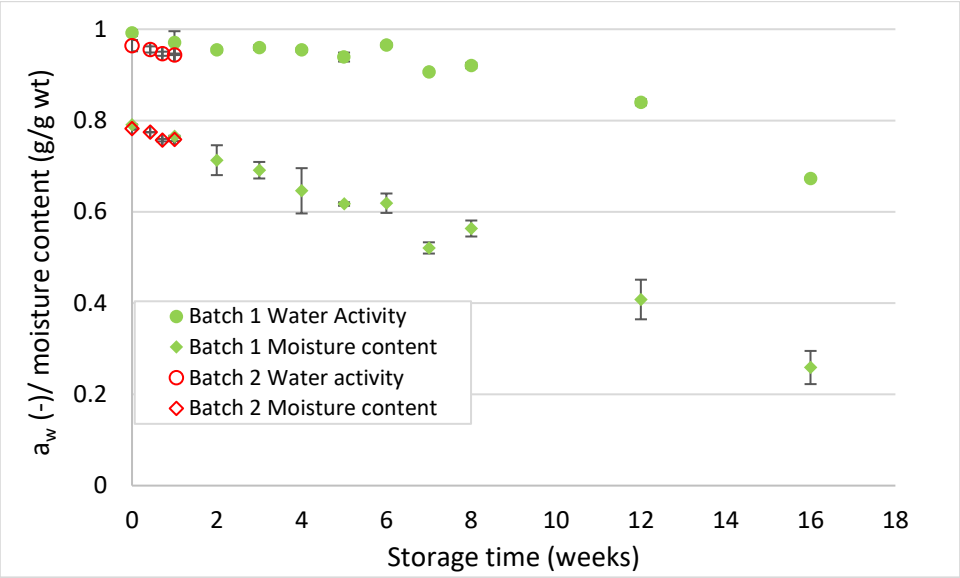

Figure 4.6 Change of water activity with moisture content as faeces aged over sixteen weeks in storage

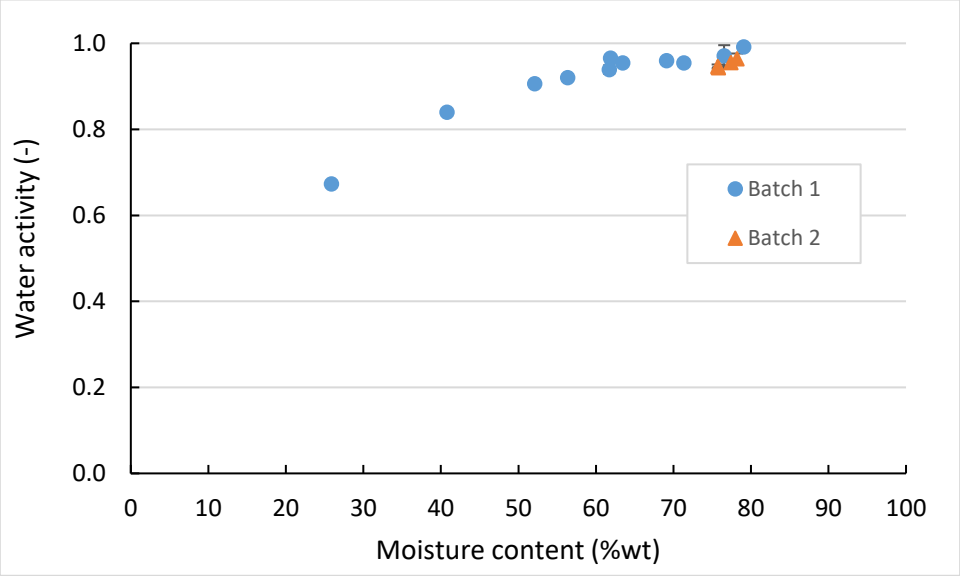

Figure 4.7 Moisture content as a function of water activity of faeces that aged onsite over 16 weeks

Figure 4.6 shows the effect of faecal waste storage for varied periods on water activity and how this trend compared with the pattern for sample moisture content. The direct relationship between water activity and moisture content of the samples in this study is displayed in Figure 4.7. Water activity (a_w) decreased to 0.673 from the initial 0.992 after 16 weeks of stool containment. The raw data for water activity can be found in Appendix D. The initial value of 0.992 (at 79 %wt moisture content) fell within the range of 0.93-1 (at 63-86 %wt moisture content) found in the study of fresh faeces by Remington (2019). Water activity was relatively stable in the first eight weeks of storage, where moisture was between 0.56 and 0.78 g/g wt (56-78 %wt). A significant decrease occurred when moisture went below 0.56 g/g wt, indicating moisture in the faeces became more and more bound. Figure 4.6 established that

the sample water activity was less than 1 throughout storage irrespective of sample age. Therefore it was assumed that initially, there was no unbound moisture in the faeces. These results were consistent with the lack of dewaterability in faeces discussed in the results section 4.2.3 of this research. Remington (2019) reported a lack of unbound water at a_w values higher than 0.85, which substantiated the current study's a_w results. Figure 4.7 revealed that samples drying during storage caused a reduction in a_w, supported by Sagar and Kumar (2010). The trend shown in Figure 4.6 showed that water activity declined as storage time was increased and was backed by Strande and Brdjanovic (2014). Water activity decreased with drying (and ageing) because moisture boundedness became stronger as the sample dried.

Pathogens were possibly inactivated after 12 weeks when a_w fell to 0.84, implying the material was possibly safe to handle from the twelfth week. The assumption was because faecal pathogens are inactivated when a_w goes lower than the range of 0.85-0.90, according to Sagar and Kumar (2010), Cairns-Smith et al. (2014) and Strande and Brdjanovic (2014). Microbes in the waste may still have been active at a_w 0.673 (~25.9%wt) after four months of storage. An assumption was based on the report by Sagar and Kumar (2010) that microbial activity is impeded at $a_w < 0.62$ (~ 20%wt).

During the storage period, water activity was less than 1 ($a_w < 1$), so faeces had an insignificant measure of unbound moisture. Therefore, storing faeces for longer, increasing the storage period decreased water activity through drying (and ageing) and this reflected increased boundedness in the moisture remaining in the faeces.

4.3 Rheological Properties

4.3.1 Flow curves

Figure 4.8 illustrates the influence ageing had on the viscosity of faeces as a function of the shear rate. Sample viscosity generally reduced with increasing shear rate and confirmed the non-Newtonian nature of faeces and their shear-thinning properties, as observed by Woolley et al. (2014a, 2014b). A change in the faeces rheology with storage time was evidenced by the general increase in viscosity, except for week one for Batch 1, where viscosity decreased compared to the initial sample viscosity. The swelling in the first week due to assumed biodegradation may have contributed to the improved fluidity of the week one sample (i.e. decrease of viscosity), as also reported by Agoda-Tandjawa et al. (2013) and Feng et al. (2014). Beyond week 4, measurements were only possible at low shear rates due to increased viscosity as faecal material aged. The pattern of rising viscosity with ageing is consistent with the results in section 4.2.1. where sample moisture content diminished with ageing, which ultimately causes an increase in sample viscosity. There was a lack of results from week 7 onwards because the samples

were too dry and could not flow. A report by Septien et al. (2018) stated that it becomes non-viable to induce flow in faecal material that is advanced in age because it is too dry (low moisture content).

It was imperative to investigate further how the rheology changed within the first week of storage due to the sample swelling in the first batch. Batch 2 samples similarly went through shear thinning with increasing shear rate. However, the initial sample and the Day-7-sample had similar viscosities, which differed from the drop in viscosity observed at the 7-day mark in the first batch of experiments. Laboratory work had to be halted due to the COVID lockdown implemented, and Batch 2 samples were stored at 4 °C for four months to prevent degradation. Since samples could not be analysed immediately after ageing the required period, the difference may have stemmed from settling of the swelling during the four months of storage.

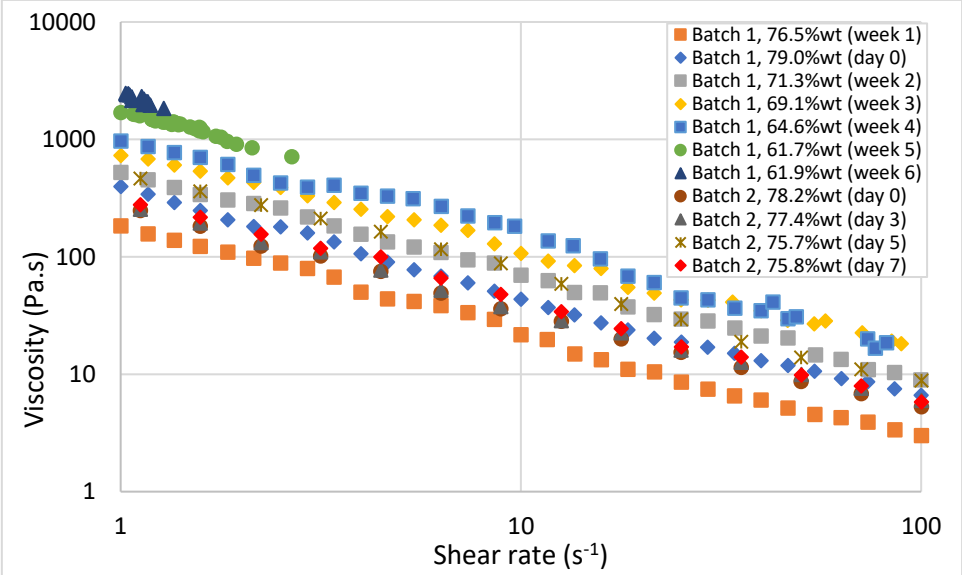

Figure 4.8 Viscosity against shear rate for the faecal samples stored at different times

4.3.2 Viscosity at a constant shear rate

Figure 4.9 provides evidence that moisture content majorly influences viscosity of faecal waste. At a shear rate of 1 s^{-1}, faeces became more viscous as moisture content diminished over time. The same relationship was found by Woolley et al. (2014a, 2014b) in their study on fresh faeces. The general trend excluded the first week due to the hypothesized biodegradation of the faecal matter. The drying of the solid waste with lengthened storage contributed to the overall increase in viscosity. Keita et al. (2019) also confirmed that drying has a cumulative effect on viscosity.

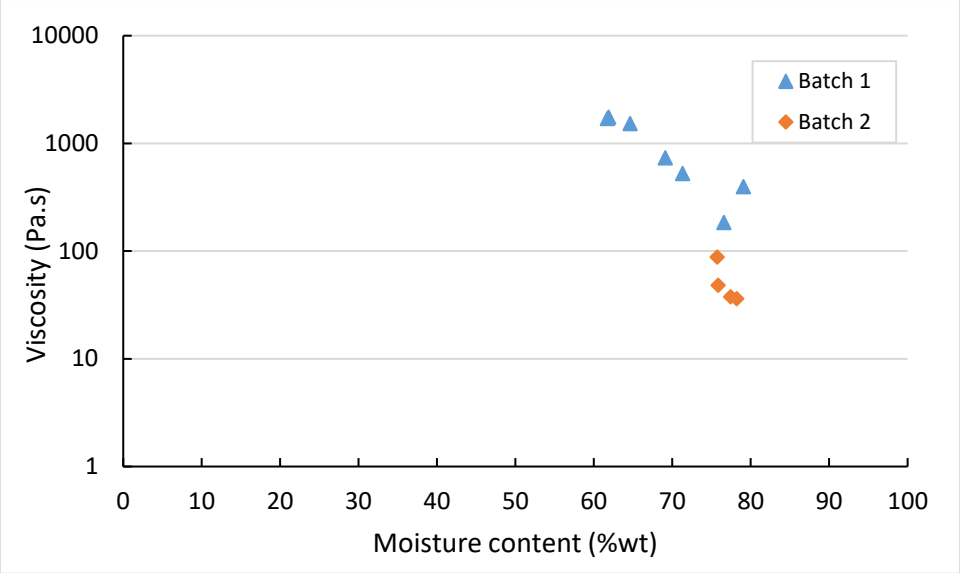

Figure 4.9 The relationship between viscosity and moisture content of faeces at a fixed shear rate

4.3.3 Yield stress

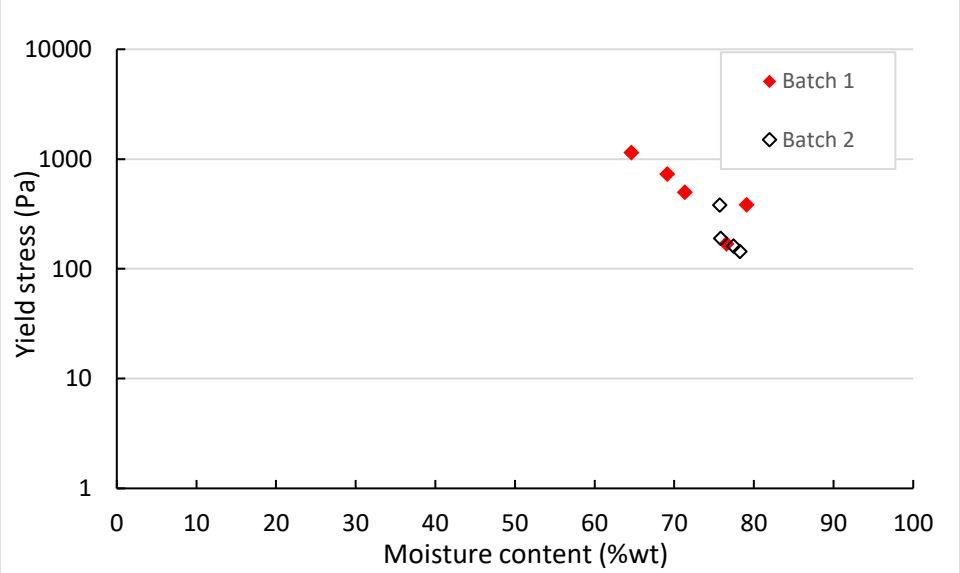

Figure 4.10 Yield stress as a function of moisture content at different storing times

Yield stress is the shear stress applied to a fluid to overcome its resistance to initial flow to start moving. Figure 4.10 displays the consequence of the moisture content changes on the yield stress during the faeces' storage. Results showed that faeces possessed yield stress that increased from 385 to 1 145 Pa as the moisture decreased from 79.1 to 65.8 %wt. As samples aged, they exhibited an overall increase in the magnitude of yield stress that needed to be exceeded to initiate flow in the faecal materials. A study by Septien et al. (2018) on faecal sludge supported the general trend of increasing yield stress by reducing the moisture content. However, in the first week, the sample did show deviant behaviour from the general pattern. Although the sample had a lower moisture content (77 %wt) relative to the initial

sample, its yield stress was lower (169 Pa). The low yield stress resulted from the reduced viscosity in week 1 (Figures 4.8 and 4.9), probably due to biodegradation that supposedly occurred in this period.

4.3.4 Particle Size Distribution

Figure 4.11 gives a graphical representation of how the size of particles in the stool samples and particle size distribution were affected by the process of ageing. Particle size ranged from 0.49 – 3 284 µm in all samples belonging to batch 1 and 2. It was apparent that the particle size distribution (PSD) was unchanged as the samples aged. Overall, the particle size distribution narrowly varied with age and did not seem to follow any specific pattern, as seen in Figure 4.11.

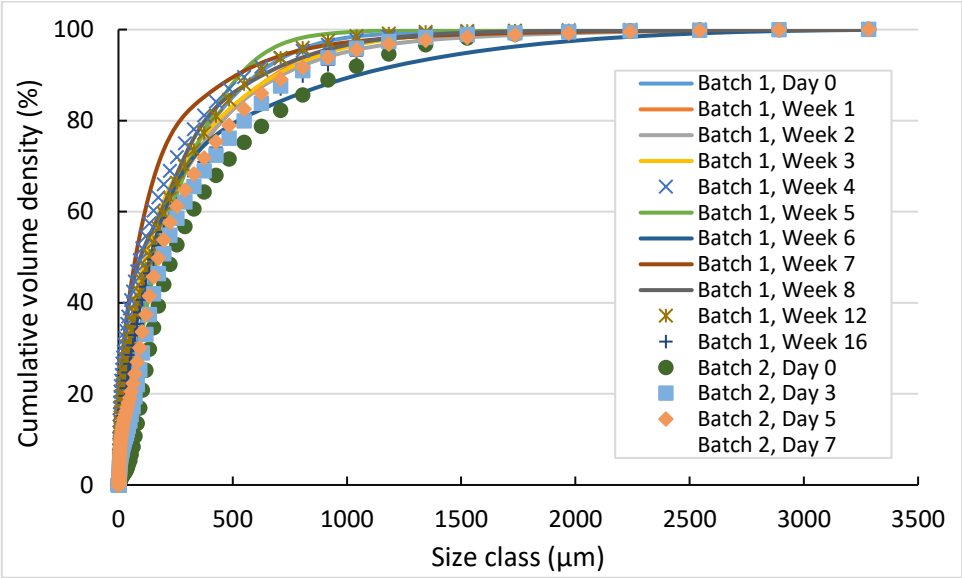

Figure 4.11 Cumulative volume distribution of particles in ageing faeces over sixteen weeks

A point of note is that the laser diffraction analysis method assumes all particles to be spherical. Table 4.1 shows the variation of the mean particle diameter in a sample with sample ageing. Average particle diameter (d_v 50) was considered the same between the different samples due to the negligible statistical differences between samples. This implied that the change in particle size was not affected as faeces were aged during storage. The particle size range was consistent during ageing, with the smallest and largest particles of faeces being 0.49 µm and 624 µm, respectively. Rheology can depend on moisture content and particle size. However, in this study, it was evident that rheological properties were only affected by moisture reduction because the particle size distribution was approximately the same between samples of different ages. The viscosity and yield stress kept increasing despite a regular particle size with age.

Table 4.1 Evolution of particle size with changing age of faecal material

BATCH 1		
Storage time (weeks)	**Particle diameter [µm]**	
	Average	**±Error margin**
0	168.7	76.8
1	124.7	111.7
2	156.0	15.5
3	125.0	55.5
4	105.8	84.7
5	181.3	53.3
6	212.6	516.7
7	91.1	115.4
8	105.6	153.4
12	142.0	21.2
16	171.3	78.6
BATCH 2		
Storage time (days)	**Particle diameter [µm]**	
	Average	**± Error margin**
0	281.3	84.3
3	215.3	65.3
5	196.0	50.3
7	222.0	77.2

4.4 Effect of ageing on the degradation of the faecal matter

4.4.1 Volatile solids

Figure 4.12 reflects how the volatile solids (VS) content was affected as stool samples aged in storage. A mean value of about 0.84 g/g db was maintained in the four months of in-situ containment. The average VS values agreed with the findings of Bakare (2014), where the mean content for fresh faeces was 0.84 g/g db. Batch 2 did not show any variation in volatile solids present in the faeces, as shown in Figure 4.12. Therefore, the assumed biodegradation during the early days was not significant enough to manifest a VS concentration decrease. The quantity of volatile solids gives a measure of stabilisation of the sample or level of biodegradation samples have undergone. The results implied that ageing faecal matter under storage did not experience significant biological degradation because volatile solids stayed constant, thus sustaining abundant organic material. Though transformation into other compounds including volatiles could have occurred at the temperature of testing.

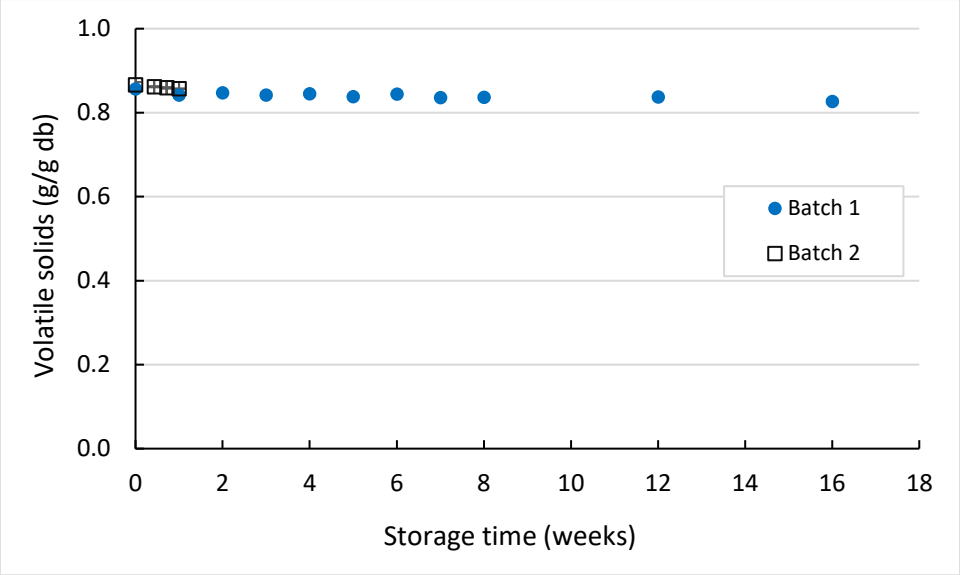

Figure 4.12 Effect of ageing on the volatile solids content of stool samples over sixteen weeks

4.4.2 COD

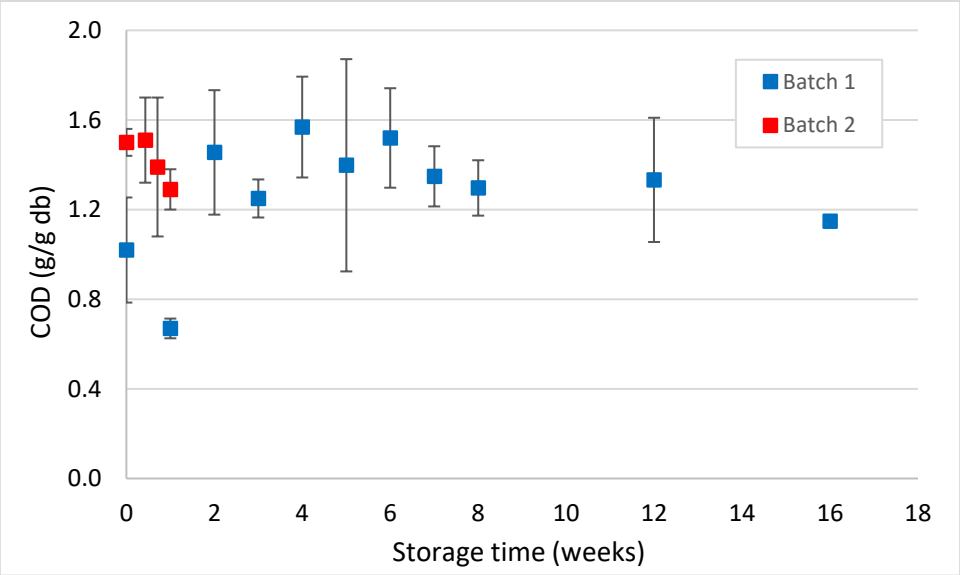

Figure 4.13 Evolution of COD as faeces aged in-situ over sixteen weeks

Figure 4.13 shows how COD evolved as the faecal material aged, and Table D.2 (Appendix D) provides the primary data. The COD quantifies organic matter that can be oxidised chemically. Raw faeces from both batches had COD values of 1.02±0.23 g/g db and 1.50±0.06 g/g db, comparable to the range of 1.13–1.45 g/g db reported in literature. The difference in the initial CODs can arise from diet diversity in study participants, as suggested by Tilley (2014), ZAVALA et al. (2002). Buckley et al. (2008) reported that a COD reduction in storage is a sign of faecal matter breaking down. Similar to the volatile solids results in Figure 4.12, the COD difference between the initial sample and the following weeks for the first batch of experiments was not significant enough to conclude that biodegradation occurred. The COD remained constant for the samples from batch 2 during a week of storage. These results

corroborated with the volatile solid content analysis that no significant organic matter was broken down during storage.

In general, there was no apparent variation of the COD evolution over sixteen weeks of ageing in storage, so it was considered constant (see Appendix D for primary data). This trend is different from findings in studies on faecal sludge from dry pit toilets, where the COD declined during storage. However, pit sludge is contained on-site for years which could be how long it takes for the COD to decrease (Nwaneri et al., 2008, Bakare, 2014, Zuma et al., 2015).

4.4.3 Ammonium and nitrates

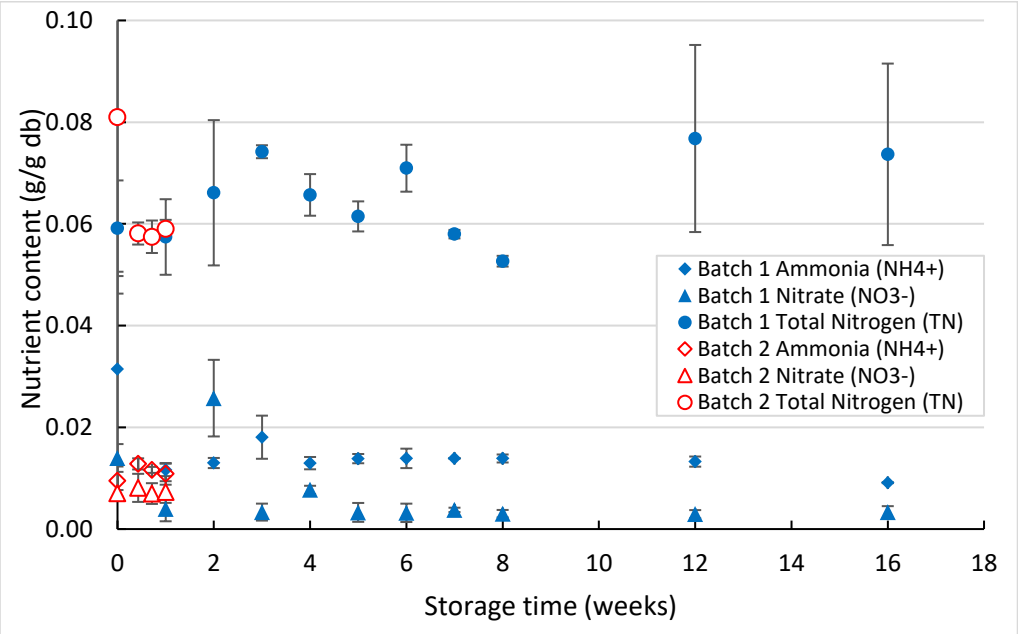

Figure 4.14 Variation in total nitrogen, ammonia and nitrates as faeces aged over sixteen weeks

Figure 4.14 depicts how nitrogenous content (TN, NH_4^+ and NO_3^-) in fresh faeces evolved during ageing. TN content was determined through CNS analysis and remained constant at around 0.06 g/gdb (6%). This value was supported by the 5-7% range suggested by Feachem and Cairncross (1978). The study of Septien et al. (2020) on drying faecal sludge supported the current study trend. NH_4^+ and NO_3^- were the two nitrogen forms measured in this study. Ammonium was the main constituent at around 0.03 g/g db, and nitrates were in considerably lower concentrations of ~0.01 g/g db for the first batch (see Table D.3 and Table D.4 in Appendix D for numeric data). Batch 2 samples had an average of about 0.01 g/g db for NH_4^+ and ~0.007 g/g db for NO_3^-. The difference in initial values of the two batches probably came about because of different participants and diets, similar to initial COD values. The values for ammonium and nitrates for fresh faeces were lower than those for raw faecal sludge from VIP latrines in the study of Septien et al. (2020), 24±4 g/g db and 1.6±0.2 g/g db, respectively. This was because faecal sludge from pit latrines has urine, and urine contributes most of the material's nitrogen. In contrast, fresh faeces do not contain urine, so the nitrogen content is low.

The trend in Figure 4.14 showed that, like the total nitrogen, the ammonium and nitrate in the waste remained constant along the course of transformation in storage. Ageing and drying did not alter the faeces' nutrient composition while in storage in terms of nitrogen.

4.4.4 Carbon content analysis

Figure 4.15 shows the elemental analysis results to determine the fate of carbon content over time during storage. Carbon was the primary element in the faecal samples at ~0.5 g/g db for both batches, and that is approximately 50% on a dry basis which is supported by Onabanjo et al. (2016a) who found 51±2 % on a dry basis. According to Harder et al. (2019), Muspratt et al. (2014), carbon content reducing over time can be expected when biologically degradable carbon breaks down. However, in this study, carbon concentration in the stool remained constant over 16 weeks. The implication was no significant quantity of carbonaceous matter (a fraction of volatile solids) was degraded to conclude that biodegradation took place. Therefore, faecal carbon was unaffected as ageing and drying took place in-situ, as suggested in the study of faecal sludge drying by Septien et al. (2020).

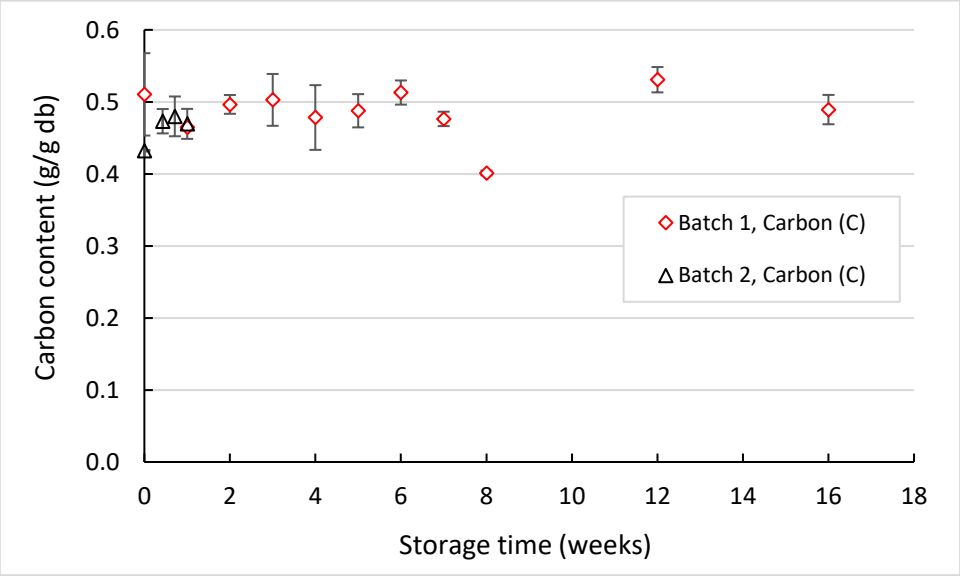

Figure 4.15 Change in carbon contained in faeces over sixteen weeks of ageing

4.4.5 Calorific value

The effect of ageing on the gross calorific value of faeces was evaluated through Figure 4.16. A steady calorific value of ~ 22 MJ/kg db was observed over sixteen weeks, as seen in Figure 4.16. The results served as evidence that the calorific value was independent of sample age, as put forward by Muspratt et al. (2014) in their research on untreated faecal sludge. Calorific content was most likely conserved due to insignificant biological degradation levels supported by the constant volatile solids and carbon content discussed in sections 4.4.1 and 4.4.4. Another possible reason was that since sample drying occurred at ambient conditions (~ 25 °C), the temperatures were too low to degrade the stool thermally. Getahun et al. (2020) suggested that calorific value decreases when faecal waste is dried above 200 °C.

The average value of ~22 MJ/kgdb for fresh faeces in this study was lower than the average of ~25 MJ/kg db obtained by Onabanjo et al. (2016a). However, the calorific content of all samples in this study was on the upper end of the range of 8.0 -23.0 MJ/kg db stated by Muspratt et al. (2014) for conventional biosolids and faecal sludge. The current research found that when raw faeces were left to age in a ventilated environment at ambient conditions, their calorific content was unaffected.

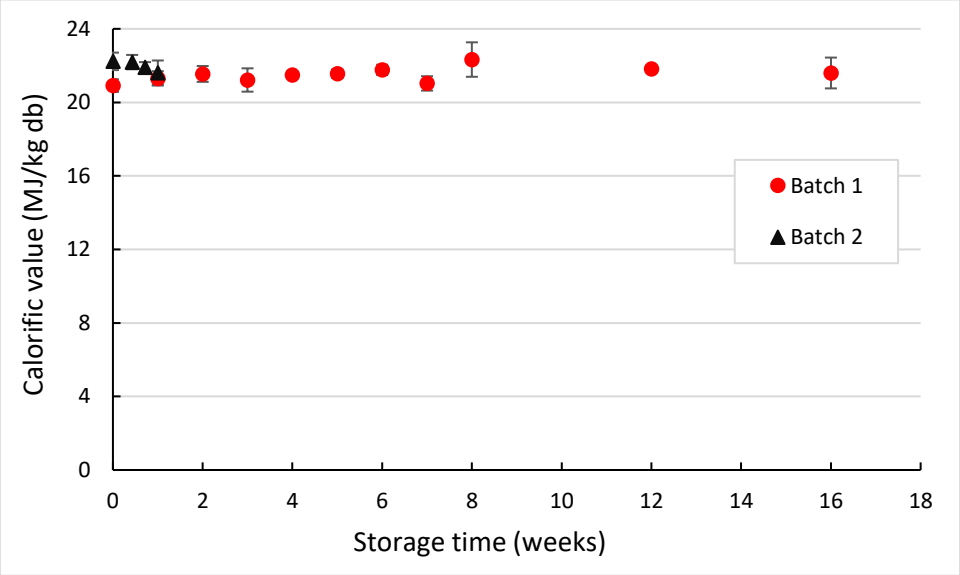

Figure 4.16 Calorific value of different aged faecal samples over sixteen weeks

4.5 Thermal Properties

4.5.1 Thermal conductivity

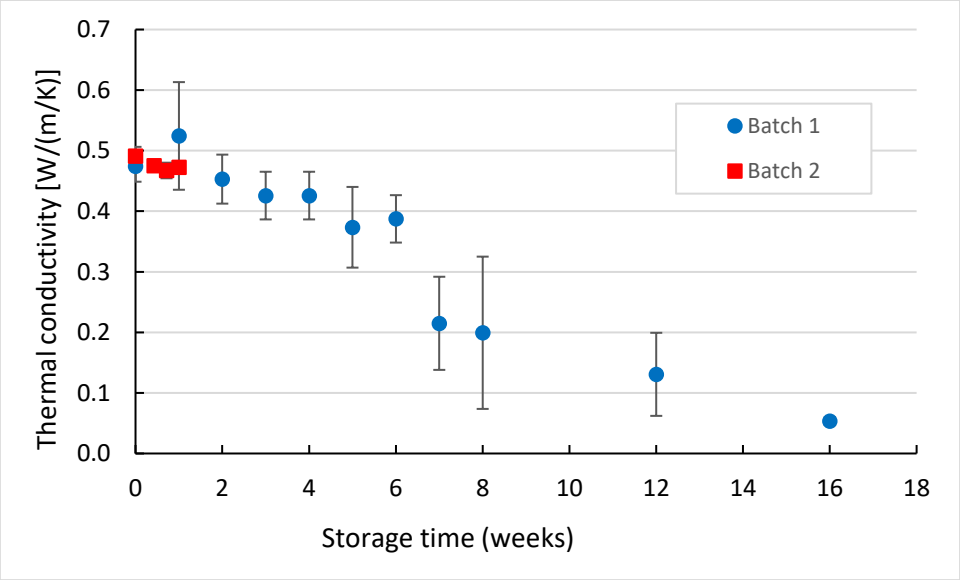

Figure 4.17 Change in thermal conductivity as faeces aged over sixteen weeks

Figure 4.17 displays how the thermal conductivity of faecal material changed with age (refer to Table D.1 in Appendix D for source data). This parameter reflects the inherent ability of the samples to

conduct heat. Thermal conductivity varied during storage by declining over time for the samples from the first and second batches. Fresher samples displayed higher thermal conductivities due to their higher moisture content. The initial value of fresh faeces of ~ 0.5 W/(m/K) was close to the value of pure water [0.6 W/(m/K)], probably due to the high moisture presence in fresh faeces (79.1 %wt). There was a subsequent decrease in thermal conductivity during storage because the faeces dried with ageing. Makununika (2016) found a similar trend while drying faecal sludge, supporting the current study results. Thermal conductivity progressively decreased as the ageing progressed due to the samples drying as more storage time lapsed.

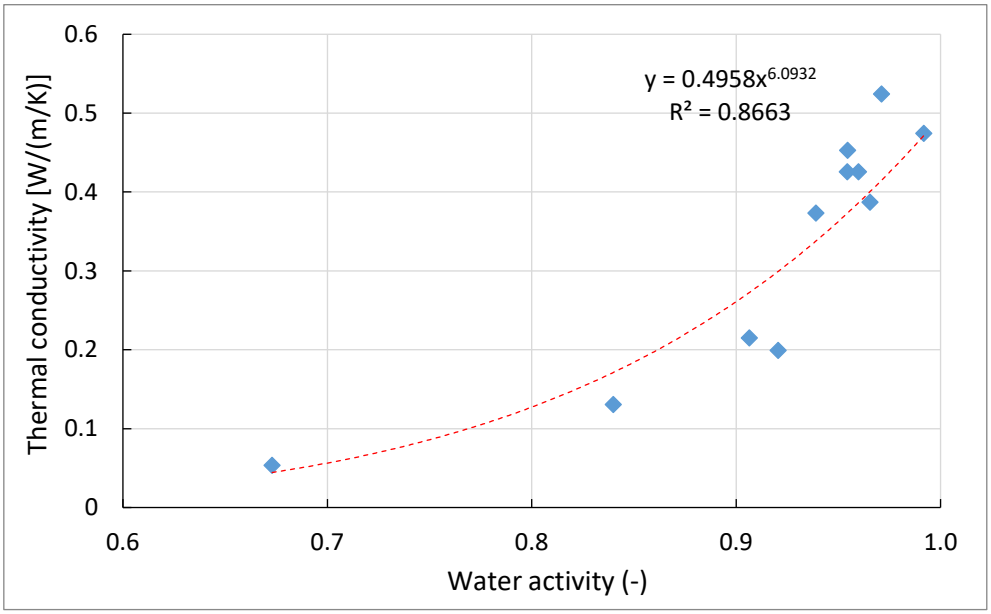

Figure 4.18 Variation of thermal conductivity with water activity

Figure 4.18 relates the thermal conductivity of the aged samples to their water activity. A gradual decrease in water activity above 0.9390 caused a gradual reduction in thermal conductivity. However, below 0.9390, water activity decrease became increasingly rapid and resulted in a fast decline in the thermal conductivity. The trend in Figure 4.18 indicated that water activity influenced thermal conductivity (with a coefficient of determination, R^2 = 0.9074). The main contributor to thermal conductivity is water, which was assumed to be present mainly in bound form in this study. As drying progresses, the water trapped in the pores and structural matter is removed first, lowering a_w. The result is that firmly bound moisture is left in the structure (probably as part of the cells or bound through strong interactions) and air inside the material after replacing the evaporated moisture. Air has a smaller thermal conductivity compared to water, and so the increased air presence in the solid causes the material to have a low thermal conductivity. The remaining water is too bound in the material, and it is in inadequate quantities to impact the thermal conductivity. The decrease in thermal conductivity makes it a good heat insulator making it suitable for building material. Thermal conductivity generally decreased with decreasing water activity in this study.

4.5.2 Heat capacity

The heat capacity of the faecal samples was plotted as a function of ageing in Figure 4.19 (see Table D.1 in Appendix D for raw data). The general trend for batch 1 samples showed a reduction of the heat capacity over time. The initial sample measured 4 230 J/(kg.K), almost equivalent to that of pure water [~4 180 J/(kg.K)] because the sample comprised 79.1% water by mass. Heat capacity had a similar pattern to thermal conductivity (section 4.5.1), where the decrease occurred as the moisture content diminished.

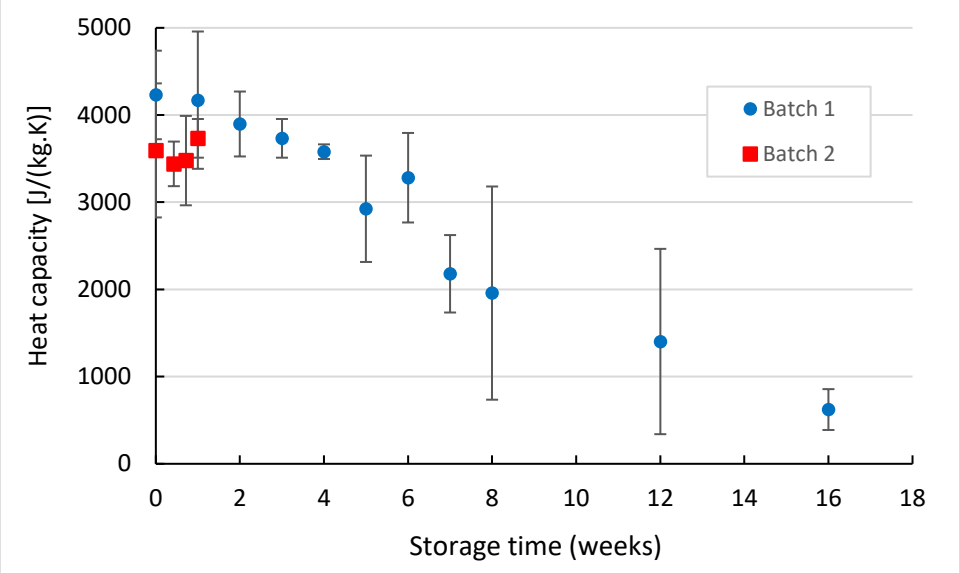

Figure 4.19 Change in heat capacity as faeces aged under storage for sixteen weeks

4.1.1.1 Effect of water activity on heat capacity

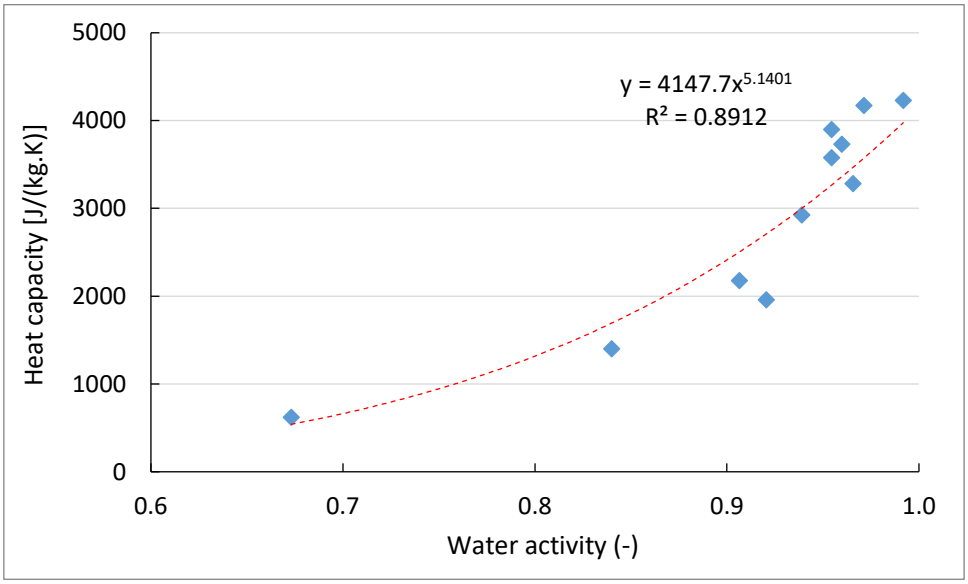

Figure 4.20 Variation of heat capacity with water activity

Figure 4.20 exhibits how water activity affects the heat capacity of faeces while contained over sixteen weeks. It was evident that heat capacity decreased as water activity decreased (with a coefficient of determination, R^2= 0.9244). The rate of decrease in heat capacity increased when water activity fell below 0.9544. Results of thermal conductivity as a function of water activity in section 4.5.1 confirmed the same behaviour, where the loss of moisture reduced the moisture influence on the thermal properties. The pores/crevices in the dried sample structure contain air that has a low heat capacity. Therefore, as more moisture is lost, air replaces the volume occupied by the evaporated moisture, thus causing a decrease in heat capacity. The decrease in heat capacity is advantageous with thermal processes because it would take less energy input to cause the waste material to heat up. Therefore, dried faeces would be a better fuel than conventional ones, ranging between 1 200 J/(kg.K) and 2 900 J/(kg.K).

5 CONCLUSION

In the sixteen weeks, faeces dried since they experienced moisture loss from 79.1 to 26.9 %wt. It was concluded that raw or ageing faeces could not be mechanically dewatered by centrifugation. The lack of dewaterability and a water activity value less than 1 throughout storage indicated that moisture in faeces is mainly bound. Therefore, faeces only lost moisture through progressive drying during storage and had similar drying abilities regardless of the initial moisture content, as shown by the similar moisture ratio-time graphs. Samples swelled in the early stages due to suspected gas evolution from biodegradation. However, the volatile solids, COD, ammonia, nitrates, total nitrogen and total carbon content did not support this hypothesis. Perhaps the swelling resulted from microbial activity; however, the impact on the physicochemical properties was too low. The end-product contained approximately the same quantity of volatile solids as the initial sample (~0.84 g/g db), which indicated that organic matter present was preserved throughout the process of ageing. The same applied to the calorific value, where it averaged 22 MJ/kg db over the entire storage duration.

Stable organic matter and calorific contents were maintained due to the absence of any considerable degradation and sample drying at ambient temperatures. However, there were characteristics of fresh faeces altered in the process, which included rheological and thermal properties. This was because moisture content is one of the known factors that majorly influences them. Thermal conductivity considerably reduced by tenfold to ~0.05 W/(m.K), and heat capacity declined from about 4 200 to 600 J/(kg.K) as the waste dried from 79.1 to 26.9 %wt moisture content. Since water activity is a function of moisture content, a_w reduction also affected thermal properties. In this study, viscosity and yield stress increased solely due to the faeces getting dehydrated as storage was prolonged. In the process, the particle size distribution stayed constant and did not contribute to modifying the rheological properties. In general, fresh faeces stored under ambient and aerated conditions only underwent drying and modification of properties dependent on moisture content.

The storage product should be stable because the considerable dehydration decreases water activity and consequently inactivates microbes and pathogens. Therefore, at the end of storage, the faeces could be disposed of or reused safely. The storage would not affect the nutrient content and calorific value. Therefore, dried faeces could be used in agriculture as a good soil conditioner because of the high carbon and nitrogen content or biofuel since it will have a high calorific value. The current study did not include pathogen data so the risks of reactivating certain pathogens when the aged faecal material is subsequently exposed to or used in humid environments cannot be stated with certainty.

The experimental findings imply that when fresh faeces are deposited and stored onsite, the principal process was dehydration through drying. Dewatering was non-applicable in reducing the bulk volume further regardless of how long the faeces have been stored. No significant biodegradation was observed contrary to what could be expected, and thus the samples exhibited a high organic content. The results

from this study could be applicable in the context of short-term storage of faeces onsite in urine diversion toilets, open defaecation and reinvented toilets that separately collect stool and urine. Short-term storage would generally serve in reducing the bulk volume, rheological characteristics and thermal properties. With the flowability of the faeces compromised with extended storage, emptying of the faecal matter from the onsite area may prove challenging.

6 RECOMMENDATIONS

Further investigations would be required to give a conclusive explanation for the swelling that took place at the beginning of the process. The aspects to take into consideration should include:

- It is suspected that the extraction may have enhanced the drying of the samples when they were stored in the fume hood extractor. Since the influence of the extraction on drying is unclear, it is necessary to set up a control with no extraction to see whether a similar or different outcome is obtained.
- Setting up a system to capture and analyse the gases potentially produced during the faecal sample swelling. Gas production is a consequence of biodegradation and establishes if biodegradation took place.
- Analysis of the microbial activity and count analysis as samples progress in age, particularly at the beginning of the storage when the samples swole. The findings would further support or refute the assumption of biodegradation since the presence of active microorganisms can reflect biodegradation.

- Analysis of pathogenic activity to investigate the behaviour of pathogens before, during and after the desired period of ageing. It may be worthwhile to re-expose the dried and aged faecal matter to humid conditions to establish whether pathogens are re-activated or not. This finding would add further clarity to the question of which stages are safe to handle faecal matter and whether it remains viable for land application without risking reactivating pathogens.

REFERENCES

AGODA-TANDJAWA, G., DIEUDÉ-FAUVEL, E., GIRAULT, R. & BAUDEZ, J.-C. 2013. Using water activity measurements to evaluate rheological consistency and structure strength of sludge. *Chemical engineering journal,* 228**,** 799-805.

ALMEIDA, M., BUTLER, D. & FRIEDLER, E. 1999. At-source domestic wastewater quality. *Urban water,* 1**,** 49-55.

ANDERSON, K., SALLIS, P. & UYANIK, S. 2003. Anaerobic treatment processes. *Handbook of water and wastewater microbiology***,** 391-426.

ANDRIESSEN, N., WARD, B. J. & STRANDE, L. 2019. To char or not to char? Review of technologies to produce solid fuels for resource recovery from faecal sludge. *Journal of Water, Sanitation and Hygiene for Development,* 9**,** 210-224.

APHA 2017. *Standard Methods for the Examination of Water and Wastewater* Washington D.C., APHA/AWWA/WEF.

BAKARE, B., FOXON, K., BROUCKAERT, C. & BUCKLEY, C. 2012. Variation in VIP latrine sludge contents. *Water SA,* 38**,** 479-486.

BAKARE, B. F. 2014. *Scientific and management support for ventilated improved pit latrines (VIP) sludge content. MScEng Thesis: University of KwaZulu Natal.* MScEng University of KwaZulu Natal.

BERENDES, D. M., YANG, P. J., LAI, A., HU, D. & BROWN, J. 2018. Estimation of global recoverable human and animal faecal biomass. *Nature Sustainability,* 1**,** 679-685.

BERGMAN, T. L., INCROPERA, F. P., DEWITT, D. P. & LAVINE, A. S. 2011. *Fundamentals of heat and mass transfer,* Hoboken, NJ, USA, John Wiley & Sons.

BMGF. 2012. *Reinvent The Toilet Challenge* [Online]. Available: http://www.gatesfoundation.org/What-We-Do/Global-Development/Reinvent-the-Toilet-Challenge [Accessed 29 August 2020].

BMGF. 2014. *Reinvent the Toilet Fair India 2014 Techincal Guide* [Online]. Available: https://docs.gatesfoundation.org/documents/Reinvent%20the%20Toilet%20Fair%20India%202014%20Technical%20Guide.pdf [Accessed 29 August 2020].

BOURGAULT, C., LESSARD, P., REMINGTON, C. & DOREA, C. C. 2019. Experimental determination of moisture sorption isotherm of fecal sludge. *Water,* 11**,** 303.

BRIKKÉ, F., BREDERO, M., SUPPLY, W. & NETWORK, M. 2003. Linking technology choice with operation and maintenance in the context of community water supply and sanitation. *In:* ORGANISATION, W. H. (ed.) *A REFERENCE DOCUMENT FOR PLANNERS AND PROJECT STAFF.* Geneva, Switzerland: World Health Organisation.

BUCKLEY, C., FOXON, K., BROUCKAERT, C., RODDA, N., NWANERI, C., BALBONI, E., COUDERC, A. & MAGAGNA, D. 2008. Scientific support for the design and operation of ventilated improved pit latrines (VIPs) and the efficacy of pit latrine additives. *Report for Water Research Commission, South Africa.*

CAIRNS-SMITH, S., HILL, H. & NAZARENKO, E. 2014. Urban Sanitation: Why a portfolio of solutions is needed. *The Boston Consulting Group, Boston, USA*.

CELMA, A. R., CUADROS, F. & LÓPEZ-RODRÍGUEZ, F. 2012. Convective drying characteristics of sludge from treatment plants in tomato processing industries. *Food and Bioproducts Processing,* 90**,** 224-234.

CHAGGU, E. J. 2004. *Sustainable environmental protection using modified pit-latrines.* PhD thesis, Wageningen University.

CHEN, G., LOCK YUE, P. & MUJUMDAR, A. S. 2002. Sludge dewatering and drying. *Drying Technology,* 20**,** 883-916.

CHENG, Y. & LI, H. 2015. Rheological behavior of sewage sludge with high solid content. *Water Science and Technology,* 71**,** 1686-1693.

DIENER, S., SEMIYAGA, S., NIWAGABA, C. B., MUSPRATT, A. M., GNING, J. B., MBÉGUÉRÉ, M., ENNIN, J. E., ZURBRUGG, C. & STRANDE, L. 2014. A value proposition: Resource recovery from faecal sludge—Can it be the driver for improved sanitation? *Resources, Conservation and Recycling,* 88**,** 32-38.

EKECHUKWU, O. 1999. Review of solar-energy drying systems I: an overview of drying principles and theory. *Energy conversion and management,* 40**,** 593-613.

ELSAESSER, T., BORAN, J. & HOUDKOVA, L. 2009. Dewatering of thermally disintegrated sewage sludge. *Chemical Engineering Transactions,* 18**,** 983-988.

FEACHEM, R. & CAIRNCROSS, A. 1978. *Small excreta disposal systems,* London, UK, The ROSS Institute of Tropical Hygiene.

FENG, G., LIU, L. & TAN, W. 2014. Effect of thermal hydrolysis on rheological behavior of municipal sludge. *Industrial & Engineering Chemistry Research,* 53**,** 11185-11192.

FLAGA, A. Sludge drying. Proceedings of Polish-Swedish seminars, Integration and optimization of urban sanitation systems. Cracow March, 2005. 17-18.

FOURIE, A. & VAN RYNEVELD, M. 1995. The fate in the subsurface of contaminants associated with on-site sanitation: A review. *Water S. A.,* 21**,** 101-111.

FOXON, K., BUCKLEY, C., BROUCKAERT, C. & BAKARE, B. 2011. What Happens When the Pit is Full? Developments in on-site Faecal Sludge Management (FSM). *Water Research Commission, Durban.* Durban, South Africa.

FRANCEYS, R., PICKFORD, J., REED, R. & ORGANIZATION, W. H. 1992. A guide to the development of on-site sanitation. England: WHO.

GAVRILA, C., GHIAUS, A. G. & GRUIA, I. 2008. Heat and mass transfer in convective drying processes. *Transport Phenomena,* 2**,** 18.

GETAHUN, S., SEPTIEN, S., MATA, J., SOMORIN, T., MABBETT, I. & BUCKLEY, C. 2020. Drying characteristics of faecal sludge from different on-site sanitation facilities. *Journal of Environmental Management,* 261**,** 110267.

GOLD, M., NIANG, S., NIWAGABA, C., EDER, G., MUSPRATT, A. M., DIOP, P. & STRANDE, L. Results from FaME (Faecal Management Enterprises)–can dried faecal sludge fuel the sanitation service chain. 37th WEDC International Conference, 2014.

GOUNDEN, T., PFAFF, B., MACLEOD, N. & BUCKLEY, C. 2006. Provision of free sustainable basic sanitation: the Durban experience. *32nd WEDC International Conference.* Colombo, Sri Lanka: WEDC, Loughborough University.

GREEN, W. & HO, G. 2005. Small scale sanitation technologies. *Water Science and Technology,* 51**,** 29-38.

HARDER, R., WIELEMAKER, R., LARSEN, T. A., ZEEMAN, G. & ÖBERG, G. 2019. Recycling nutrients contained in human excreta to agriculture: Pathways, processes, and products. *Critical Reviews in Environmental Science and Technology,* 49**,** 695-743.

HAWKINS, B. T., SELLGREN, K. L., KLEM, E. J., PIASCIK, J. R. & STONER, B. R. 2017a. Electrochemical disinfection of repeatedly recycled blackwater in a free-standing, additive-free toilet. *Water and Environment Journal,* 31**,** 545-551.

HAWKINS, P., BLACKETT, I. & HEYMANS, C. 2017b. Poor-inclusive urban sanitation: An overview. *Targeting the Urban Poor and Improving Services*

in Small Towns. Washington, D.C.

HERLINA, N., LUBIS, M. T., HUSIN, A. & PUTRI, I. Studies on decreasing Chemical Oxygen Demand (COD) on artificial laundry wastewater using anaerobic-aerobic biofilter dipped with bio ball media. MATEC Web of Conferences, 2019. EDP Sciences, 06015.

IGUAZ, A., ESNOZ, A., MARTíNEZ, G., LÓPEZ, A. & VıRSEDA, P. 2003. Mathematical modelling and simulation for the drying process of vegetable wholesale by-products in a rotary dryer. *Journal of food engineering,* 59**,** 151-160.

ILIC, M. & TURNER, I. 1989. Convective drying of a consolidated slab of wet porous material. *International Journal of Heat and Mass Transfer,* 32**,** 2351-2362.

INGALLINELLA, A., SANGUINETTI, G., KOOTTATEP, T., MONTANGERO, A. & STRAUSS, M. 2002. The challenge of faecal sludge management in urban areas-strategies, regulations and treatment options. *Water Science and Technology,* 46**,** 285-294.

KEITA, E., RIFAAI, Y., BELIN, P. & ROUSSEL, N. 2019. Influence of non-adsorbing polymers on drying of fresh mortars. *Cement and Concrete Research,* 116**,** 38-44.

KELLEHER, B., LEAHY, J. J., HENIHAN, A., O'DWYER, T., SUTTON, D. & LEAHY, M. 2002. Advances in poultry litter disposal technology–a review. *Bioresource technology,* 83**,** 27-36.

LAWRENCE, A., MACDONALD, D., HOWARD, A., BARRETT, M., PEDLEY, S., AHMED, K. & NALUBEGA, M. 2001. Guidelines for assessing the risk to groundwater from on-site sanitation. UK: British Geological Survey.

LÉONARD, A., BLACHER, S., MARCHOT, P., PIRARD, J.-P. & CRINE, M. 2004. Measurement of shrinkage and cracks associated to convective drying of soft materials by X-ray microtomography. *Drying technology,* 22**,** 1695-1708.

MAGRI, M. E. & SÏ, L. 2013. Inactivation of pathogens in feces by desiccation and urea treatment for application in urine-diverting dry toilets. *Applied and environmental microbiology,* 79**,** 2156-2163.

MAKUNUNIKA, B. S. N. 2016. *Thermal drying of faecal sludge from vip latrines and characterisation of dried faecal material.* MScEng, University of KwaZulu Natal.

MANGESANA, N., CHIKUKU, R., MAINZA, A., GOVENDER, I., VAN DER WESTHUIZEN, A. & NARASHIMA, M. 2008. The effect of particle sizes and solids concentration on the rheology of silica sand based suspensions. *Journal of the Southern African Institute of Mining and Metallurgy,* 108**,** 237-243.

MARA, D. D. 1984. *The design of ventilated improved pit latrines*, International Bank for Reconstruction and Development/The World Bank Washington, DC.

MOWLA, D., TRAN, H. & ALLEN, D. G. 2013. A review of the properties of biosludge and its relevance to enhanced dewatering processes. *Biomass and Bioenergy,* 58**,** 365-378.

MUJUMDAR, A. S. 2014. *Handbook of industrial drying*, CRC press.

MUJUMDAR, A. S. & DEVAHASTIN, S. 2000. Fundamental principles of drying. *Exergex, Brossard, Canada,* 1**,** 1-22.

MUSPRATT, A. M., NAKATO, T., NIWAGABA, C., DIONE, H., KANG, J., STUPIN, L., REGULINSKI, J., MBÉGUÉRÉ, M. & STRANDE, L. 2014. Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal. *Journal of Water, Sanitation and Hygiene for Development,* 4**,** 223-230.

NIWAGABA, C. 2009. *Treatment technologies for human faeces and urine*.

NWANERI, C., FOXON, K., BAKARE, B. & BUCKLEY, C. Biological degradation processes within a pit latrine. WISA Biennial Conference & Exhibition, 2008. 22.

NWANERI, C. F. 2009. *Physico-chemical characteristics and biodegradability of contents of ventilated improved pit latrines (VIPs) in eThekwini Municipality.* Citeseer.

ONABANJO, T., KOLIOS, A. J., PATCHIGOLLA, K., WAGLAND, S. T., FIDALGO, B., JURADO, N., HANAK, D. P., MANOVIC, V., PARKER, A. & MCADAM, E. 2016a. An experimental investigation of the combustion performance of human faeces. *Fuel,* 184**,** 780-791.

ONABANJO, T., PATCHIGOLLA, K., WAGLAND, S. T., FIDALGO, B., KOLIOS, A., MCADAM, E., PARKER, A., WILLIAMS, L., TYRREL, S. & CARTMELL, E. 2016b. Energy recovery from human faeces via gasification: a thermodynamic equilibrium modelling approach. *Energy conversion and management,* 118**,** 364-376.

OSTREM, K. M., MILLRATH, K. & THEMELIS, N. J. Combining anaerobic digestion and waste-to-energy. 12th Annual North American Waste-to-Energy Conference, 2004. American Society of Mechanical Engineers Digital Collection, 265-271.

PANUVATVANICH, A., KOOTTATEP, T. & KONE, D. 2009. Influence of sand layer depth and percolate impounding regime on nitrogen transformation in vertical-flow constructed wetlands treating faecal sludge. *Water research,* 43**,** 2623-2630.

PEASEY, A. 2000. Health aspects of dry sanitation with waste reuse. *WELL studies in water and environmental health, task*.

PORRAS, J. P. & GEBRESENBET, G. 2003. *Review of biogas development in developing countries with special emphasis in India*, Sveriges lantbruksuniv.

REMINGTON, C. M. 2019. *Countering the porcelain dream: key findings from an evaluation of the global nitrogen cycle, a fundamental characterization of fresh faeces, and a campus composting toilet.* Masters of Applied Science Masters Thesis, University of Victoria.

ROSE, C., PARKER, A., JEFFERSON, B. & CARTMELL, E. 2015. The characterization of feces and urine: a review of the literature to inform advanced treatment technology. *Critical reviews in environmental science and technology,* 45**,** 1827-1879.

SAGAR, V. & KUMAR, P. S. 2010. Recent advances in drying and dehydration of fruits and vegetables: a review. *Journal of food science and technology,* 47**,** 15-26.

SAXENA, S., EBRAZIBAKHSHAYESH, B., DENTEL, S. K., IMHOFF, P. T. & CHA, D. K. 2019. In-situ drying of faecal sludge in breathable membrane-lined collection containers. *Journal of Water, Sanitation and Hygiene for Development,* 9**,** 281-288.

SEADER, J. D., HENLEY, E. J. & ROPER, D. K. 1998. Separation process principles. *In:* JENNIFER WELTER, P. M., THOMAS KULESA (ed.) 2nd ed. Hoboken, NJ, USA: John Wiley & Sons, Inc.

SEMIYAGA, S., OKURE, M. A., NIWAGABA, C. B., KATUKIZA, A. Y. & KANSIIME, F. 2015. Decentralized options for faecal sludge management in urban slum areas of Sub-Saharan Africa: a review of technologies, practices and end-uses. *Resources, Conservation and Recycling,* 104**,** 109-119.

SEPTIEN, S., MIRARA, S., MAKUNUNIKA, B., SINGH, A., POCOCK, J., VELKUSHANOVA, K. & BUCKLEY, C. 2020. Effect of drying on the physical and chemical properties of faecal sludge for its reuse. *Journal of environmental chemical engineering,* 8**,** 103652.

SEPTIEN, S., POCOCK, J., TEBA, L., VELKUSHANOVA, K. & BUCKLEY, C. 2018. Rheological characteristics of faecal sludge from VIP latrines and implications on pit emptying. *Journal of environmental management,* 228**,** 149-157.

SINGH, N. K., KAZMI, A. & STARKL, M. 2015. A review on full-scale decentralized wastewater treatment systems: techno-economical approach. *Water Science and Technology,* 71**,** 468-478.

SIRI HARBOE , M. M. 2012. The influence of particle size on viscosity in thixo material. *Key Engineering Materials,* Vols 504-506**,** pp 333-338.

STILL, D. After the pit latrine is full… What then? Effective options for pit latrine management. WISA Biennial Conference, 2002. 19-23.

STILL, D., FOXON, K. & O'RIORDAN, M. 2012. Tackling the challenges of full pit latrines. *Understanding sludge accumulation in VIPs and strategies for*

emptying full pits. WRC Report No. 1745/1/12. Water Research Commission, South Africa.

STRANDE, L. & BRDJANOVIC, D. 2014. *Faecal sludge management: Systems approach for implementation and operation*, IWA publishing.

TALJAARD, L., VENTER, A. & GORTON, D. 2005. *An evaluation of different commercial microbial or microbially-derived products for the treatment of organic waste in pit latrines. Report for the Water Research Commission,* South Africa, Water Research Commission.

TARUYA, T., OKUNO, N. & KANAYA, K. 2002. Reuse of sewage sludge as raw material of Portland cement in Japan. *Water Science and Technology,* 46**,** 255-258.

TCHOBANOGLUS, G., BURTON, F. & STENSEL, H. D. 2003. Wastewater engineering: Treatment and reuse. *American Water Works Association. Journal,* 95**,** 201.

TILLEY, E. 2014. *Compendium of sanitation systems and technologies*, Eawag.

TORONDEL, B. 2010. Sanitation ventures literature review: on-site sanitation waste characteristics. *London, UK: London School of Hygiene & Tropical Medicine*.

TORONDEL, B., ENSINK, J. H., GUNDOGDU, O., IJAZ, U. Z., PARKHILL, J., ABDELAHI, F., NGUYEN, V. A., SUDGEN, S., GIBSON, W. & WALKER, A. W. 2016. Assessment of the influence of intrinsic environmental and geographical factors on the bacterial ecology of pit latrines. *Microbial biotechnology,* 9**,** 209-223.

VAXELAIRE, J. & CÉZAC, P. 2004. Moisture distribution in activated sludges: a review. *Water research,* 38**,** 2215-2230.

WHO. 2017. *Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines* [Online]. Geneva, Switzerland: WHO & UNICEF. Available: https://www.who.int/publications/i/item/9789241512893 [Accessed 31 August 2020].

WHO. 2019. *Progress on household drinking water, sanitation and hygiene 2000-2017: special focus on inequalities* [Online]. New York, USA: World Health Organization & UNICEF. Available: https://www.who.int/water_sanitation_health/publications/jmp-2019-full-report.pdf?ua=1 [Accessed 30 October 2020].

WOOD, K. & BUCKLEY, C. 2013. Transformation of faecal sludge in VIPs: Modelling fill rate with an unsteady-state mass balance. *MScEng thesis, University of KwaZulu-Natal*.

WOOLLEY, S., BUCKLEY, C., POCOCK, J. & FOUTCH, G. 2014a. Rheological modelling of fresh human faeces. *Journal of Water, Sanitation and Hygiene for Development,* 4**,** 484-489.

WOOLLEY, S., COTTINGHAM, R., POCOCK, J. & BUCKLEY, C. 2014b. Shear rheological properties of fresh human faeces with different moisture content. *Water sa,* 40**,** 273-276.

WRONG, O. M. & VINCE, A. 1984. Urea and ammonia metabolism in the human large intestine. *Proceedings of the Nutrition Society,* 43**,** 77-86.

ZAVALA, M. A. L., FUNAMIZU, N. & TAKAKUWA, T. 2002. Characterization of feces for describing the aerobic biodegradation of feces. *Doboku Gakkai Ronbunshu,* 2002**,** 99-105.

ZUMA, L., VELKUSHANOVA, K. & BUCKLEY, C. 2015. Chemical and thermal properties of VIP latrine sludge. *Water SA,* 41**,** 534-540.

ZUMA, L. N. 2016. AN INVESTIGATION INTO THE CHARACTERISTICS OF ON-SITE FAECAL SLUDGE IN DURBAN IN A STUDY OF VENTILATED IMPROVED PIT (VIP) LATRINES AND URINE DIVERSION (UD) TOILETS. MScEng thesis. University of Kwazulu Natal.

APPENDICES

APPENDIX A Ethical clearance certificate

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

22 January 2020

Miss Tanaka Marcia Chatema (218086901)
School of Engineering Howard College
Dear Miss Tanaka Marcia Chatema,

Protocol reference number: BREC/00000524/2019
Project title: The Effect of Ageing on Physical Properties of Faecal Matter
Degree: Masters

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 22 January 2020. **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 **22 January 2020.** 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 **11 February 2020.**

Yours sincerely

Prof V Rambiritch
Chair: Biomedical Research Ethics Committee

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

APPENDIX B Standard Operating Procedure for the thermal drying tests

Standard Operation Procedure –Radwag Moisture analyser MAX series

Introduction

A Radwag moisture analyser MAX series determines the relative moisture content in sample masses on a small scale and the dry mass content in small samples. The instrument provides a reasonably quick and accurate determination of water content in the target substance. Furthermore, the device features a graphic display which then significantly simplifies the procedure of operating, measuring and recording results. Moisture analyser MAX series can determine the moisture contained in material or change in mass at selected time intervals.

Operating procedure

1. Press the on/off button to switch on the instrument. Please wait until the analyser completes its self-examination. To deliver accurate results and enable the moisture analyser to reach the required operating temperature, it must be switched on for at least 20-30 minutes every time before use.
2. Check that the temperature is 105 °C for moisture analysis.
3. Press “Start Program” and follow prompts on the display screen; this may vary per model and brand.
4. Open the lid of the moisture analyser, place the clean and empty weighing boat on the weighing cradle.
5. Close the cover gently and tare the boat weight, the LCD screen should show weight as ‘0’ and a flashing icon to indicate that the machine is ready status for loading the sample.
6. Lift the lid of the moisture analyser and then evenly spread approximately 1-3 g of the wet sample on the weighing boat.
7. Close the cover gently. The halogen light will start to heat the sample until it reaches a steady reading. Note: this process usually takes between 2-15 min, depending on sample weight and its moisture content.
8. Record the mass of the sample every 30 seconds for until the mass reading stabilizes/is constant.
9. Record the moisture reading (before lifting the lid), end of drying procedure.
10. Press ‘Stop’ or lift the lid to end current testing.
11. Clean the weigh boat for future use.

Safety

- Before using a moisture analyser, make sure the instrument was left on power for a sufficient period (mentioned in the user manual).
- Minimize external environmental influences such as air draft, vibrations, or direct sunlight.

- Ensure the analyser is level. This is essential for testing liquid samples, which must be uniform in the sample pan.
- Do not place any flammable substances on or near the moisture analyser because the heating unit area will heat up.

APPENDIX C Qualitative observation for Batch 2 samples

Figure C.1: Batch 2 swelling in 5 L buckets within 24 hours of storage. The black ink mark indicates the initial volume level of faeces

APPENDIX D Tabulated raw numeric data of properties evolution during ageing

Table D.1 Thermal Properties of batch 1 and 2 ageing faeces

Thermal Properties						
Batch 1						
Sample age (weeks)	**Replicate**	**Mass (g)**	**Volume (ml)**	**Density (kg/m^3)**	**Thermal conductivity (W/mK)**	**Heat Capacity (J/kg/K)**
0	a	1.652	1.88	878.88	0.48	4416.18
	b	1.793	1.88	953.46	0.46	4011.46
	c	1.718	1.88	913.72	0.48	4263.25
Average		**1.721**	**1.88**	**915.35**	**0.47**	**4230.30**
Error margin		**0.070**	**-**	**37.31**	**0.01**	**204.36**
1	a	1.929	1.88	1025.85	0.56	4407.46
	b	1.762	1.88	937.07	0.49	3810.57
	c	1.739	1.88	925.16	0.53	4293.82
Average		**1.810**	**1.88**	**962.70**	**0.52**	**4170.62**
Error margin		**0.103**	**-**	**55.02**	**0.04**	**316.95**
2	a	1.889	1.88	1004.95	0.46	3812.42
	b	1.762	1.88	937.18	0.46	4070.31
	c	1.831	1.88	974.10	0.43	3809.04
Average		**1.828**	**1.88**	**972.07**	**0.45**	**3897.26**
Error margin		**0.064**	**-**	**33.93**	**0.02**	**149.87**
3	a	1.873	1.88	996.06	0.44	3745.10
	b	1.816	1.88	965.69	0.43	3815.12
	c	1.860	1.88	989.36	0.41	3637.88
Average		**1.849**	**1.88**	**983.71**	**0.43**	**3732.70**
Error margin		**0.030**	**-**	**15.96**	**0.02**	**89.27**
4	a	1.914	1.88	1018.30	0.44	3596.27
	b	1.932	1.88	1027.66	0.43	3601.85
	c	2.012	1.88	1070.00	0.41	3540.70
Average		**1.953**	**1.88**	**1038.65**	**0.43**	**3579.61**
Error margin		**0.052**	**-**	**27.55**	**0.02**	**33.81**
5	a	2.015	1.88	1071.54	0.37	3175.18
	b	1.843	1.88	980.05	0.40	3641.98
	c	2.116	1.88	1125.27	0.35	3540.70
Average		**1.991**	**1.88**	**1058.95**	**0.37**	**2924.78**
Error margin		**0.138**	**-**	**73.42**	**0.03**	**245.55**
6	a	2.015	1.88	1071.54	0.41	3083.84
	b	1.843	1.88	980.05	0.38	3496.06
	c	2.116	1.88	1125.27	0.38	3263.42
Average		**1.991**	**1.88**	**1058.95**	**0.39**	**3281.11**
Error margin		**0.138**	**-**	**1058.95**	**0.02**	**206.68**
7	a	2.051	1.88	1090.90	0.25	2371.97
	b	1.878	1.88	998.94	0.19	2019.03
	c	1.950	1.88	1037.45	0.21	2146.16
Average		**1.960**	**1.88**	**1042.43**	**0.21**	**2179.05**
Error margin		**0.087**	**-**	**46.19**	**0.03**	**178.76**
8	a	2.139	1.88	1137.93	0.17	1610.45
	b	1.965	1.88	1044.95	0.17	1742.13
	c	1.985	1.88	1055.96	0.26	2521.05
Average		**2.030**	**1.88**	**1079.61**	**0.20**	**1957.88**
Error margin		**0.096**	**-**	**50.80**	**0.05**	**492.14**
12	a	1.890	1.88	1005.37	0.11	1118.24
	b	1.854	1.88	985.90	0.12	1194.11
	c	1.729	1.88	919.52	0.16	1894.18
Average		**1.824**	**1.88**	**970.27**	**0.13**	**1402.18**

Error margin		**0.085**	**-**	**45.01**	**0.03**	**427.78**
16	a	0.876	1.88	466.01	0.05	557.32
	b	0.836	1.88	444.63	0.06	730.34
	c	0.852	1.88	453.40	0.05	578.91
Average		**0.855**	**1.88**	**454.68**	**0.05**	**622.19**
Error margin		**0.020**	**-**	**10.75**	**0.00**	**94.28**
Batch 2						
Sample age (days)	**Replicate**	**Mass (g)**	**Volume (ml)**	**Density (kg/m^3)**	**Thermal conductivity (W/mK)**	**Heat Capacity (J/kg/K)**
0	a	2.268	1.88	1206.12	0.48	3236.85
	b	1.959	1.88	1042.02	0.49	3773.44
	c	1.966	1.88	1045.48	0.50	3772.12
Average		**2.064**	**1.88**	**1097.87**	**0.49**	**3594.14**
Error margin		**0.176**	**-**	**-93.76**	**0.01**	**309.42**
3	a	2.156	1.88	1146.54	0.47	3365.49
	b	2.049	1.88	1089.89	0.48	3557.29
	c	2.145	1.88	1141.17	0.48	3396.54
Average		**2.117**	**1.88**	**1125.87**	**0.48**	**3439.77**
Error margin		**0.059**	**-**	**25.53**	**0.00**	**102.95**
5	a	2.082	1.88	1107.61	0.46	3452.89
	b	2.198	1.88	1168.99	0.47	3284.32
	c	1.965	1.88	1045.37	0.47	3694.77
Average		**2.082**	**1.88**	**1107.32**	**0.47**	**3477.32**
Error margin		**0.116**	**-**	**61.81**	**0.01**	**206.31**
7	a	2.027	1.88	1078.30	0.47	3576.21
	b	2.037	1.88	1083.51	0.47	3569.19
	c	2.003	1.88	1065.48	0.47	3622.59
Average		**2.022**	**1.88**	**1075.76**	**0.47**	**3732.70**
Error margin		**0.017**	**-**	**9.28**	**0.00**	**89.27**

Table D.2 Evolution of COD for batch 1 and 2

COD (g/g db)				
Batch 1				
Sample age (weeks)	**Sample name**	**Replicate**	**Mean**	**Error Margin**
0	0a	1.038586	1.01953	0.23
	0b	1.000473		
1	1a	0.66393	0.669605	0.044
	1b	0.689466		
	1c	0.655418		
2	2a	1.408766	1.455145	0.278
	2b	1.582688		
	2c	1.373982		
3	3a	1.418897	1.249597	0.085
	3b	1.273783		
	3c	1.225411		
4	4a	1.605844	1.56828	0.225
	4b	1.46498		
	4c	1.634016		
5	5a	1.617747	1.397733	0.474
	5b	1.294197		
	5c	1.281256		
6	6a	1.42308	1.51963	0.222
	6b	1.59939		
	6c	1.53642		
7	7a	1.310173	1.348386	0.134
	7b	1.506699		
	7c	1.386599		
8	8a	1.341738	1.296603	0.124
	8b	1.30481		
	8c	1.243262		
12	12a	1.204703	1.33261	0.277
	12b	1.383177		
	12c	1.409949		
16	16a	1.136046	1.14788	0.027
	16b	1.157347		
	16c	1.150247		
Batch 2				
Sample age (days)	**Sample name**	**Replicate**	**Mean**	**Error margin**
0	0a	1.51089222	1.49944606	0.06
	0b	1.47655376		
	0c	1.51089222		
3	3a	1.5571965	1.51302072	0.190
	3b	1.42466914		
	3c	1.5571965		
5	5a	1.50895954	1.38577916	0.306
	5b	1.26259879		
	5c	1.38577916		
7	7a	1.32869143	1.28749169	0.089
	7b	1.26689183		
	7c	1.26689183		

Table D.3 Evolution of ammonium content for batch 1 and 2

NH_4^+ (g/g db)				
Batch 1				
Sample age (weeks)	**Sample name**	**Replicate**	**Mean**	**Error Margin**
0	0a	0.029538	0.031443	0.019
	0b	0.033349		
1	1a	0.011917	0.011633	0.001
	1b	0.011917		
	1c	0.011065		
2	2a	0.013218	0.012986	0.001
	2b	0.012522		
	2c	0.013218		
3	3a	0.018704	0.018059	0.004
	3b	0.019349		
	3c	0.016124		
4	4a	0.013523	0.012959	0.001
	4b	0.012678		
	4c	0.012678		
5	5a	0.014107	0.013848	0.001
	5b	0.015142		
	5c	0.013589		
6	6a	0.01373	0.013890	0.002
	6b	0.01473		
	6c	0.01322		
7	7a	0.013896	0.013896	0.000
	7b	0.013896		
	7c	0.013896		
8	8a	0.013652	0.013876	0.001
	8b	0.015443		
	8c	0.0141		
12	12a	0.014359	0.013264	0.001
	12b	0.013548		
	12c	0.01298		
16	16a	0.009166	0.009123	0.000
	16b	0.009101		
	16c	0.009101		
Batch 2				
Sample age (days)	**Sample name**	**Replicate**	**Mean**	**Error Margin**
0	0a	0.00824123	0.009462153	0.003
	0b	0.010072615		
	0c	0.010072615		
3	3a	0.013252736	0.012810978	0.001
	3b	0.01236922		
	3c	0.012810978		
5	5a	0.011496835	0.011633702	0.001
	5b	0.011907436		
	5c	0.011496835		
7	7a	0.011535926	0.010849263	0.002
	7b	0.009887936		
	7c	0.011123928		

Table D.4 Evolution of Nitrates content with storage time for batch 1 and 2

NO_3^- (g/gdb)				
Batch 1				
Sample age (weeks)	**Sample name**	**Replicate**	**Mean**	**Error Margin**
0	0a	0.013339643	0.013974864	0.003
	0b	0.013339643		
	0c	0.015245306		
1	1a	0.003404769	0.00397223	0.002
	1b	0.003404769		
	1c	0.005107153		
2	2a	0.024349043	0.025740416	0.008
	2b	0.023653356		
	2c	0.029218851		
3	3a	0.003869719	0.003332258	0.002
	3b	0.002579813		
	3c	0.003547243		
4	4a	0.007888354	0.007700536	0.001
	4b	0.007325		
	4c	0.007888354		
5	5a	0.002847234	0.003278634	0.002
	5b	0.004141432		
	5c	0.002847234		
6	6a	0.00277	0.00319	0.002
	6b	0.00403		
	6c	0.00277		
7	7a	0.00397022	0.003771709	0.000
	7b	0.003672454		
	7c	0.003672454		
8	8a	0.003357143	0.003021429	0.001
	8b	0.002797619		
	8c	0.002909524		
12	12a	0.002920492	0.002920492	0.001
	12b	0.002595993		
	12c	0.003244991		
16	16a	0.003356501	0.003291952	0.001
	16b	0.003743789		
	16c	0.002775568		
Batch 2				
Sample age (days)	**Sample name**	**Replicate**	**Mean**	**Error Margin**
0	0a	0.006867692	0.007020307	0.001
	0b	0.007325538		
	0c	0.006867692		
3	3a	0.007951642	0.008098894	0.003
	3b	0.007068126		
	3c	0.009276915		
5	5a	0.006159019	0.006980221	0.002
	5b	0.006980221		
	5c	0.007801423		
7	7a	0.008239947	0.00727862	0.002
	7b	0.007003955		
	7c	0.006591957		

APPENDIX E Drying curves for batch 1 and batch 2

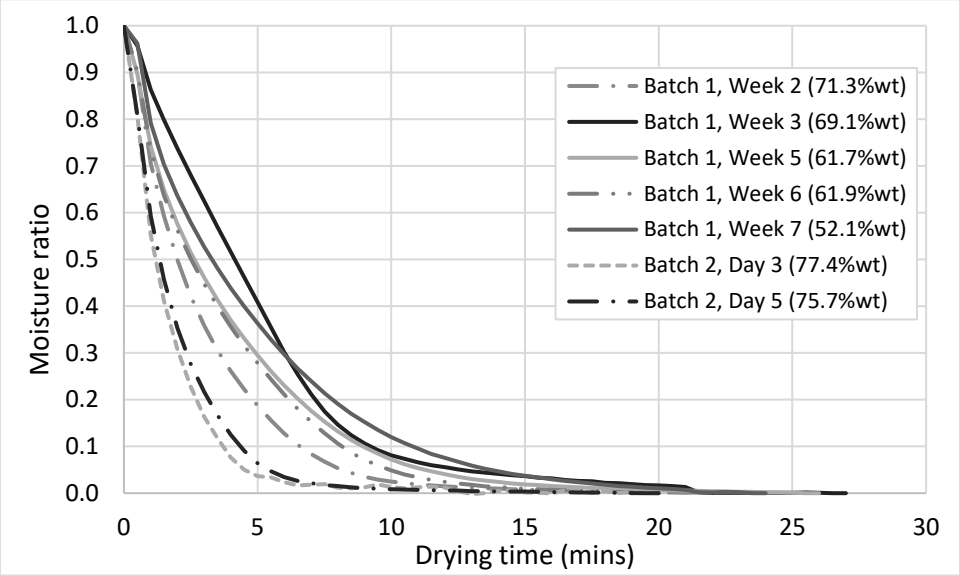

Figure E.1 Change in drying ability of faeces with storage time for batch 1 and 2

APPENDIX F Comparison of results from the two sample batches

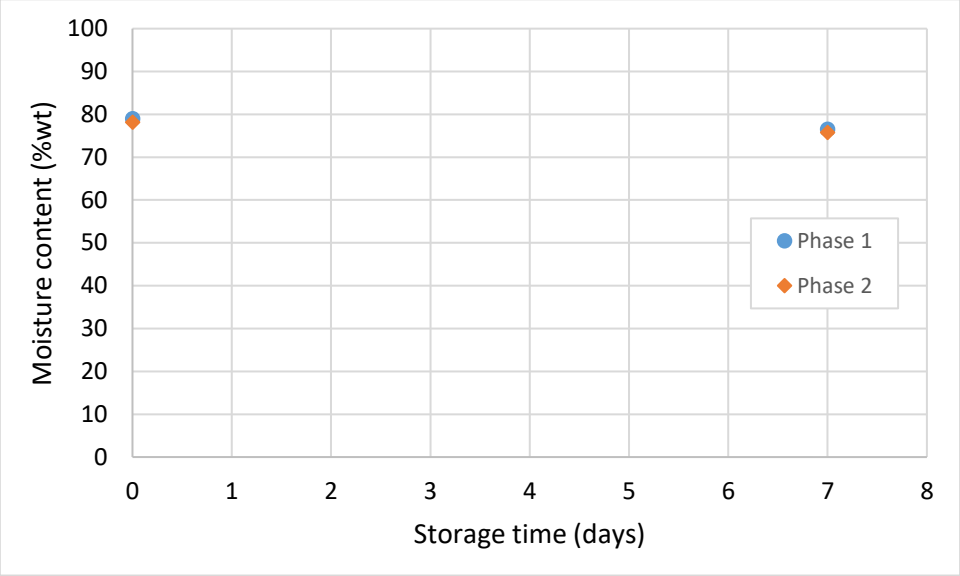

Figure F.1 Moisture content as a function of storage time

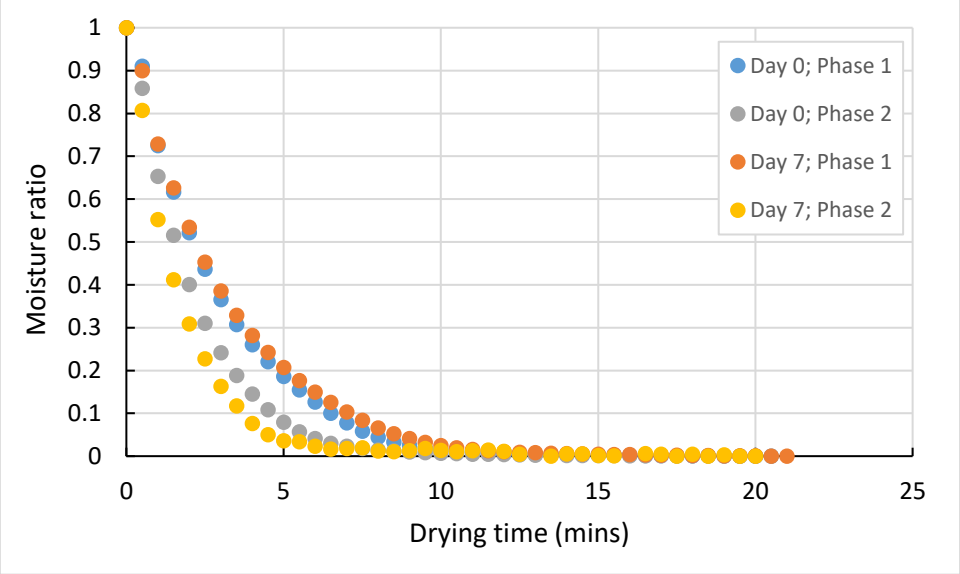

Figure F.2 Comparison of drying ability of initial sample and week 1 sample

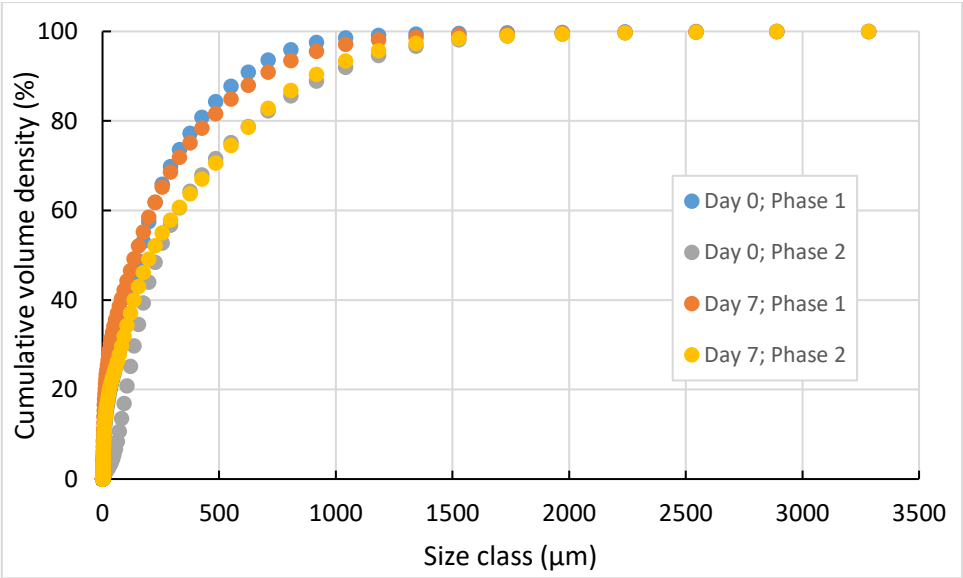

Figure F.3 Cumulative volume distribution of particles in ageing faeces over one week

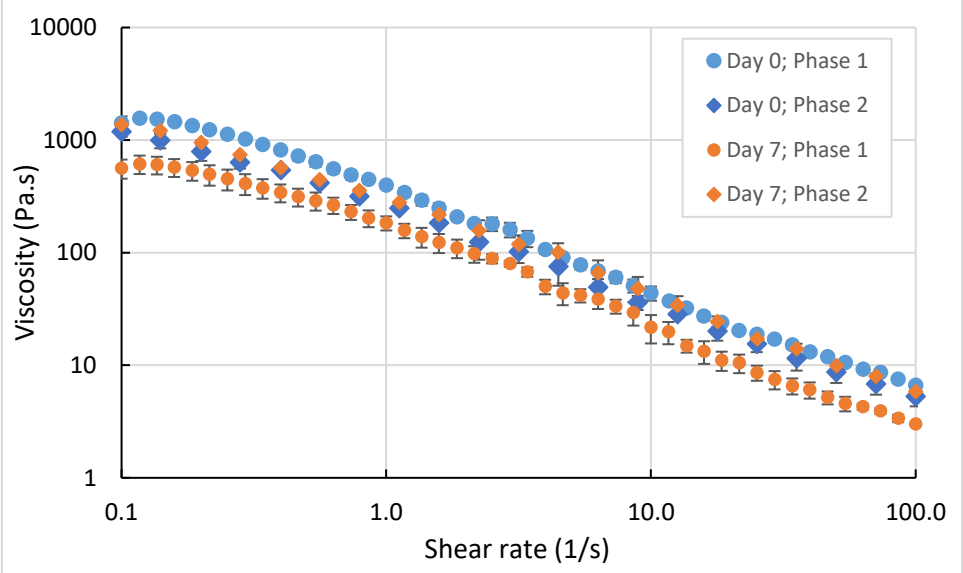

Figure F.4 Viscosity against shear rate for faecal samples stored at different times

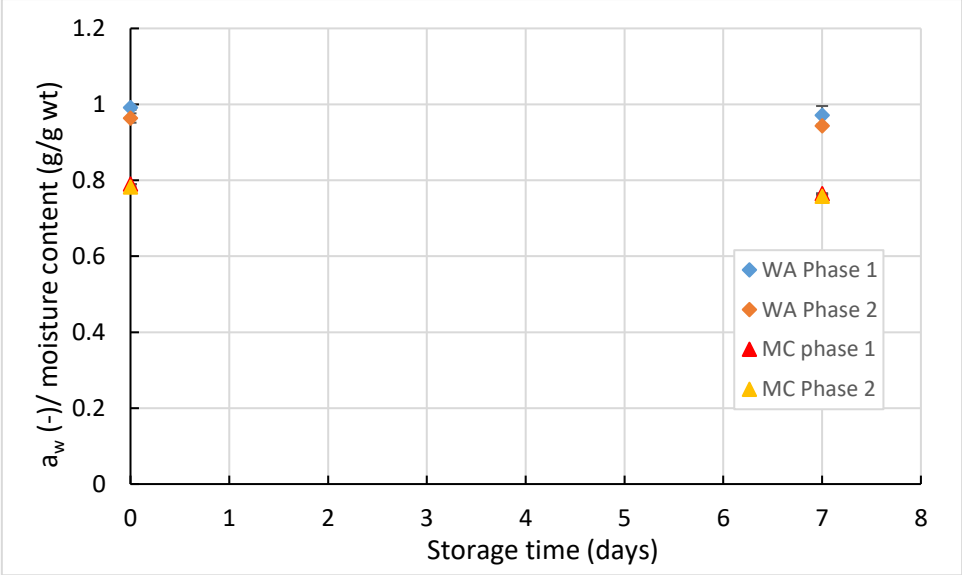

Figure F.5 Change of water activity with moisture content in first week of faeces storage

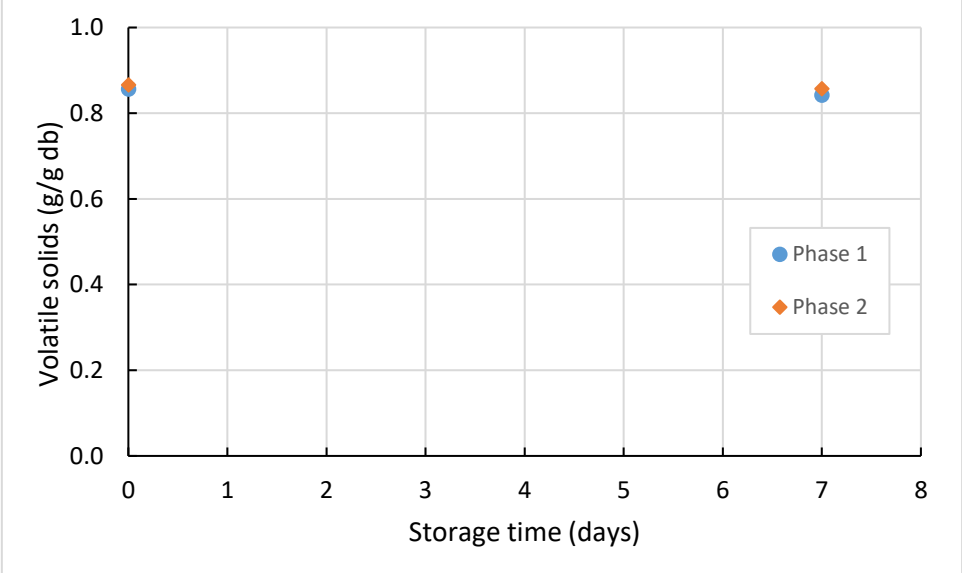

Figure F.6 Effect of storage on the volatile solids content of stool samples in first week of storage

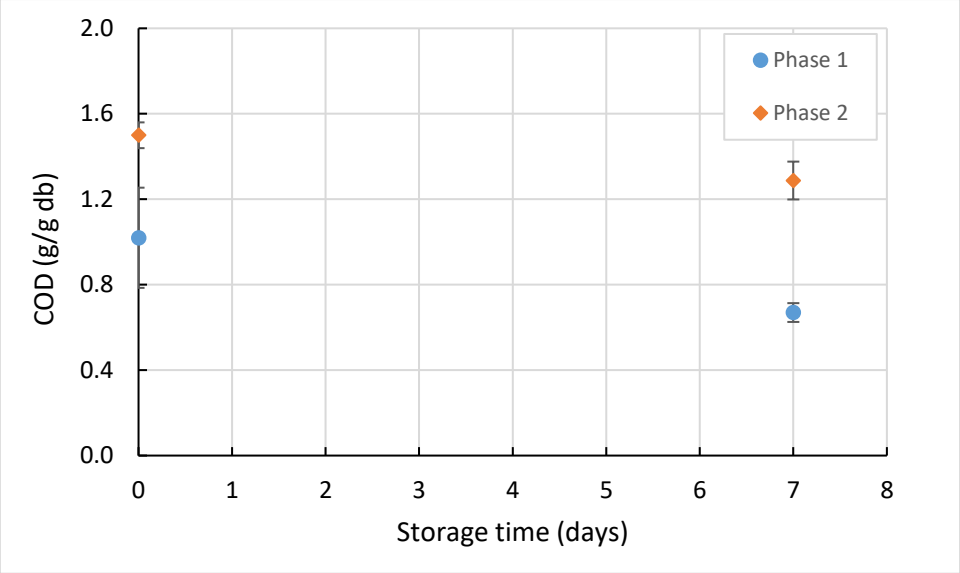

Figure F.7 Evolution of COD as faeces aged in-situ in the first week of storage

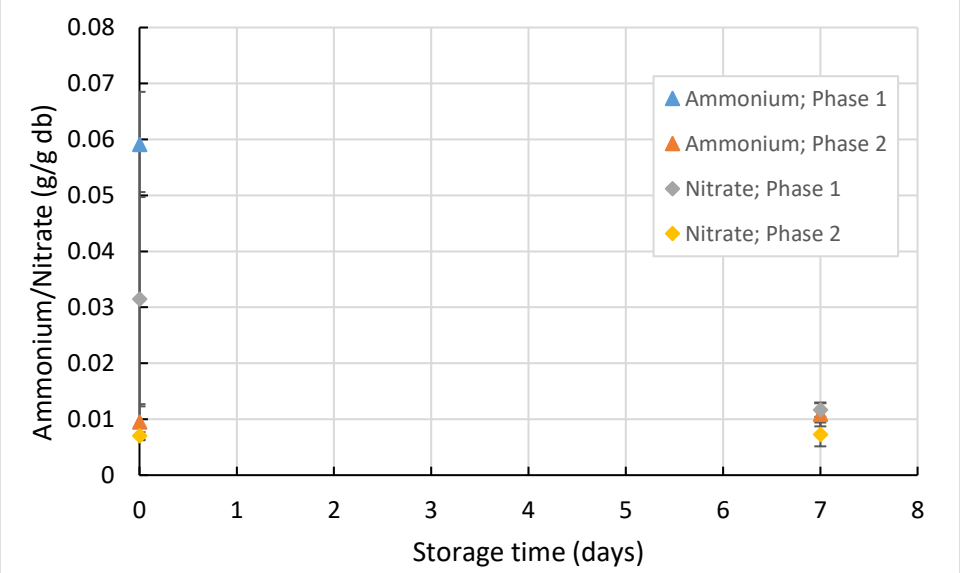

Figure F.8 Variation of ammonium and nitrates of faeces in initial week of storage

N

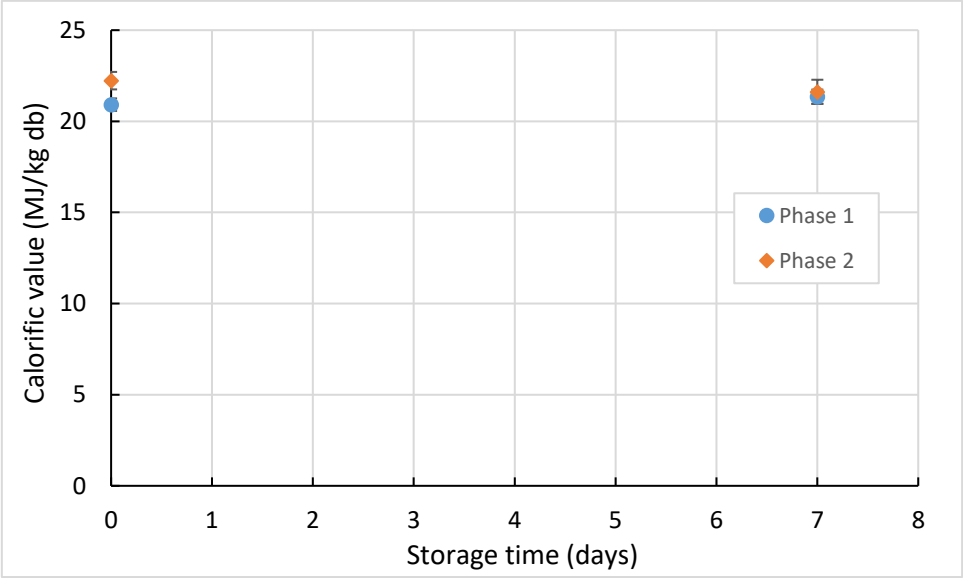

Figure F.9 Change in calorific value of faeces in initial storage

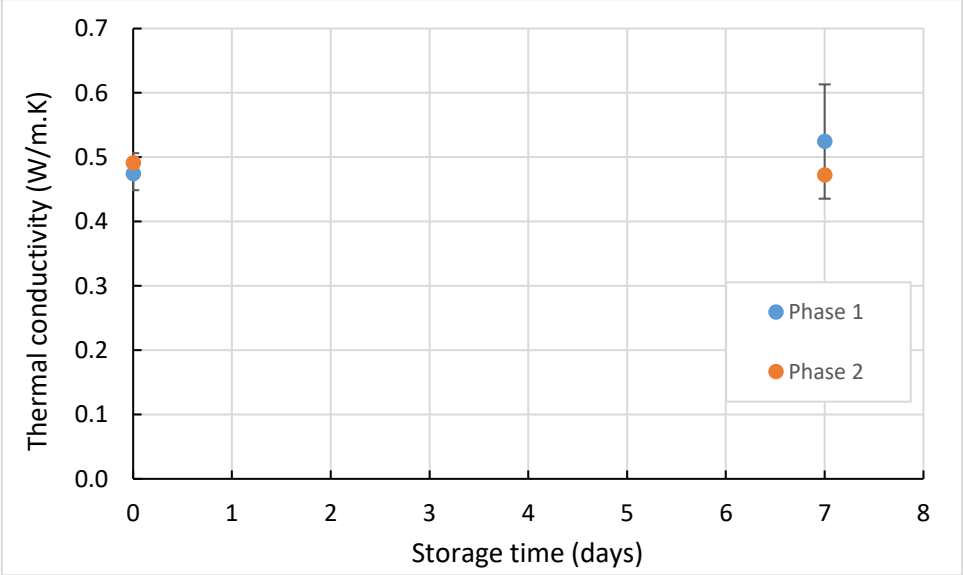

Figure F.10 Change in thermal conductivity with ageing of faeces during initial week of storage

O

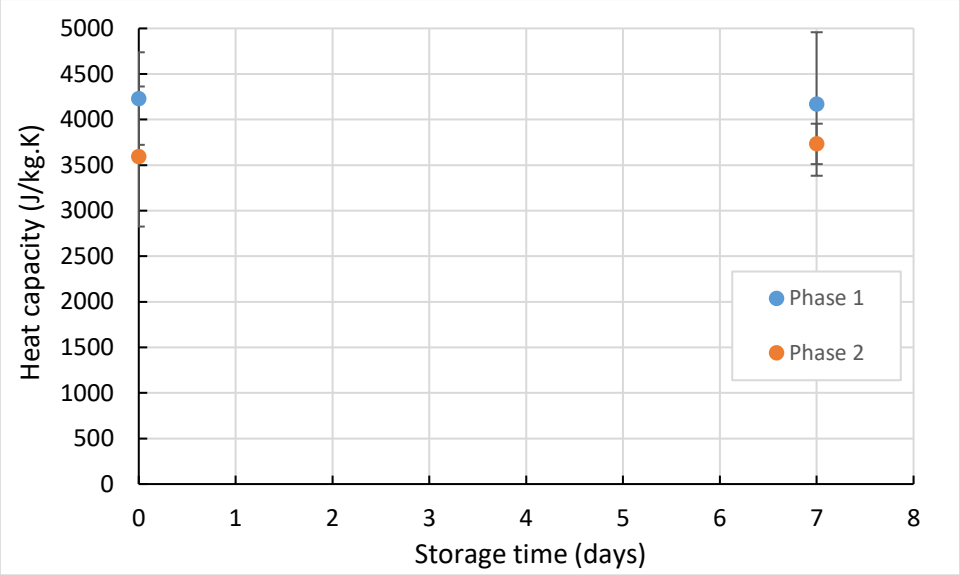

Figure F.11 Change in heat capacity with ageing of faeces during initial week of storage