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INVESTIGATING THE DEWATERING CHARACTERISTICS OF FAECAL SLUDGE IN THE CONTEXT OF FAECAL SLUDGE WATER BOUNDNESS

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This submitted final version is done with the supervisor's approval, and that corrections were added as recommended by the examination committee.

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ABBREVIATIONS AND ACRONYMS

CST	Capillary suction time
DSVI	Diluted sludge volume index
FS	Faecal sludge
FSM	Faecal sludge management
FSTP	Faecal sludge treatment plant
JMP	Joint Monitoring Programme
MDGs	Millennium development goals
OSS	Onsite sanitation systems
PSD	Particle size distribution
RPM	Revolutions per min
SDGs	Sustainable development goals
SRF	Specific resistance to filtration
SVI	Sludge volume index
STS	Septic tank systems
UDDT	Urine diversion dehydrating/drying toilets
UN	United Nations
VIP	Ventilated improved pit
WASH	Water sanitation and hygiene

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ABSTRACT

Access to adequate sanitation is still elusive in many parts of the world, with approximately 2 billion people lacking sanitation globally. The impacts of poor or lacking sanitation service delivery systems include negatively impacting water quality and causing health risks to the populations involved. The preferred centralized sanitation systems have gaps and can barely help the situation, especially in developing countries, which points to the necessity of a paradigm shift in wastewater management to include interventions that would make proper sanitation accessible to all. Such interventions include onsite sanitation systems (OSSs) and subsequent faecal sludge management (FSM), which with appropriate treatment, have a lot of potential to produce environmentally acceptable effluents and are also pertinent in achieving decreased costs for sanitation systems sanitation more affordable to all.

Faecal sludge (FS) dewatering is indispensable for adequate FSM. However, there is a shortage of knowledge on FS characterization and dewatering tendencies. This thesis work investigated the dewatering characteristics of faecal sludge in the context of faecal sludge water boundness. Six samples from ventilated improved latrines (VIP), Urine diversion dehydrating/drying toilets (UDDT), and septic tank (ST) in Ethekwini Municipality in Durban, South Africa, were analysed. Evaluation indices of dewatering and moisture release, settleability, filterability, and centrifugability; by sludge volume index (SVI), specific resistance to filtration (SRF), and centrifugation tests were determined. In addition, sludge physical properties – density, porosity, and particle size distribution (PSD) - effect on FS dewatering was analysed.

Data was analysed in an Excel spreadsheet to compare the mean results of each sample category and correlation and multiple regression analysis to quantify the relative importance of FS physical characteristics on dewatering. Results showed that dewatering was different between FS from different OSSs. Correlation between sludge physical properties and settleability and filterability were also identified. The results identify potential characteristics that influence faecal sludge moisture release and predict dewatering rate.

1. INTRODUCTION

1.1. Background Information

Man's adoption of a sedentary life, the building of villages and towns, coupled with rapid population growth and industrialization, brought new challenges experienced to date (Angelakis & Zheng, 2015). These challenges are the supply of drinkable water, water for economic production, and safe management of waste generated, especially human excreta (Vuorinen et al., 2007).

Sanitation is the safe handling and disposal of human excreta and other waste products through its safe containment, handling, and final disposal or reuse, thereby preventing the waste's disposal directly into the environment. In the Bronze Age, sanitation developments were driven by the need to make efficient use of natural resources, make civilizations more resistant to destructive natural elements, and improve standards of living, both at the public and private levels (Angelakis & Rose, 2014). The evolution and development of bathing, sanitary and other purgatory structures can be traced from Crete, the Indus valley, to the cities of Ancient Egypt, the Hellenistic period, the Chinese Dynasties and Empires, to the facilities built during the Roman period (Yannopoulos et al., 2017). During the Sanitary Dark Ages, very unsanitary conditions and overcrowding were prevalent in Europe and Asia (Roca, 2017 and Everret, 2019). These conditions resulted in cataclysmic pandemics such as the Justinian Plague (541–542AD) and the Black Death (1347–1351AD), which killed tens of millions of people and radically changed societies (De Feo et al., 2014).

Between the 16th and 19th centuries, the modern age of sanitation began in Europe when pail closets, outhouses and cesspits were used to collect human waste (Schladweiler, 2020). Plumbing, latrines and personal toilets inventions enabled coordinated collection of human faeces and their delivery to sewage networks. During the same time, water purification techniques, the creation of drinking water, and its transport to the human population started the era where personal hygiene could be easily enforced by everyone (Juuti et al., 2007). These events all culminated in the 'Sanitary Revolution' age of the 19th and 20th centuries, when governments began to enforce strict hygiene rules, organized garbage collection, the development of public health departments and water and wastewater treatment networks (Lofrano & Brown, 2010).

Presently, under international law, water and sanitation services are human rights (Howard, 2021). The United Nations Millennium Development Goals (MDGs) increased attention by crucial decision-

makers on the need for investments in sanitation. Although the world missed the MDG sanitation target in 2015, between 1990 and 2015, more than 1.9 billion people acquired access to improved sanitation, equating to more than 200,000 individuals per day (Peal et al., 2020).

The Sustainable Development Goals (SDGs) recognize the significance of water and sanitation. By 2030, SDG 6 aims to ensure the availability and sustainable management of water and sanitation for all. SDG 6 has six objectives aiming at measurable improvements in water and sanitation and two additional targets to identify how to meet the standards. SDG 6's first two targets are related to providing safe drinking water and sanitation services (Howard, 2021).

SDGs Targets 6.1 and 6.2 calls for eliminating open defecation and universal access to drinking water, sanitation, and hygiene (WASH), while proposing ambitious new service norms for drinking water and sanitation (Odagiri et al., 2021). By 2030, approximately 5.6 billion more people would need to utilize safely managed services, and around 1.3 billion will need to shift from open defecation to a sanitation system (Mara & Evans, 2018; and Dickin et al., 2020). On the other hand, SDG target 6.3 addresses the need for more effective wastewater treatment, as most wastewater is discharged untreated.

The criteria for a 'safely managed' sanitation service (SDG 6.2) goes beyond access to improved sanitation (which hygienically separates excreta from human contact) with a focus on safe excreta management across the entire sanitation service chain (Odagiri et al., 2021). According to the Joint Monitoring Programme (JMP), a safely managed sanitation service entails: the presence of improved sanitation facilities not shared with other households, in-situ treatment and disposal of excreta, or temporarily stored and then emptied and transported to off-site treatment, or transported through a sewer with wastewater and then treated off-site (Mara & Evans, 2018; and Dickin et al., 2020).

1.1.1. Centralized versus decentralized wastewater management

Human excreta have a high load of microorganisms, and thus it can be a biohazard. Unfortunately, there is insufficient data on human excreta management (UNICEF & WHO, 2020). .

Centralized wastewater management systems, also referred to as off-site management, have been the preferred response to managing human excreta by planners and decision-makers. The centralized strategy is, and has been the conventional wastewater management strategy of the past and present centuries and was regarded efficient in wastewater treatment and pollution control (De Feo et al.,

2014). Centralized wastewater management consists of: a centralized wastewater collection system (sewers) that collects wastewater from households, commercial areas, industrial plants, and institutions and moves it to a centralized wastewater treatment plant in an off-site location outside the settlement; and a finally, a wastewater disposal/reuse facility. Despite being the preferred option, a centralized system requires intensive treatment technologies, a high level of capital, effective urban planning strategies, and stable socio-economic conditions and thus difficult to install and operate (Zaqout & Hueso, 2020).

On the other hand, decentralized wastewater management systems (also known as onsite management) collect, treat, and dispose of/ reuse human excreta at or near the generation point. Decentralisation can also take the form of a cluster system where wastewater collects from a small number of households in a community, in sewers usually much smaller than those in the central system, and led to a small-scale treatment plant near the wastewater source (Nansubuga et al., 2016). The decentralized wastewater management system was historically common until the 19th century when centralized wastewater management became preferred. However, the previously discarded decentralized management strategy has been of interest over the last few decades. Interest in these technologies has been renewed, as it has become clear that a centralized strategy is not feasible in many places or, in some cases, is simply not the most cost-effective alternative (Septien, 2015).

It has become clear that a centralized strategy is not feasible in many places or, in some cases, is simply not the most cost-effective alternative. The systems are very costly and complex to build, operate, maintain, and require highly efficient water use. Centralized water systems may be less suitable in low-income areas, low population areas, water shortage areas, and areas with no adequate water supply network.

Within the framework of a decentralized strategy, wet or dry, basic or more advanced technologies exist, all with the same principle of treating smaller quantities at or near the source. Basic technologies are currently in use; septic tanks and pit latrines, but there are other variants (Ecosan / toilet composting and pour-flush). The advantages of the decentralized strategy include lower construction and maintenance costs, lower environmental impact due to system failure and separation of industrial wastewater treatment; more significant potential for effluent and solids reuse; and less water-intensive. A decentralized system is a viable alternative if it is highly effective and provides

advanced treatment; it is easy to operate and low cost. In addition, decentralized systems require efficient operation and maintenance.

1.1.2. Faecal sludge management

After many years of neglect, governments, development agencies, and research organizations worldwide are giving faecal sludge management (FSM) attention (Strande et al., 2014). The increasing use of onsite systems to improve sanitation access makes faecal sludge management (FSM) increasingly hard to ignore (Hawkins et al., 2013). According to the JMP database, as of 2017, approximately 2.7 billion people globally are dependent on onsite sanitation systems (OSSs) for their sanitation needs (UNICEF & WHO, 2020). However, many lack the means to manage faecal sludge (FS), which may have significant health and environmental implications. The public and environmental health implications reflect a critical global need for effective fecal sludge management and a crucial component of universal access to sanitation (USAID, 2018).

Faecal sludge comes from onsite sanitation technologies and is not transported through a sewer. It is raw or partially digested, slurry or semisolid, and results from collecting, storing, or treating excreta and blackwater, with or without greywater (Tayler, 2018). Examples of onsite technologies include pit latrines, non-sewered public ablution blocks, septic tanks, privies, and dry toilets (Tilley et al., 2008). Faecal sludge from a septic tank is called septage.

Faecal sludge management is a system approach towards building sustainable and environmentally safe infrastructure across all components of the sanitation value chain for non-networked households. FSM includes the storage, collection, transport, treatment, and safe end-use or disposal of FS and resource recovery (Strande et al., 2014). Therefore, a functioning FSM approach ensures that untreated fecal sludge is deposited, stored/ contained, and removed from the community hygienically and safely, does not remain at the household level, and treated, reused, or disposed of safely effectively.

1.1.3. Faecal sludge treatment and dewatering

The main objective of the FS treatment process is to ensure the protection of human and environmental health (Strande et al., 2014 and Tayler, 2018). It is noteworthy that the FS treatment goals are decided by the sludge's expected end or disposal purpose and by the end-use or release of liquid waste. The objectives of treatment systems for the environment and public health are met by

reducing pathogens, stabilizing organic materials and nutrients, and ensuring a safe end-use or disposal of treated end-products.

Faecal sludge dewatering is a vital treatment objective since FS contains a high proportion of moisture, and the reduction in this volume significantly reduces the expenses of transporting water weight. FS dewatering also simplifies subsequent treatment steps. The main objective of FS dewatering is to increase its solid content to the point at which it acts as a 'cake' and is treated as a solid (Tayler, 2018). Increased performance of FS dewatering subsequently reduces the amount of FS needed for transportation, reduces the required land area of FS treatment plants, and improves the potential for recovery of FS treatment products (Gold et al., 2018).

Although suitable for cities of low and middle-income countries, onsite sanitation systems remain poorly implemented, suffering from the inadequacy of specific scientific database data (Kodom et al., 2021). In addition, FS treatment is often neglected, just like the other FSM services (Philippe et al., 2016). There is a general lack of appropriate treatment and disposal facilities (Hawkins et al., 2014). There are relatively few examples of successful adoption and implementation of FSM models across the sanitation industry. The discussion is on properly managing the entire sanitation service chain and which stakeholders are ideally suited to the different roles.

Since sanitation decision-makers have only recently recognized onsite sanitation systems as long-term sustainable solutions, there has been relatively little research on fecal sludge treatment processes. In contrast, centralized treatment processes have over a century of research (Ward et al., 2019). Furthermore, several unknowns in the science of faecal sludge have led relevant authorities to manage fecal sludge-like wastewater, which is an incorrect approach due to the different nature of both waste streams, leading to major technical failures.

1.2. Problem Statement

While eliminating open defecation is the first step towards ensuring that everyone has safely managed sanitation services, improved FSM services play a vital role in managing public and environmental health for many years to come. Therefore, FSM is an essential and significant element of sanitation beyond the short-term capacity of most onsite-sanitation systems. FSM is an integral component of every sanitation plan, which builds on OSSs (UNICEF & WHO, 2020).

Globally, approximately 2.7 billion people rely on onsite sanitation and need the services of FSM (UNICEF & WHO, 2020). These populations consist of households and communities, mostly in urban areas that use latrines but do not have access to or cannot provide FSM services (USAID, 2018). If current sanitation trends continue, the number of people in need of FSM services will rise to 4.9 billion by 2030 (Philippe et al., 2016). This number could increase even faster as water scarcity becomes more severe and there is a shift away from water-intensive off-site sanitation systems, especially in African cities (Cairns-Smith et al., 2014).

Although sewer network systems are still the most preferred choice by most local authorities, such as in eThekwini Municipality, less than 10% of urban areas have sewers connections in low-income countries (Ward et al., 2019). Nonetheless, there have been substantial gains in formalizing FSM services for those with OSSs in low and middle-income countries due to the growing use and importance of onsite sanitation facilities (Strande et al., 2014).

There is still a broad knowledge and skills gap associated with FS and FSM. In terms of experience and research, FS and FSM are at least a century behind wastewater management (Philippe et al., 2016 and Strande et al., 2014). In addition, there is a shortage of information on FS characteristics affecting FS treatment processes such as dewatering and the correlation among various measurable properties. Little attention focuses on the characterization and estimation of FS quantities produced in various OSSs. Faecal sludge (FS) treatment presents a huge urban sanitation management challenge mainly due to the high variability of FS characteristics and high water content. The absence of a method to physically characterize faecal sludge has made objective and quantitative comparisons of the effectiveness of different technologies impossible, and comparisons made based on anecdotal evidence and personal preference (Radford & Sugden, 2014).

Besides the organic content and microorganisms, FS consists primarily of water proportions that depend on the type of onsite technology (Strande et al., 2014). Although the dewatering processes of wastewater treatment sludge are well understood, it is not clear how the dewatering of FS fits into the existing knowledge (Ward et al., 2019). Studies show that FS from septic tanks typically contains more than 95% water. In comparison, the FS collected from dry onsite sanitation (such as latrines and urine diversion dry toilets) contains 70-80% water content (Zuma et al., 2015) (Bakare et al., 2012). This water needs to be removed for efficient treatment and reuse of treated FS. However, the challenge lies in removing the water content within the FS to improve subsequent treatment

procedures and achieve overall treatment objectives. The challenge is further complicated by diminishing land spaces to set up traditional dewatering technologies (such as unplanted drying beds and planted drying beds) and the high energy costs associated with thermal drying.

Thus, the increasing number of onsite sanitation users, diminishing land space, and high energy costs call for efficiency in the entire FSM service chain. Before implementing management solutions, knowledge is needed to predict and improve the dewatering performance of FS and to increase the capacity of existing fecal sludge treatment plants (FSTPs) (Gold et al., 2016; Strande et al., 2018). Therefore, there is a need to understand moisture distribution or water boundness in faecal sludge and the characteristics affecting dewatering to inform the FS dewatering process, thus expediting the process and using available resources sparingly. Understanding faecal sludge dewatering and moisture boundness can optimize the performance of faecal sludge dewatering processes.

1.3. Objectives

1.3.1. Main objective

The main objective of this research project was to investigate the dewatering characteristics of faecal sludge in the context of faecal sludge water boundness.

1.3.2. Specific objectives

The specific objectives of this study were to:

i. Examine the evaluation indices of faecal sludge dewatering from different onsite sanitation systems.
ii. Evaluate the relation between sludge physical properties and faecal sludge settleability and filterability.

1.4. Research Questions

The study set out to answer the following research questions:

i. How do the faecal sludge dewatering evaluation indices of different onsite sanitation systems differ?
ii. What is the relationship between sludge physical properties and faecal sludge settleability and filterability?

1.5. Hypothesis

The following hypotheses apply in this study:

i. The evaluation indices of faecal sludge dewatering vary from one onsite sanitation system to another.
ii. There is a relationship between sludge physical properties and the settleability and filterability of faecal sludge.

1.6. Justification

The necessity of sludge dewatering is unquestionable and obvious. Usually, dewatering is the first line of defence for FS treatment. Proper design and thus the optimal operation of FS treatment facilities, to a great extent, rely on accurate knowledge of FS characteristics. Therefore, knowledge of FS quantities generated and their characteristics is inevitable (Doglas et al., 2021). Several factors influence the dewaterability of a sludge which can change the sludge characteristics before dewatering. Some of these characteristics are readily measured with equipment available at most sludge treatment facilities. In contrast, others are difficult or impossible for the plant operator to measure daily and can only be measured using advanced analytical techniques and equipment (Gumerman & Burris, 1982).

The selection of FS dewatering technologies depends on the type and characteristics of FS, space availability, and capital costs, among other factors (Tunçal & Uslu, 2014). It is pertinent to understand the dewaterability aspects of FS from sanitation facilitates such as pit latrines, septic tanks, and urine diversion toilets. The dewaterability characteristics of sewage sludge have been extensively published, but FS lacks the literature, yet the results are not transferable (Semiyaga et al., 2017). The dewatering process has to be fast to accommodate increasing volumes of FS generated from growing populations and increasing preference for onsite sanitation systems to cope with water scarcity.

Research on the quantification and comparison of FS dewatering performance from different countries and onsite sanitation technologies (Gold et al., 2018) shows that the dewatering rate is significantly different between FS from different technologies. Dewaterability, on the other hand, varies substantially within the same technology. Ward et al. (2019) recommend that the emerging FS dewatering research topic be approached in different ways and not solved with a direct transfer of

wastewater knowledge. Sludge dewatering from fields such as pulp and paper, sediment dredging, food science, and soil science could provide fresh insights for meeting the challenge of FS dewatering because FS behaves differently from wastewater sludges. Therefore, no one reference sludge can act as a proxy for faecal sludge.

An essential step in sludge treatment is sludge dewatering, primarily affected by the sludge moisture distribution (Jin et al., 2015). Unpredictable dewatering performance is a hindrance to effective faecal sludge management and treatment and thus a contributor to inaccessible sanitation services. Therefore, solutions for improved dewatering performance are needed to increase access to improved sanitation services and progress towards achieving the SDGs; by hastening .

1.7. Scope and Limitation of the Study

This study borrows on principles applied in sludge and soil science. The research study was restricted to the investigation of evaluation indices of faecal sludge samples collected from ventilated pit latrines (VIP), urine diversion dry toilets (UDDTs), and septic tanks (ST) and the sludge physical properties influence on dewatering. The samples used were collected from the different OSSs within the limits of Durban City (eThekwini Municipality).

1.8. Structure of the Research Thesis

This research study consists of five chapters.

Chapter One gives a broad introduction to key features of the study. It begins with a background overview of the evolution of sanitation systems throughout history, the different strategies for wastewater management, and an introduction to faecal sludge (FS) and faecal sludge management (FSM). It also presents the hypotheses and objectives for the study. Chapter Two presents and critically reviews the literature that is relevant to this study. The study identifies the gaps in knowledge and shows how this study plans to address them.

Chapter Three details the materials and methods used to test the hypotheses to achieve the objectives of this study set in chapter one. Chapter Four presents and discusses the laboratory results from analysed faecal sludge samples. Chapter Five summarises the major conclusions from this study and lists the recommendations for further research not covered by this study.

2. LITERATURE REVIEW

2.1. Onsite Sanitation Systems

By necessity or choice, many countries depend on 'onsite' sanitation facilities: systems "in which excreta and wastewater are collected, stored and treated on the plot where generated" (Greene et al., 2021). The onsite sanitation system is the most popular method in Africa, accounting for 60–100 % sanitation coverage in many African cities (AfWA, 2017). Even though over 70 distinct onsite systems are available, facilities for providing onsite sanitation services in Africa often take the form of simple traditional latrines, septic tanks, and Ventilated Improved Pit latrines (VIP) (Nansubuga et al., 2016).

Where space is limiting in peri-urban and slums, Ecological sanitation (EcoSan) facilities such as composting toilets and urine diversion and dehydrating toilets (UDDT) are necessary. EcoSan toilets are also a good sanitation option for shallow bedrock or high water tables where pit latrines are not viable (Moe & Rheingans, 2006). Ecological sanitation is a three-step process of containment, sanitization, and recycling of human excreta. The objective is to protect human and environmental health, reduce water usage in sanitation systems, and recycle nutrients to help reduce the need for artificial fertilizers in agriculture. Ecosan represents a conceptual shift in the relationship between people and the environment built on the vital link between people and soil. Ecosan systems contain pathogens and provide two ways to render human excreta innocuous: dehydration and decomposition (Austin, 2007). The preferred method depends on the climate, groundwater tables, amount of space, and intended purpose for the sanitized excreta (Nienhuys, 2012).

An effective onsite system can safely contain the excreta in a well-designed, well-constructed, well-maintained pit or tank without giving off unpleasant odours. The common feature in all onsite sanitation systems is the pit, vault, or tank that collects faeces, urine, anal cleansing material, and all other household waste disposed of by the users (WRC, 2007). The basic processes that occur include: filling with faeces, urine, water, and other material; water transfer into and out of the pit or tank; biological transformation; and pathogen deactivation.

After a specific time, depending on the user habits, the pit, vaults, and tank will fill up, and emptying will require. Shorter lifespans due to bad user habits increase maintenance costs should the desludging of containment be required.

2.1.1. Ventilated improved pit (VIP) latrines

VIP systems are dry sanitation technologies, hence not requiring water input. VIP latrines are an improvement on standard/basic pit latrines. Although it is clear that VIP toilets, when properly planned and built, provide an economical and practical sanitation alternative to most rural and peri-urban communities, there remains much ignorance regarding the proper engineering of VIP toilets. VIP latrines are built according to various designs and materials, with a corresponding diversity of performance and user acceptance (Gudda et al., 2019). Although some designs are of high quality, many toilets have been built that do not function correctly and are thus unpleasant to use. Fly control is often insufficient, and issues such as poor construction, excessive temperatures, and foul odors can all contribute to an unpleasant user experience and, as a result, opinions of the systems as second-rate or inferior (Bester & Austin, 1997).

Therefore, a VIP latrine must: provide separation of waste from the users in a hygienic manner; include a ventilation pipe with a fly screen at the top-end; must be constructed on a secure slab; and must be private and dignified for the user (Foxon & Buckley, 2008). A standard VIP latrine comprises a pit, cover slab, superstructure, vent pipe with fly screen, pedestal, lid, roof, and a superstructure door, as illustrated in Figure 1.

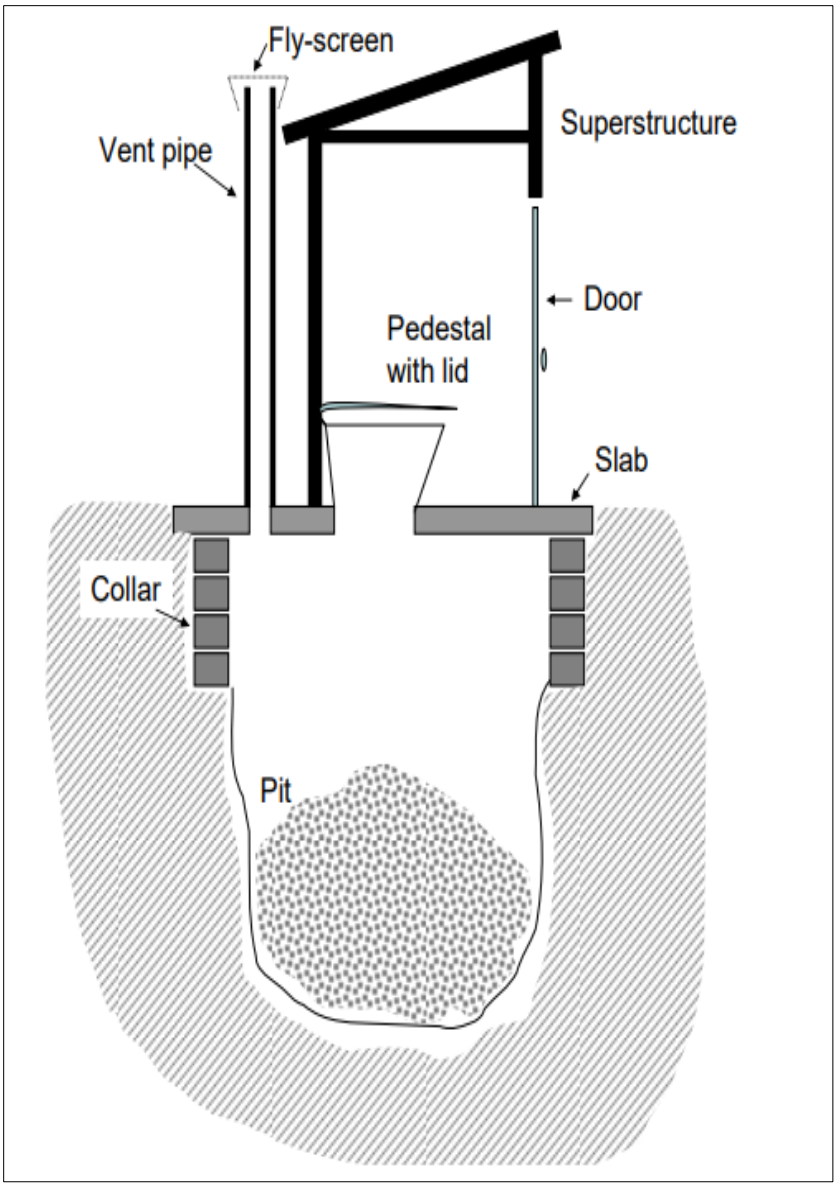

Figure 1: Basic structure of VIP

Source: Foxon & Buckley, (2008)

According to Foxon and Buckey (2008), the rate of degradation or leaching of the material in a pit should be similar to the filling rate; thus, the pit has a long service life. Pits may fill rapidly if a significant portion of the material added is non-degradable. Management of full VIP pits presents several challenges because households or communities with full pits have no difference from those without sanitation (Gudda et al., 2019). VIP users might opt to add pit latrine additives, abandon it, or hire desludging services once the pit is full (Foxon & Buckley, 2008; Appiah-Effah et al., 2020; and

Nansubuga et al., 2016). The additives are ineffective with subsequent negative environmental impact; desludging followed by proper treatment is recommended (Foxon & Buckley, 2008; and Appiah-Effah et al., 2020).

2.1.2. Urine diverting dry toilet (UDDT)

Urine-diverting dry toilets (UDDTs) is a dry excreta management system seen as a viable alternative to pit latrines and flush toilets (Rieck et al., 2013). A UDDT allows the source separation of urine and faeces through a specially designed user interface (Tilley et al., 2008) (Schönning, 2001). Urine diversion serves several essential functions, including reducing odour and simplifying the faecal sludge management process.

A UDDT (as illustrated in Figure 2) consists of eight essential functional elements: (i) A urine diversion toilet seat or squatting pan; (ii) One or two vaults, usually above ground, or one shallow pit for faeces collection and storage; (iii) A urine piping system leading from the user interface to an infiltration or collection system; (iv) A ventilation pipe to exhaust moisture and odours from the vault or pit; (v) An anal cleansing area with mechanisms for the separate collection and drainage of anal wash water, if required; (vi) A toilet super-structure unless the toilet is installed inside an existing house; (vii) A bucket with dry cover material; and (viii) A hand washing facility with soap and water (Tilley et al., 2008 and Rieck et al., 2013).

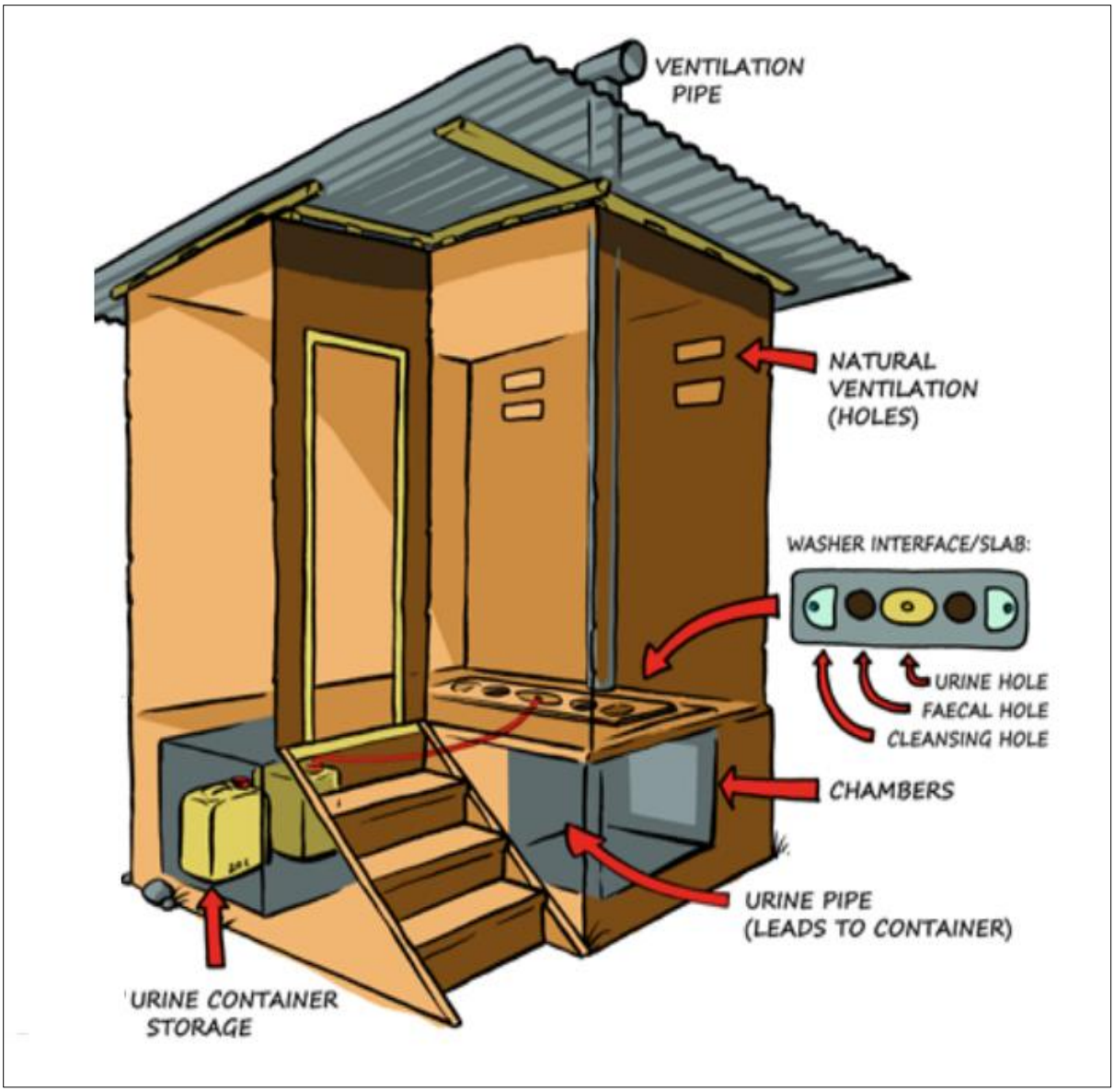

Figure 2: The principle of urine diversion dry toilet (UDDT)

Source: Global Dry Toilet Association of Finland (2017)

Urine separated at the user interface, drains through a piping system, infiltrates into the soil for disposal, or collects, stored, and sanitized in containers as a fertilizer. Faeces goes through a larger hole to a chamber below. There may be the third hole for washing. Following defecation, the user covers the fresh faeces with a small volume of dry cover material to absorb moisture, control initial odour and prevent insect infestation. The faeces vaults may be located above or below ground (Schönning, 2001).

According to Rieck et al. (2013), there are four distinct methods of UDDT faeces management, namely: Type 1- Faeces dehydration using double (two) dehydration vaults; Type 2- Faeces collection using a single vault with interchangeable containers with external treatment; Type 3 - Faeces mineralisation in shallow pits; and Type 4 - Faeces composting using dedicated containers. Most faeces management methods require the periodic removal of all faecal material from the toilet for disposal or reuse as an agricultural soil conditioner (a batch system). However, for shallow pit systems (Type 3) faecal matter can permanently remain in the soil, and no emptying is required (one example is the Arborloo)

The effectiveness of faeces management in most UDDTs relies on the faecal material remaining as dry as possible in the vault (Nienhuys, 2012). Dryness is by proper and diligent use of the user interface, preventing rainwater entry into the faeces vault, using adequate dry cover material, separating anal wash water, and the appropriate design of vault ventilation systems. The dehydration process in the faeces vaults will substantially reduce the faecal pathogen load, allowing the treated matter to be more safely handled.

Pathogens are primarily concentrated in human faeces and absent in the urine of healthy persons. When properly designed, built, and maintained, UDDTs can effectively contain pathogens from human contact and reduce the pathogen content in the faeces to enable reasonably safe handling of the faecal matter once the vaults need to be emptied. However, it is noted that a complete pathogen removal, including inactivation of all helminth eggs, cannot be guaranteed under ordinary circumstances with any UDDT (Schönning, 2001).

2.1.3. Septic tank systems (STS)

As illustrated in Figure 3, a septic tank is a watertight chamber built from concrete, fiberglass, PVC, or plastic. Blackwater and greywater flow into a septic tank system for primary domestic wastewater treatment from individual or small groups of dwellings in rural (and some peri-urban and urban) areas (Withers et al., 2014). The design of a septic tank is dependant on the number of users, the amount of water used per capita; the average annual temperature; the desludging frequency; and the characteristics of the wastewater.

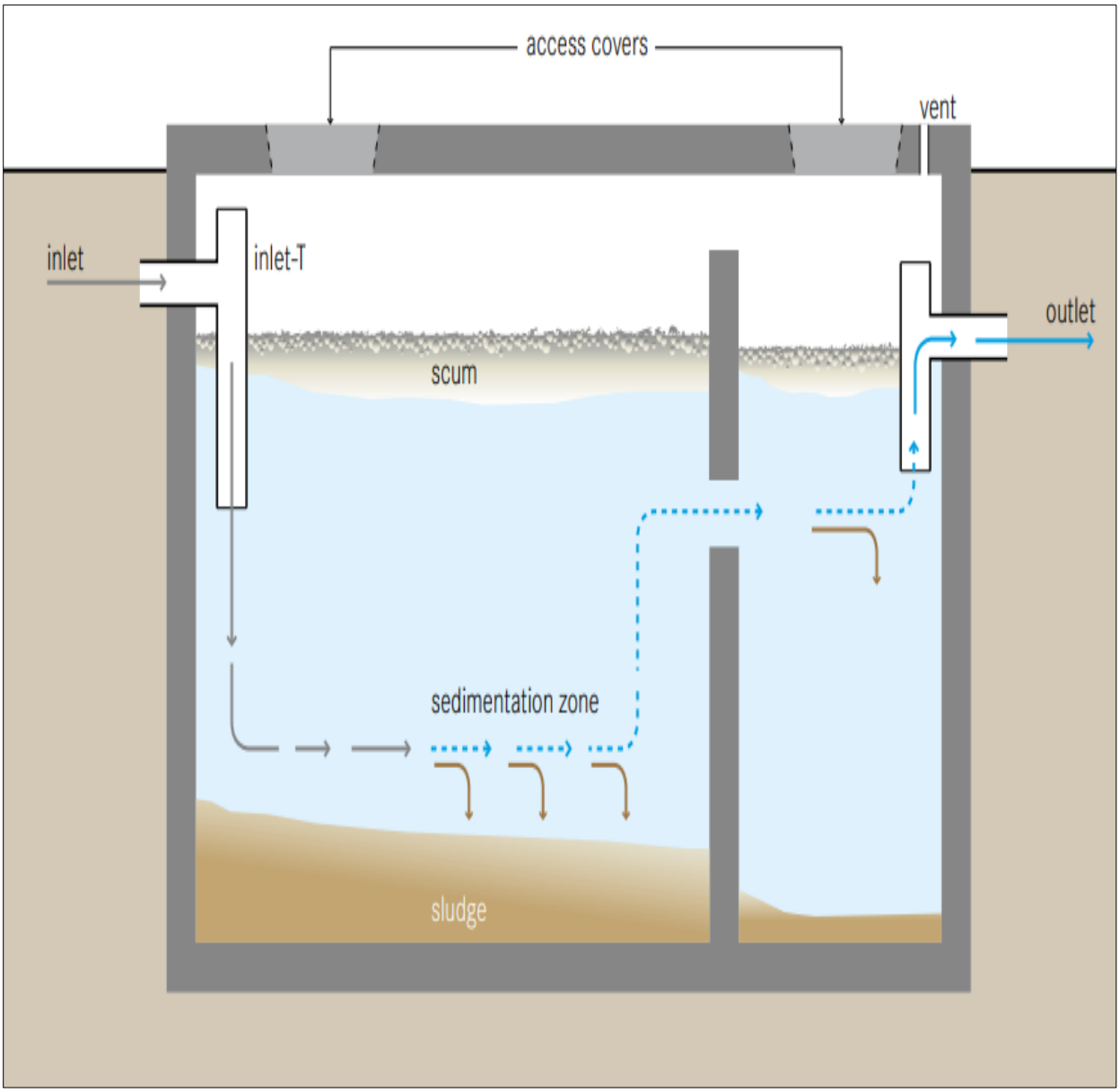

Figure 3: Septic Tank System

Source: Tilley et al., (2008)

Septic tank receives blackwater from pour-flush toilet and greywater which flows through the tank, and heavy particles sink to the bottom, while scum (mainly oil and grease) floats to the top. Over time, the solids that settle to the bottom are degraded anaerobically. However, the accumulation rate is faster than the decomposition rate, and the accumulated sludge and scum are periodically removed.

The septic tank's effluent is dispersed by a soak pit or leach field or transported to a treatment facility via a solids-free sewer.

Settling and anaerobic processes in septic tanks reduce solids and organics but have moderate treatment (Tilley et al., 2008 and Taweesan et al., 2015). As such, septic tank systems are one potential source of water pollution in headwater catchments and groundwater (Withers et al., 2014). Onsite infiltration from septic tanks is thus not recommended in densely populated areas (Tilley et al., 2008).

Due to limited space and technical know-how coupled with financial constraints and relaxed municipal regulations, home and property owners prefer to construct cesspools for onsite wastewater management, especially in developing countries (Hyeng et al., 2018). A cesspool is an underground pit that receives raw household wastewater and from which the wastewater seeps into the surrounding soil, and it may or may not be partially lined (Surinkul et al., 2017).

Cesspool walls are built from concrete, brick, or concrete blocks and poured concrete slab or timbers as a top cover. The sidewalls are perforated, allowing the effluent water to pass into the native soil while the solids build up in the pit. Therefore, unlike septic systems, a cesspool provides no raw sewage treatment, thereby discharging untreated human waste into the soil and ultimately contaminating the ground water (Abu-Rizaiza, 1999 and Surinkul et al., 2017).

2.2. Faecal Sludge Properties, Treatment, and Dewatering

2.2.1. Faecal sludge characterization

FS characteristics are very heterogeneous and vary depending on different factors (Bakare et al., 2012). These include (i) Environmental factors such as geographical and demographic location, climatic conditions, and the presence of groundwater; (ii) The type of onsite sanitation technology as well as its construction quality; (iii) The age of the sludge inside the storage compartment which is a factor of its filling rate; (iv) The toilet usage which is defined by the number of users and their diet, the frequency of usage, use of water in the system (dry or pour/flush), and the culture of toilet users (that is, wipers of washers); (v) The addition of additives into the toilet system such as ash; (vi) The disposal of trash and grey water into the toilet system; and (vii) The frequency and type of sludge collection (whether it is mechanized or manual).

According to the above factors, different types of faecal sludge can be distinguished depending on: (1) Type of onsite sanitation sources (pit latrine sludge from pit latrines, Septage from septic tanks, and Dry sludge from dry toilets (Semiyaga et al., 2015); (2) Age and storage of the first treatment (Stabilized or digested sludge, Semi-digested sludge, and Fresh sludge); and (3) The use of water in the system (Wet sludge and Dry sludge).

Human excreta are a biological hazard, thus understanding their properties and characteristics are necessary to reduce their potency and treat them efficiently. Analysed FS characteristics are currently grouped into four properties detailed in Table 1; physical and mechanical properties, chemical and physico-chemical properties, thermal properties, and biological properties (Velkushanova et al., 2021). Physical properties do not change the chemical composition of a material. Examples of physical properties are density and particle size (Septien et al., 2018). Mechanical properties are the physical properties measured by the application of force. These include shear strength, viscosity, and plasticity. Chemical properties of FS change as a result of chemical reactions, while physico-chemical properties depend on both physical and chemical processes and are determined by the interactions of components within faecal sludge (Niwagaba et al., 2014; Zuma et al., 2015).

Biological examinations of faecal sludge samples are essential along the entire service chain since the other properties create a habitat for many organisms. Biological activities related to the production and consumption of organic matter, or respiration, are investigated under the physico-chemical. Additional analytical methods for biological examinations include: identifying pathogens (virus, bacteria, protozoa, helminths), metrics of toxicity (use of bioassays), enumeration (plate 38 counts, flow cytometry, MPN), and types and functions of organisms (DNA/RNA analysis) (Velkushanova et al., 2021).

Table 1: Faecal sludge properties

FS Properties	Characteristics	Purpose for analysis
Physio-chemical properties	Moisture content Total dry solids	To assess the mechanical behaviour influencing FS's mixing, drying, flowing, viscosity, and combustion. To predict the migration of pathogens. To assess FS biodegradation potential.
	Total volatile solids Ash content (fixed solids)	To show the ratio of organic solids in FS that will change over time and FS's combustion potential and biodegradability potential.
	Total suspended solids	To get an indication of the potential settling and clogging for ease of pit emptying and processing at an FS treatment plant.
	COD total	To get an indication of the organic content and the biodegradability rate of the sludge.
	pH	Monitor and regulate pH as it affects the rate of degradation of the FS and the sanitizing effects of ammonia. To get an indication of the corrosive effects on pit emptying and sludge treatment devices.
	TKN (Total Kjeldahl Nitrogen), K (Potassium), Phosphates, Total phosphate, Orthophosphate, Ammonia	To assess the potential of nutrient recovery from treated FS. To assess the level of final disinfection of treated sludge.
Physical and mechanical properties	Density (solids, dry, bulk) Particle size distribution	For the pit emptying equipment and mechanical process design recommendation.
	Sludge volume index (SVI)	To estimate settling characteristics of sludge, pit emptying, and processing.
	Osmotic pressure	To estimate vapour pressure and the success of FS membrane processing.

	Rheological properties, Sludge penetration resistance	To recommend design parameters for pit emptying equipment, extruders, and mechanical treatment.
Thermal properties	Thermal conductivity, Specific heat, Calorific value	To recommend drying, combusting, heating potential, and thermal treatment equipment design.
Biological properties	Parasites content (for example, Ascaris), Pathogens (for example, E. coli)	To identify potential biohazards and the need for pre-treatment before reuse of treated FS.

2.2.2. Faecal sludge treatment and dewatering

Faecal sludge has the potential to be a valuable resource, provided that it is subjected to a suitable treatment (Septien et al., 2018). The primary objective of FS treatment is to render it safe for either reuse or disposal to the environment (Tayler, 2018). FS treatment processes aim to do this by 'stabilizing' faecal waste, converting it from its untreated condition. Untreated faecal sludge is unpleasant, unstable, high in pathogens, and has a high oxygen demand. Treated faecal sludge is a stable product that is low in pathogens and oxygen demand. Most faecal sludge treatment processes produce a liquid effluent and a sludge residue. Among the specific treatment objectives are reducing the faecal sludge water content to the point at which the sludge acts as a solid, is much reduced in volume, and is easier and cheaper to handle and transport (Strande et al., 2014).

There are various wastewater and wastewater sludge dewatering and drying methods and technologies. Stefanakis et al. (2014) give an overview of the methods and technologies that include: (i) Mechanical dewatering by vacuum filters, gravity belt thickening, filter belt press, gravity thickening, centrifuge, and membrane press; (ii) Direct drying by rotating drums, lamps, belt dryers, spray dryers, and solar energy dewatering systems; (iii) Indirect drying by rotary plate indirect dryer, kneading and self-cleaning disc dryer, porcupine processor, and paddle dryer; (iv) Fluidized bed dryers; (v) Combination of drying and incineration; and (vi) Drying sand beds.

Dewatering of FS is a vital treatment objective. FS contains a high proportion of liquid whose volume reduction greatly reduces the cost of transporting water weight and simplifies subsequent treatment

steps (Semiyaga et al., 2017 and Septien et al., 2018). Although many FS treatment technologies are based on those developed for wastewater and wastewater sludge treatment, these technologies are not directly transferred because FS characteristics differ significantly from wastewater and directly impact the efficiency of treatment mechanisms (Ward et al., 2019).

Faecal sludge treatment processes are based on physical, biological, and chemical mechanisms (Strande et al., 2014). Physical mechanisms are generally considered robust and are the most widely employed mechanisms in current FS treatment methodologies. They include dewatering, drying, and volume reduction. FS dewatering is based on physical processes such as evaporation, evapotranspiration, filtration, gravity, surface charge attraction, centrifugal force, and pressure.

Gravity and filtration are the most commonly employed liquid-solid separation methods in FSM and achieve the separation of suspended particles and unbound water (Strande et al., 2014). Particles heavier than water settle out under gravity quiescent conditions at rates based on particle size, suspended solids concentration, and flocculation. Although several filtration media, such as membrane and granular, and types (for example, slow, rapid, gravity-driven, or pressurised) are applied to water, wastewater, and treated sludge (biosolids) processing; in FSM, the most common types are unplanted and planted drying beds. The beds use filter media to trap solids on the surface of the filter bed, as the liquid percolates through the filter bed and collects in a drain or evaporates from the solids.

2.3. Faecal sludge water boundness and dewatering

The water in sludges is in various forms and affects the dewatering process (Rowe & Abdel-Magid, 1995). Since FS is 70-95% water, dewatering presents an essential first step of treating it effectively (Semiyaga et al., 2017). Dewatering techniques apply evaporation, sedimentation, filtration (by vacuum or pressure), and centrifugation principles (Rowe & Abdel-Magid, 1995).

Dewatering performance is a function of sludge dewatering rate and dewaterability values (Gold et al., 2018). For sludge cakes, dewaterability indicates the final water content or the full solid content that may be achieved (To et al., 2016). According to (Dick et al., 1980), dewaterability is affected by: fluid properties such as viscosity, ionic strength, density, and bound water; sludge particle properties like particle size and shape distribution, surface area; and finally, sludge properties such as suspended solids (SS) concentration, permeability, yield strength, pH and electrokinetic. Sludge characteristics

and their inter-relationships significantly affect dewatering (Gumerman & Burris, 1982). The characteristics of sludges and the nature of the dewatering device are essential in determining the amount and rate of water removal (Novak, 2006).

All factors that impact dewatering are related to forcing sludge solids closer together or the difficulty of water movement through the pores between the sludge solids in general. Intermolecular forces of different types are responsible for water bonding to sludge solids. Andreoli et al. (2007) provide four distinct classes of water occurrence in sludge listed according to the ease of separation: free water (or bulk water); adsorbed water; capillary water; and cellular water. The sludge water content influences the mechanical properties, which affects the handling processes and the final disposal of the sludge (Von Sperling, 2007). Table 2 illustrates the relationship between the water content and the mechanical properties in most forms of sludges.

Table 2: Relationship between the water content and the mechanical properties in sludge

Water content	Dry-solids content	Mechanical properties of sludge
100% to 75%	0% to 25%	Fluid sludge
75% to 65%	25% to 35%	Semi-solid cake
65% to 40%	35% to 60%	Hard solid
40% to 15%	60% to 85%	Sludge in granules
15% to 0%	85% to 100%	Sludge disintegrating into a fine powder

Source: Von Sperling, (2007)

The ratio of free to bound water influence the dewatering approach (Von Sperling, 2007). Most of the water in FS is free (also known as bulk water) and is not bound to the solids contained in the sludge (Tayler, 2018). The smaller bound water component includes interstitial water, colloidal or vicinal water, and intracellular water or water of hydration (Vesilind, 1994, Andreoli et al., 2007; and Franceschini, 2010). Interstitial waster is found in the pore spaces between solid particles and bound to those particles by capillary forces. Colloidal or vicinal water is located on the surfaces of solids and bound to those solids by adsorption and adhesion. Finally, intracellular water or water of hydration is contained within microorganism cells and thus impossible to remove except by mechanisms that break down those microorganisms.

The easiest water to remove is bulk water. Gravitational action (floatation or drainage) or mechanical dewatering (settling and filtration mechanisms) removes bulk water. Nonetheless, most dewatering processes remove both bulk water and interstitial water from sludge. Removal of bound water requires some combination of chemical dosing, centrifugation, pressure, and evaporation. The drying test measures bound water content because it is more resistant to evaporation (Lee et al., 2006). The release of interstitial water trapped within the flocs is only by either the destruction or compression of floc structures using sufficient mechanical energy to take the water out. Vicinal water requires prior conditioning for mechanical removal.

Similarly, mechanical dewatering cannot remove the water of hydration that is chemically bound to the solids. It is interesting to know precisely how much vicinal water and water of hydration exists in a given sludge because this represents the limit of mechanical dewatering (Vesilind, 1994). Information of moisture distribution within sludge and understanding the bond strength (boundedness) of the moisture to the solid are vital for selecting optimal dewatering and drying methods (Getahun et al., 2020).

Common methods for the dewatering of FS include gravity settling and drying beds based on evaporation/evapotranspiration (Niwagaba et al., 2014). FS dewatering characteristics differ from wastewater sludge in that it tends to foam upon agitation and resist settling and dewatering. FS's age and storage duration also affect its dewatering; older, more stabilized FS dewaters easily than fresh or raw FS. The dewatering can also include adding dry materials such as sawdust to increase the solids' content. It is worth noting that further treatment is required for effluent produced during dewatering as it can be high in ammonia, salts, and pathogens.

2.4. Dewatering Performance

2.4.1. Evaluation indices of sludge dewatering

One of sludge dewatering's most bothersome aspects is that there seem to be no accepted means to evaluate the ease with which a sludge will release its water (Visilind, 1988). However, several classical methods have been used to evaluate sludge dewatering processes (To et al., 2016). Most of these methods and tests are simple but empirical and shed light on dewaterability mechanisms that could be described mathematically (Scholz, 2005). These include sludge volume index (SVI), specific

resistance to filtration (SRF), centrifugability, and capillary suction time (CST). These methods are particular to each dewatering process, such as settling, filtration, and centrifugation (To et al., 2016).

2.4.1.1.Settleability

The quantitative measure of the settleability of wastewater and sludge can be obtained from several parameters. The sludge settleability parameters (SSPs) are based on the volume occupied by sludge after a fixed settling period. Among these, the Sludge Volume Index (SVI) is the most known. Where a sludge sample is too thick or too dark such that the settled sludge volume level is unreadable, a diluted sludge volume index (DSVI) is used to measure the sludge settleability. The DSVI is insensitive to the sludge concentration, allowing for a consistent comparison of sludge settleability between different sludge samples (Torfs et al., 2016).

The sludge volume index (SVI) describes the volume (in mL) occupied by 1 g of sludge after settling in a 1 L cylinder for 30 min (Dick & Vesilind, 1969) (Torfs et al., 2016). Although SVI is not supported theoretically, experience has shown to be helpful in routine process control (APHA, 2017). The SVI is a simple and inexpensive tool for the day-to-day measurement of sludge settleability. A sludge with an SVI less than 100 ml/g is a well-settling sludge, whereas an SVI greater than 100 is often troublesome (Samhan et al., 1990). SVI is commonly used in research applications to evaluate the effect of biological variables or physical or chemical treatment on sludge properties.

However, the most common parameter use has been the monitoring waste treatment plant operation and comparing the settling characteristics of various sludge. Although the SVI test is helpful as an operational tool for in-plant control, Dick & Vesilind (1969) pointed that the comparisons of SVI measurements from multiple plants are not meaningful. Sludge characteristics influencing the SVI include suspended solids concentration, rheological characteristics, interface velocity, and temperature (Dick & Vesilind, 1969). Other factors are cylinder diameter, initial depth, and stirring. Other more readily measured sludge settleability parameters include stirred specific volume index (SSVI), stirred specific volume index at 3.5 g/l ($SSVI_{3.5}$), and diluted sludge volume index (DSVI) (Bye & Dold, 1998).

2.4.1.2.Filterability

The classical parameter used to evaluate sludge filterability is the specific resistance to filtration (SRF), representing the resistance offered to filtration by a cake deposited on the filter medium

having a unit dry solids weight (Spinosa, 1985). SRF is the first widely used sludge characterization technique based on an analysis of pressure drop for flow through a porous medium using the Darcy equation. The resulting sludge characterization parameter is related to permeability and sludge filterability (Agerbrek & Keiding, 1993). A low value of SRF is desirable because sludge with a high value is challenging to dewater by filtration-based methods. The SRF measurement also provides some scalar information on the expected filtration rate but only at the pressure associated with the test (Scales et al., 2004).

Although methods for determining SRF are well known, the test conditions are often not wholly defined, such as attributing the resistance to the solids alone and not the filter medium (Spinosa, 1985). Although authors agree on the apparatus set up for the SRF test (illustrated in Figure 4), there is no agreement on neither the number of filter papers and specification, the vacuum pressure to be applied, and the time to filter. The apparatus resistance is usually considered insignificant compared to the sludge resistance (IWPC, 1981; Agerbrek & Keiding, 1993; Jimmy et al., 1993; and Rowe & Abdel-Magid, 1995).

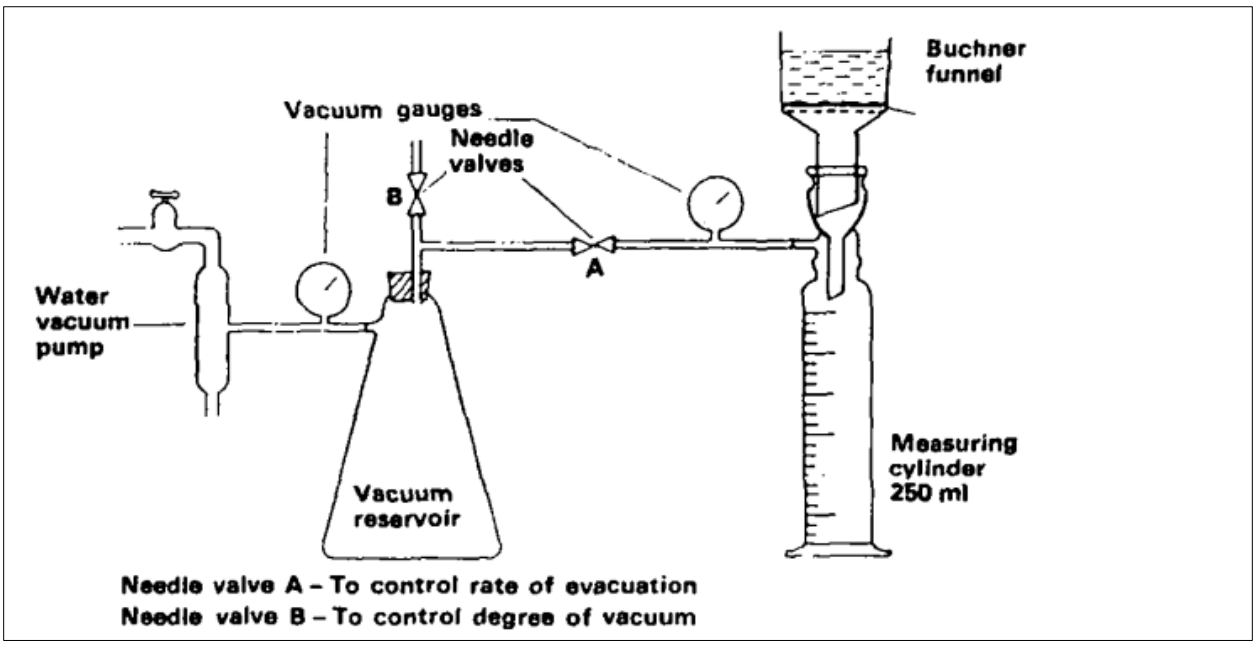

Figure 4: Simplified apparatus for determining specific resistance to filtration

Source: IWPC (1981)

2.4.1.3.Centrifugability

Centrifugability is sludge aptitude to dewater under the action of the centrifugal force (Spinosa, 1985). In the first stage, the sludge particles settle at a velocity much higher than would occur under the action of gravity. In a second stage, compaction occurs when the sludge loses part of the capillary water under the prolonged action of centrifugation (Von Sperling, 2007). Centrifugability is a function of centrifugal settleability and compactivity available for characterizing sludge behaviour in centrifuges (Spinosa, 1985). Therefore, the sludge characteristics affecting centrifugability are settleability and floc strength (Spinosa, 1985). Unfortunately, a parameter for assessing sludge centrifugability is not defined because it has not been possible to reproduce the conditions occurring in a full-scale centrifuge (Samhan et al., 1990).

Centrifuges may be used indistinctly for sludge thickening and dewatering (Andreoli et al., 2007). Centrifuges (either solid bowl, disc, or basket type) separate solids from the liquid through sedimentation (Stoke's frictional forces) and centrifugal force to increase the settling rate of sludge solids (Abdel-Magid et al., 1997). Centrifuges separate the sludge into dewatered sludge cakes and clarified liquid, which is called centrate or supernatant. The essential process variables for industrial sludge centrifugation are (i) feed rate, (ii) sludge solids characteristics, (iii) feed consistency, (iv) temperature, and (v) chemical additives. Machine variables are (i) bowl design, (ii) bowl speed, (iii) pool volume, and (iv) conveyor speed. Cake or pellet dryness and solids recovery usually determine the success or failure of centrifugation (Cheremisinoff, 2001).

In centrifuge dewatering, centrifugal force accelerates the separation of solid and liquid phases of the liquid sludge stream. The process involves clarification of the sludge and its compaction. The main advantages of this technology include the fact that solid-liquid separation takes place in complete isolation from the outside. The machine can also be relatively small, versatile, and simple to operate (Abdel-Magid et al., 1997).

The mechanism of solid/liquid separation is similar to sedimentation, but solids are subjected to forces many times greater than gravity. However, it is difficult to define a parameter for assessing the sludge suitability for centrifugation in a laboratory test. Thus, it is impossible to reproduce all the conditions occurring in an industrial centrifuge (Canziani & Spinosa, 2019).

Cheremisinoff (2001) lists two factors that usually determine the success and failure of centrifugation as (i) cake dryness and (ii) solids recovery. For increased sludge cake dryness in industrial sludge centrifugation, a recommendation is made to (i) increase the bowl speed, feed rate, and temperatures, (ii) decrease pool volume, the conveyor speed, and feed consistency, and (iii) to avoid the use of flocculants. For increased solids recovery, it is recommended to (i) increase the bowl speed, pool volume, temperatures, and feed consistency, (ii) decrease conveyor speed and feed rate, and (iii) use flocculants.

2.4.1.4.Capillary suction time (CST)

The capillary suction time (CST), illustrated in Figure 5, is a simple and precise measurement of water release rate from a sludge matrix (Scholz, 2005). CST is the time required for a specific filtrate volume to draw out of the sludge and be sucked into the blotter paper by capillary force (To et al., 2016). Sludge that releases water quickly has a low CST and vice versa. CST is affected by solids concentration, unlike SRF. According to Visilind (1988), a comparison between CST of different sludge types from various wastewater treatment plants is not meaningful . Thus, although the method is a fast way to evaluate filterability, CST is not a universal parameter in a strict sense but a comparative tool for use with specific sludge and test apparatus (Gray, 2015).

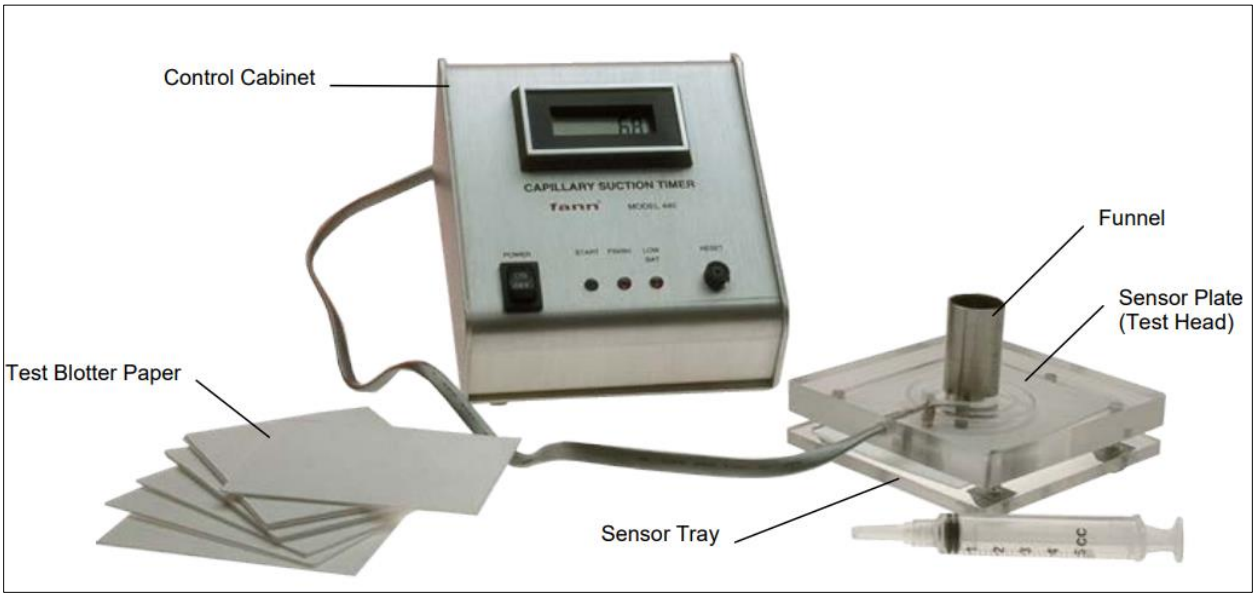

Figure 5: Capillary suction timer

Source: Fann Instrument Company, (2013)

2.4.2. Sludge properties affecting dewatering

Sludge behaves similarly to soils and other porous media in that sludge retains water. Water retention in soil science refers to a soil's ability to retain moisture against the pull of gravity because of its colloidal properties and aggregation qualities (Kodesová, 2003 and Indoria et al., 2020). The water is held within the pores and on the surface of the colloids and other particles by adhesion and cohesion forces, surface tension, or polarity. Water retention is a critical function constituting hydraulic properties of soils and other porous media (Ruiz & Medina, 2004 and Sadeghi et al., 2018).

Hydraulic properties in porous media such as soil are influenced mainly by various inherent measurable characteristics, namely: particle size distribution (PSD), bulk density (BD), porosity, and pore size distribution (Durner & Lipsius, 2005) (Mishra et al., 1989) (Schaap, 2005). Particle size distribution (PSD) is a porous medium's most fundamental physical property and defines its texture, thus affecting water-holding capacity and permeability characteristics. The bulk density (BD) is defined as its dry mass per unit of volume in a moist state. The characteristics of each element (individual and combined particles' arrangements) in a media contribute to the medium's total BD. Media components that differ significantly in particle size have higher BDs, lower total porosity (TP), and water holding capacity than media with similar particle sizes.

Lastly, the porosity of a porous media is the fraction of the bulk volume of the porous material sample occupied by pores or void space. Porosity is related to particles' shape, size, and arrangement and may vary from zero to almost unity. There are two kinds of pore or void space, one that forms a continuous phase and isolated or non-interconnected pores or voids. The interconnected pore space can significantly transport moisture and gases across the porous medium and define its effective pore space or porosity. Pore size distribution thus affects capillarity and capillary flow, an essential phenomenon of water retention in porous media.

Knowledge of density is critical to wastewater treatment and sludge management operations units. Density indicates the content of low-density components such as grease and fats, which, in turn, affect the stability of sludge and the sludge volume, hence, transport costs. In addition, density also affects sludge fluid-dynamic behaviour (Canziani & Spinosa, 2019). Density is essential in converting concentrations between weight/volume and weight/weight. Density measurement is necessary, especially when the faecal sludge to be analysed spans a range of sludge types (Velkushanova et al., 2021).

Particle size distribution (PSD), bulk density (BD), porosity, and pore size distribution values define the hydraulic properties of soil and porous media and influence dewatering indices values of municipal and industrial wastewater. However, the effects of the particle size distribution (PSD), bulk density (BD), porosity, and pore size distribution on faecal sludge dewatering are unknown.

Based on this literature review and theoretical background, the objectives of this study thus set out to add onto the knowledge of faecal sludge dewatering by comparing the dewatering of faecal sludge from different OSS; and the effect of FS physical properties on dewatering.

3. MATERIALS AND METHODS

3.1. Research Context and Setting

This study was conducted within the eThekwini Municipality. EThekwini is located on the east coast of South Africa in the Province of KwaZulu-Natal (KZN) as shown in Figure 7. KwaZulu-Natal is divided into one metropolitan municipality (eThekwini Metropolitan Municipality) and 10 district municipalities, which are further subdivided into 43 local municipalities. The area of eThekwini Municipality, the local authority of Durban, is approximately 2 297 km^2, with an estimated population of 3.44 million.

The eThekwini Municipality has a wide range of land uses, including formal and informal, urban and rural settlements, complemented by economic, transport, public and social infrastructure. Other prevalent land uses include agriculture, traditional settlement, and designated metropolitan open space systems. About 68% of the Municipal area is considered rural, with pockets of dense settlement. About 10 % of the rural areas comprise commercial farms and metropolitan open space. About 90% of the rural area is hilly, rugged terrain, dispersed settlement patterns in traditional dwellings, and communal land holdings. The remainder of the municipal area, approximately 32%, is urban and is dominated by residential, commercial/office, and industrial land uses. The economic land uses, located closer to the road-highways, are unevenly distributed throughout the Municipality and separated from the higher density residential uses (Ethekwini Municipality, 2017).

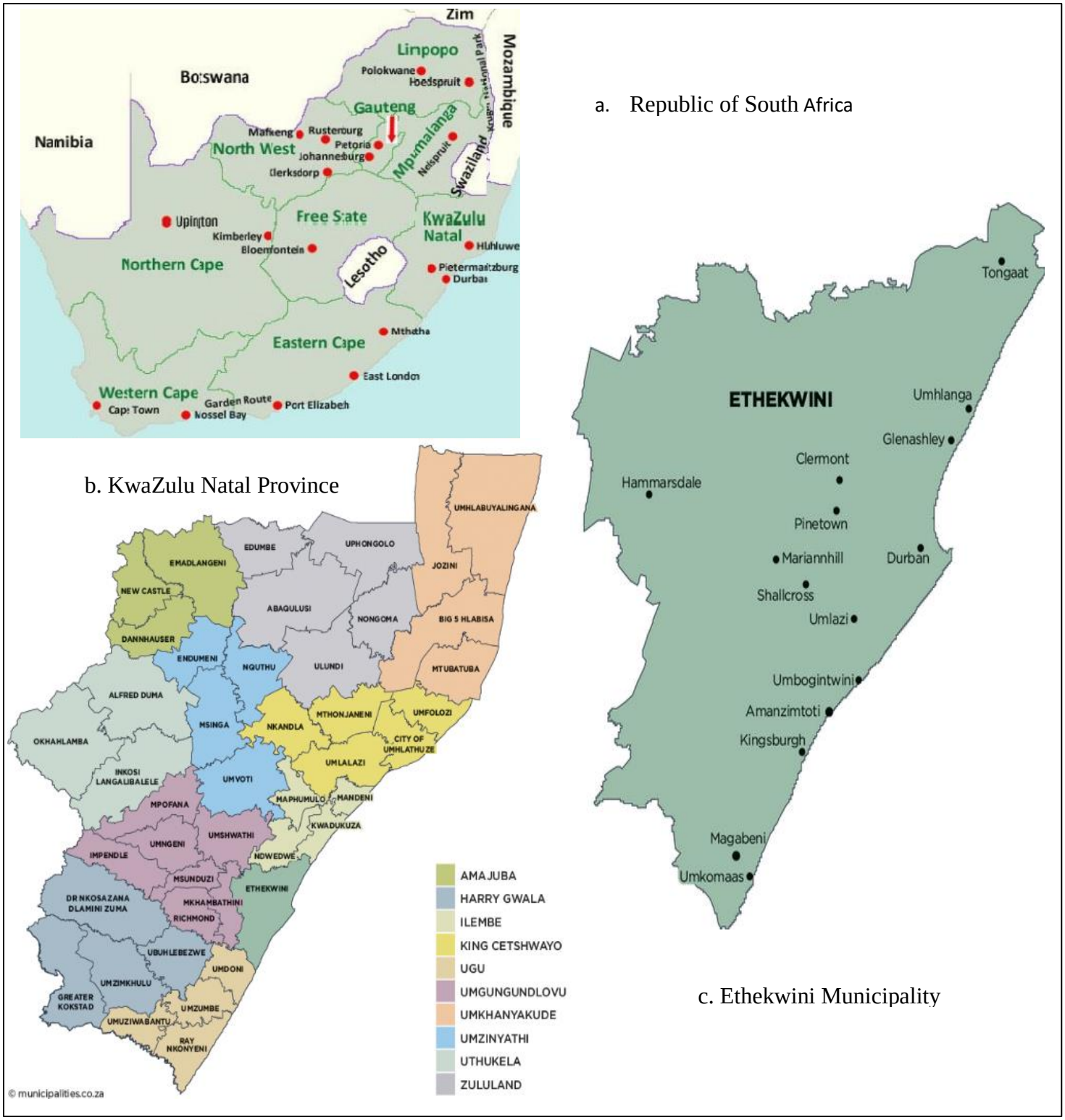

Figure 6: Map of the study area

Source: Ethekwini Municipality, (2017)

EThekwini Municipality Water and Sanitation (EWS) owns and operates 27 wastewater treatment works (WWTW's) that treat approximately 500 million litres of wastewater per day, collected and conveyed through a network of 8105km of sewer pipelines. This infrastructure spreads over the four eThekwini regions, namely South, North, Central, and Outer West, with most of the infrastructure concentrated in the Central Region, the southern portion of the North Region, and the northern boundary of the South Region.

The outer peri-urban and rural areas have onsite sewage disposal. The urine diversion toilets (UDDT) are the Municipality's preferred method of sanitation in rural areas. Sanitation for informal settlements is by a communal ablution block that provides toilets, showers, and clothes washing facilities and connects to the municipal sewerage system or an alternative system such as a septic tank. Where no such connection is available or provided, sanitation is by a toilet block consisting of VIP toilets and urinals only with no water supply provided to the toilet. By 2019, the Municipality had installed approximately 85000 onsite sanitation systems. The Municipality also offers faecal sludge emptying and treatment services to communities with onsite sanitation systems.

3.2. Description of the Faecal Sludge Samples

The study analysed FS from VIP latrines, UDDT latrines, and septic tanks. The samples were obtained from two VIPs (VIP1 and VIP2), two UDDTs (UDDT1 and UDDT2), and two septic tanks (ST1 and ST2) during containment emptying within the eThekwini municipality (KwaZulu-Natal, South Africa) by the University of Kwa-Zulu Natal (UKZN) WASH R&D Centre research team. According to the eThekwini municipality, usually, VIP pits are emptied every five years while the UDDT vaults are emptied every two years (Zuma et al., and Geetahum et al., 2020).

All samples were collected in 10L buckets with covers, transported, and kept at 4 °C in the WASH R&D Centre laboratory cold room to limit sample deterioration and moisture loss. The sampling and handling of the faecal sludge followed the standard operating procedure (SOP) presented in Chapter 3 of the Methods for Faecal Sludge Analysis (Velkushanova et al., 2021).

The sampled faecal sludge did not receive any preliminary treatment after collection; for this reason, the received sludge contained many extraneous objects (plastics, textiles, hygiene products, paper, metals, wood, twigs, and hair), gravels, and sand, as shown in Figure 8. The solid trash was thus removed before experimentation, as shown in the figure below.

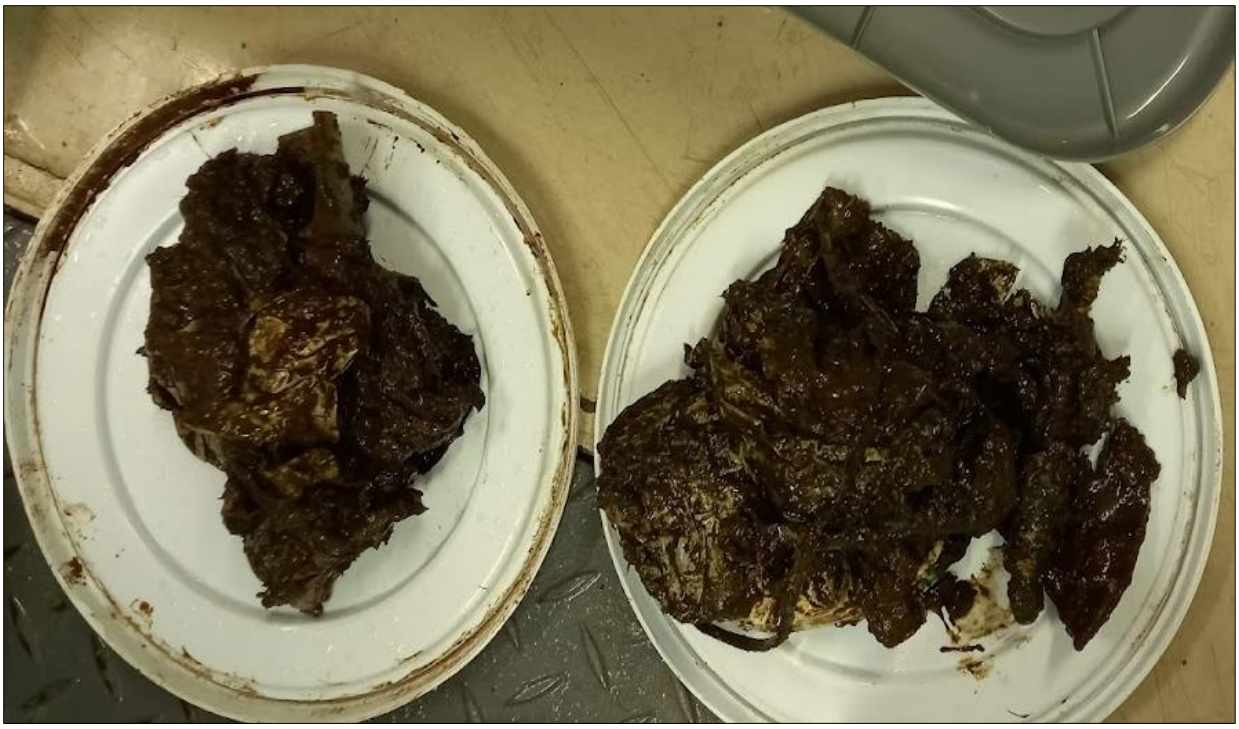

Figure 7: Trash in faecal sludge

The samples had been in storage for between 5 to 6 months before this study analysis. The assumption was that there would not be any reactions between sampling, storage, and sample analysis. The samples were also assumed to represent the entire containment as sampling was conducted at different points inside the containment (for VIP and UDDT samples). Before testing, the samples were taken from the cold room and left to attain room temperature.

General physiochemical properties of the faecal sludge, such as moisture content and total solids content, were also measured in triplicate as part of initial sample characterization as illustrated in Methods for Faecal Sludge Analysis Velkushanova et al. (2021). Table 3 below describes the samples collected.

Table 3: Sample description

Characteristic of Faecal sludge	Type of onsite sanitation facility					
	VIP		UDDT		SEPTIC TANK	
	VIP1	VIP2	UDDT1	UDDT2	ST1	ST2
Date of sampling	24th Feb, 2021	24th Feb, 2021	17th Feb, 2021	17th Feb, 2021	17th Feb, 2021	17th Feb, 2021
Colour of the sample	Black/ Brown	Black/ Brown	Brown/ Green	Brown/ Green	Black	Black
Odour of the sample	Strong	Strong	Very strong	Very strong	Fairly strong	Fairly strong
Presence of trash	A large amount of trash	A large amount of trash	Medium amount of trash	Medium amount of trash	Small amounts of trash	Small amounts of trash
Mean moisture content of the sample (%wt	80.3	73.1	78.3	68.9	98.1	99.0
Mean total solids of the sample (%wt)	20.8	26.8	21.3	28.6	1.2	0.9

3.3. Experimental Methods and Laboratory Analysis

The samples were subjected to two types of analysis: (a) physical characterization and (b) dewaterability. The physical characterization analysis entailed the determination of the samples' density, porosity, and particle distribution tests. The traditional sludge volume index (SVI), specific resistance to filtration (SRF), and centrifugation tests were performed to assess fecal sludge samples' settleability, filterability, and centrifugability.

The experimental procedures were adapted from different fields, including water and wastewater treatment, sludge treatment, and soil science. These testing procedures have been detailed and reproduced in Appendix A. In addition, a Pearson correlation analysis was also conducted between the sludge physical properties (density, porosity and PSD) and settleability and filterability values. The following coefficients were used to evaluate the strength of the relationship; 0-0.1 represented no

relation, 0.1- 0.39 represented a weak relation, 0.4- 0.69 represented a moderate relation, and 0.7 and above described a strong relation.

3.3.1. Physical characterization analysis

3.3.1.1. Density and porosity

In this study, different methods were selected to suit the diverse nature of the samples.

The bulk density of septic tank septage was measured in duplicates for each septic tank. The procedure followed the displacement technique adapted from Methods for Faecal Sludge Analysis Velkushanova et al. (2021) and reproduced in Appendix A. During the test, 10mL of septage was dried in an oven at 105ºC for 24 hours. For this procedure, porcelain crucibles were used. A crucible is initially weighted on an analytical balance with four decimals. The septage sample was added and the sample + crucible were weighted. After the 24 hours oven-drying, the dried septage sample + crucible were weighed and the mass recorded in grams (g).

The bulk density of VIP and UDDT sludge was measured by the core method where, the original sample was placed into a core of known volume and mass and weighed. The weight of the sample divided by the core volume gives the sample's bulk density (Dbwet). To find the solid density/ particle density (Dbdry): (i) 500g of faecal sludge was weighed in an aluminium dish and placed in a pre-heated oven for 24hrs drying at 105°C. (ii) The dried sample was cooled in a desiccator for 15 minutes followed by crushing and grinding to fine particles using a pestle and motor. (iii) A core of known volume and mass was filled in layers with grounded faecal sludge and compacted after every layer to remove air spaces and weighed. (iv) The weight of the dried sample divided by the core volume gives the sample's solid density/ particle density (Dbdry). The procedure was repeated for the remaining samples.

3.3.1.2.Particle size distribution (PSD)

The particle composition of any sludge is one of the essential characteristics. Since many factors determine the composition of faecal sludge in a containment system, many small particles and fibrous substances are present. Therefore, the traditional screening test is challenging to evaluate the particle size distribution.

In this study, particle analysis was performed on all the samples in duplicate. PSD of the samples was measured by the Malvern Mastersizer 3000 (Figures 8 and 9) following the standard operating procedures described in Methods for Faecal Sludge Analysis Velkushanova et al. (2021) and reproduced in Appendix A.

During the experiment, upon the system request, a sample was added in small amounts using a scoop into the wet cell of the instrument until the obscuration bar indicated about 10-20% after which the sample measurement protocol was run. After measurements were completed, the system was cleaned and the process repeated for all samples. The measured data was then transferred from the system files to a flash disk for analysis using Excel.

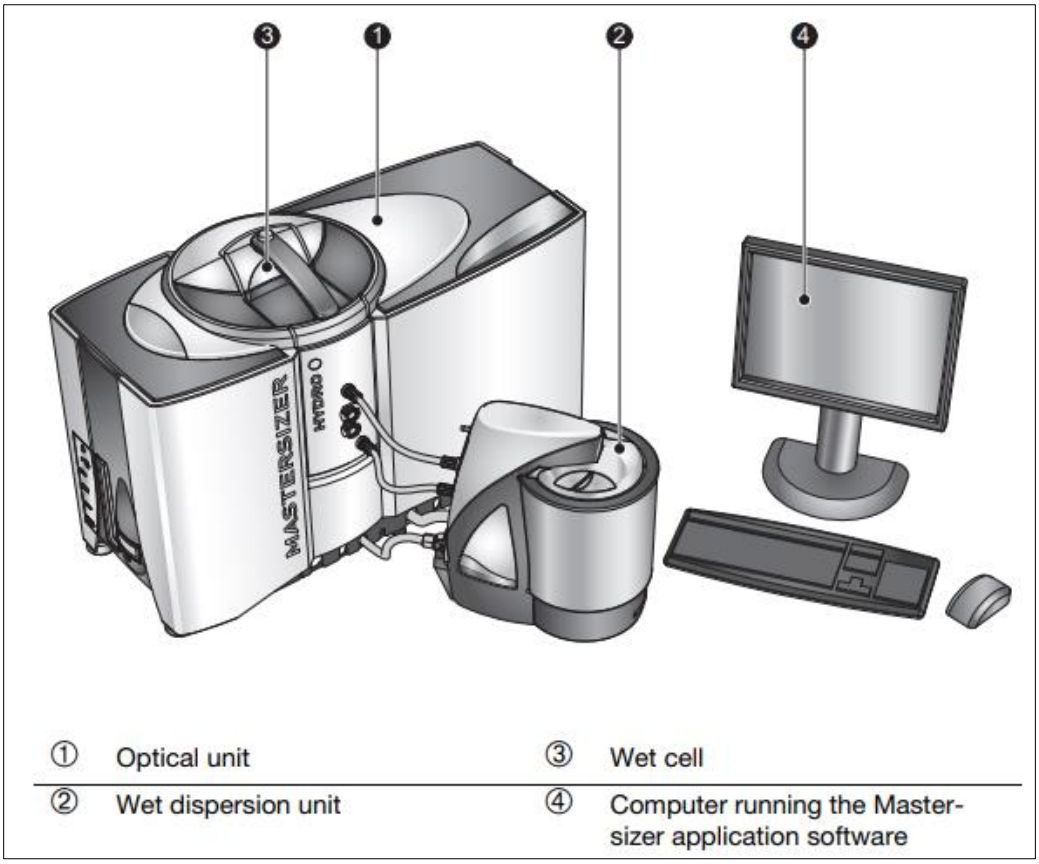

Figure 8: Malver Mastersizer 3000 unit installation

Source: Malvern Instruments Ltd, (2013)

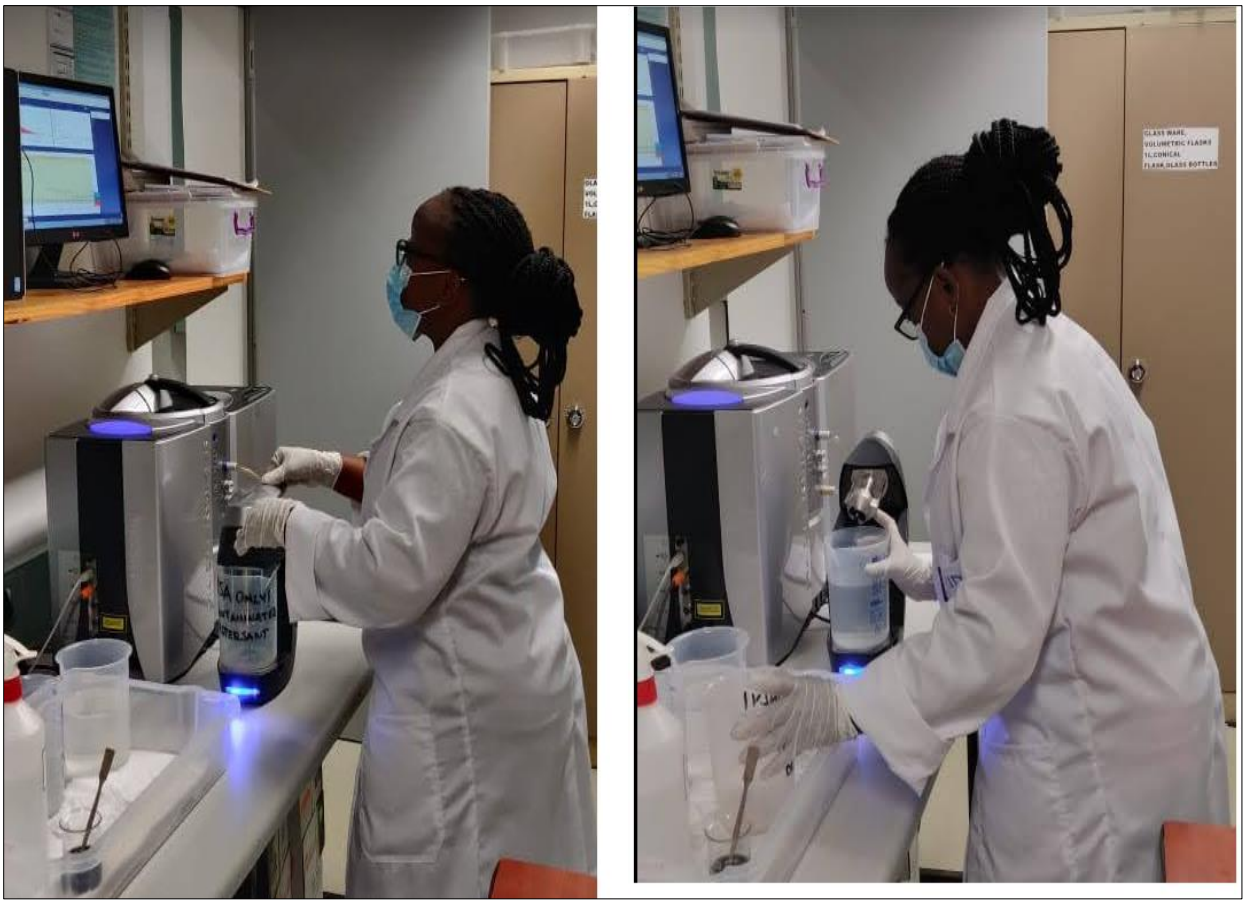

Figure 9: PSD analysis set up using Malvern Mastersizer 3000

Malvern Mastersizer 3000 works on the principle of laser detraction. The Malvern Mastersizer can measure the particles in the size range of 0.01 µm to 3500 µm. The process is fully automated, and the results are based on the manufacturers' standardized operating procedures. The Malvern Mastersizer works on the principle of laser scattering. During the laser diffraction measurement, particles pass through a focused laser beam. In between the passage, these particles scatter light at an inversely proportional to their size. A series of photosensitive detectors then measure the angle of scattering. The Malvern Mastersizer analysis is based on a 5 measurements average. The initial PSD measured by the Malvern Mastersizer is based on volume, expressing the volume percentage of particles in continuous size intervals. This volume-based PSD can be used to determine the number based PSD by the assumption of an equivalent sphere in Excel (Wu et al., 2009).

3.3.2. Dewatering test

3.3.2.1. Sludge volume index (SVI)

The SVI test procedure for the FS samples in this research is from APHA (2017) Standard Methods for the Examination of Water & Wastewater and Methods for Faecal Sludge Analysis Velkushanova et al. (2021). A mixed-liquor sludge sample was placed in an imhoff cone of 1000mL nominal volume and left to settle for 30 minutes. The volume of the settled sludge, the SSV (also SSV30), was then measured. The mixed liquor suspended solids (MLSS) measurements, also outlined in the Standard Methods, were found by filtration (using filter papers of 1.7µm pore sizes), drying the mixed liquor sample, and then computing the dry mass of particulate matter present.

Settling properties for VIP and UDDT sludge could not be determined traditionally by sludge volume index (SVI) because of their nature and the need for more precision. However, in this study, the dilute sludge volume index (DSVI) was necessary to overcome the effect of solids concentration which influences SVI measurements. A mixture was prepared from VIP and UDDT sludge separately, as explained by Yousuf (2013). 300g of each sample was transferred to a 1l graduated cylinder. Distilled water was added gradually while gently stirring to preserve original particle sizes instead of blending. After which, the contents were then transferred to the imhoff cone to measure SSV30 and subsequent MLSS content. Figure 10 illustrates the experimental laboratory setup for determining the SVI and DSVI:

Figure 10: SVI and DSVI laboratory set up

The SVI and DSVI were calculated for all samples as follows:

$$\text{SVI (mL/g)} = \frac{\text{SSV}\left(\frac{\text{mL}}{\text{L}}\right) * 10^3 \left(\frac{\text{mg}}{\text{g}}\right)}{\text{MLSS}\left(\frac{\text{mg}}{\text{L}}\right)} \qquad \text{(Equation 1)}$$

The two core components of the SVI calculation are the settled sludge volume (SSV) and mixed-liquor suspended solids (MLSS). The ratio of SSV to MLSS is the SVI. While national or international standards generally define the measurement procedure for SSV, operators and researchers use a wide variety of vessel sizes and shapes (Mullins et al., 2018) (Bye & Dold, 1998).

Therefore, Bye and Dold (1998) recommend a detailed description of the apparatus used to accompany SVI measurements.

3.3.2.2. Specific resistance to filtration (SRF)

The mechanism diagram of the test apparatus for measuring SRF is shown in Figure 11. Because of their nature, sludge from the VIP and UDDT was not used in their original state. As a preliminary, a mixture was made from VIP and UDDT sludge separately. 300g of each sample was transferred to a 1litre graduated cylinder, and distilled water was added gradually while gently stirring to preserve original particle sizes instead of blending. The prepared solutions were then used in the SRF test.

The procedure followed in this test is adapted from IWPC (1981) Unit Processes: Sewage Sludge II: Conditioning, Dewatering, and Thermal Drying and is attached in Appendix A. The filtration was carried out in the following steps: 1) A single filter paper of 1.7µm was sealed to the Buchner funnel base by moistening it before placing it in the funnel. Vacuum was applied for a few seconds to drain out the moisture in the filter paper. The water in the cylinder was drained out before proceeding further. 2) Exactly 100 mL of sludge sarnple was gently poured into the funnel and a vacuum of 49kPa was applied at zero time. A stopwatch was started simultaneously. 3) The filtrate volume collected in the cylinder was noted every 30 seconds for the first 1 minute. For the next 2 minutes, readings were taken every minute, and as the filtration proceeded, the time (t) taken for collection of filtrate volumes (V) was noted progressively until the thirty-seventh minute. 4) The time (t) taken for the collection of volume (V), of filtrate was noted as shown in Appendix B.

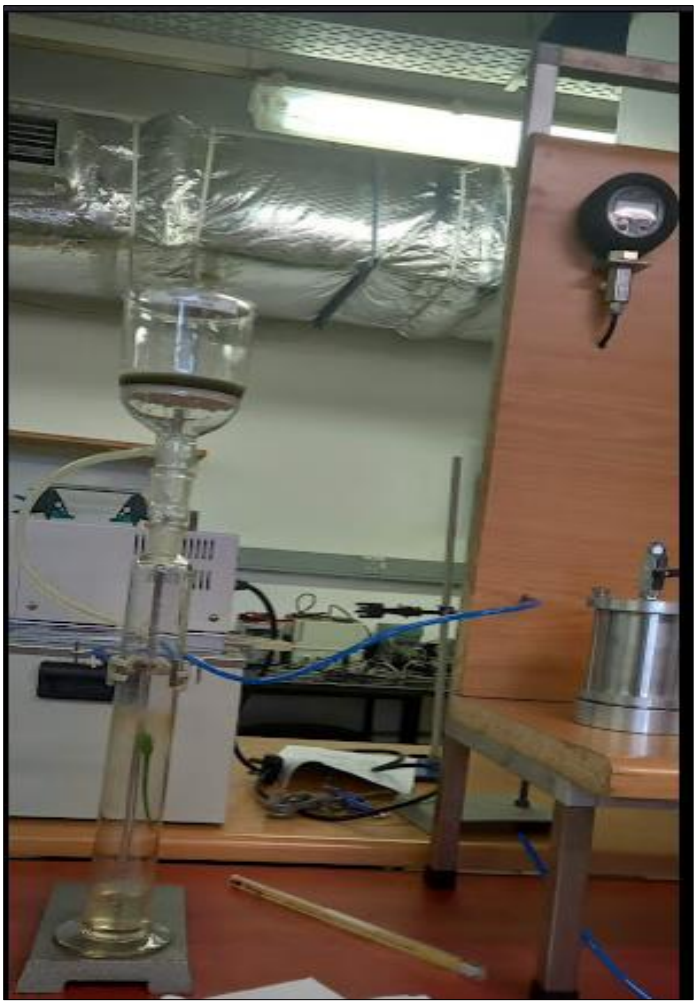

Figure 11: Specific resistance test set up

The SRF was calculated for the samples as follows:

$$r = \frac{2A^2Pb}{\eta c} \qquad \text{(Equation 2)}$$

Where: A is the filtration area, cm^2

P is the filtration pressure, kPa

η is the viscosity of the filtrate (assumed to be the same as that of water), poise

c is the mass of dry suspended solids per unit volume of liquid in the sludge being filtered, g/ml

b is the slope of the plot of $\frac{\theta n}{Vn}$ against V_n, s/ml^2

(θn is the derived time data; Vn is the derived filtrate data)

3.3.2.3.Centrifugation test

The main laboratory procedures in this test were: (i) centrifugation by a lab centrifuge, followed by (ii) moisture analysis as described in Methods for Faecal Sludge Analysis Velkushanova et al. (2021) and reproduced in Appendix A. The setup for this test is as shown in Figure 12.

A small desktop centrifuge (Hermle model) was used in this study. The centrifuge consists of four 50 ml swinging bucket rotors. Each centrifuge tubes was filled to the 30 ml mark with well stirred, mixed liquor from septic tank sludge and 28g in the case of VIP and UDDT sludge. The sludge was subjected to rotational speeds ranging from 3000, 4000, and 5000 rpm. All speeds were applied for 120 min, with an interval time of 10 min and eighteen replicates for each speed.

After switching off the centrifuge, the supernatant was discarded while the moisture content of the sludge cake was measured using a moisture analyser/ thermal balance (RADWAG MA50.R model). The disposable pan was weighed and tared as a preliminary for every analysis. 1-3 grams of sludge cake was scooped from a centrifuge tube and spread evenly on the disposable pan. The moisture analyser was left to run until a steady reading was achieved. The moisture reading was recorded before lifting the instrument lid to end the procedure and repeat the process for all centrifuge tubes with sludge cake.

Figure 12: Centrifugation and moisture content analysis set up

4. RESULTS AND DISCUSSION

4.1. Examining the Evaluation Indices of Faecal Sludge Dewatering from Different Onsite Sanitation Systems

4.1.1. Sludge settleability from different onsite sanitation systems

Settling tests provide information about the settleability of a specific faecal sludge (Heinss et al., 1999).

The settling results for the SVI from the 2 septic tanks (ST1 and ST2) and DSVI from two VIPs (VIP1 and VIP2) and two UDDT (UDDT1 and UDDT2) are given in Table 4 while the calculations are presented in Table 10 in Appendix B. The uncertainty in the average of the SVI/DSVI result is 26.8ml/g ± 8.6. From these values, it appears that the variation in the SVI is altogether different for each onsite sanitation system.

Table 4: SVI data for ST samples; and DSVI data for VIP and UDDT samples

Samples	ST1	ST2	VIP1	VIP2	UDDT1	UDDT2
SVI/ DSVI (ml/g)	35.9	26.8	19.0	18.7	25.5	35.1

In sludge management, a sludge with an SVI less than 40ml/g is considered to have excellent settling properties; while sludge with SVI between 40-75ml/g; 76-120ml/g; and 121-200ml/g has good, fair, and poor settling properties, respectively (Samhan et al., 1990; Abdel-Magid et al., 1997; and Heinss et al., 1999). The VIP faecal sludge samples have a low DSVI comparable to the UDDT faecal sludge samples, indicating the VIP sludge settles better than UDDT sludge. The SVI for the septic tank samples is between 26.83- 36.88ml/g. This value is lower than for wastewater sludge (75-100 ml/g) (Heinss et al., 1999), suggesting all the six analysed sludge samples have good settleability.

4.1.2. Sludge filterability from different onsite sanitation systems

SRF describes sludge filterability by quantifying the resistance of the sludge to the drainage of its liquid component through a porous medium by vacuum or pressure (Visilind, 1988).

The SRF test can be used to compare the characteristics of one sludge against another (Abdel-Magid et al., 1997), provided the test is conducted in a consistent manner (Smollen, 1986). As a general estimation, easily filtered sludge SRF values are between $*10^{11}$ – $*10^{12}$ m/kg, while poorly filtered sludge have SRF between $*10^{14}$- $*10^{15}$ m/kg (Rowe & Abdel-Magid, 1995).

Figures 18- 23 in Appendix B show the SRF collected data and calculations for all analysed samples; while the filterability measurements for this study are summarised in Table 5. The results indicate that all six samples have poor filtering characteristics. Thus, the sludge samples are expected to yield water by filtration poorly. Nonetheless, the SRF results among the samples indicate that the septage samples have better filtering characteristics than faecal sludge from VIP and UDDT. In addition, the UDDT faecal sludge samples have the least filtering characteristics of the analysed samples.

Table 5: SRF from VIP, UDDT, and septic tank

Samples	ST1	ST2	VIP1	VIP2	UDDT1	UDDT2
SRF Value (m/kg) $*10^{14}$	2.2	3.6	3.5	3.1	3.3	6.1

4.1.3. Sludge Centrifugability from different onsite sanitation systems

Table 11 and Table 12 in Appendix B show the centrifuged sample's percent moisture content and the percent moisture reduction of the centrifuged sample from the initial moisture content, respectively.

The mean centrifugability measurements for cake dryness in this study are shown in Table 6 and presented as the average percentage moisture content reduction. Also, the mean centrifugability measurements were calculated in Excel as illustrated in Table 13 in Appendix B.

From the data analysis, it was observed that there is no trend in moisture removal as a function of centrifugation rate and time. Centrifugation thus leads to similar results under the explored conditions. This random difference is probably due to the standard deviation measurement uncertainty, as shown in Figure 13. As such, the centrifugation rate does not seem to significantly affect moisture reduction.

Table 6: Centrifugability of VIP, UDDT, and septic tank by % moisture content reduction

Mean Moisture Content Reduction (%)									
FS Sample	**VIP**			**UDDT**			**ST**		
TIME (min)	**3000 rpm**	**4000 rpm**	**5000 rpm**	**3000 rpm**	**4000 rpm**	**5000 rpm**	**3000 rpm**	**4000 rpm**	**5000 rpm**
20	1.6	12.8	6.1	6.8	6.8	3.7	16.2	15.6	15.7
40	6.3	8.1	12.7	7.1	8.4	5.4	14.9	16.9	16.4
60	18.7	15.6	13.7	9.1	9.3	3.0	15.2	16.9	17.3
80	10.9	14.2	16.6	8.2	8.9	6.7	14.1	18.0	18.3
100	12.9	10.1	13.3	11.2	7.7	13.3	15.1	17.5	16.9
120	11.5	9.9	16.3	7.9	9.5	8.4	15.0	17.7	16.6

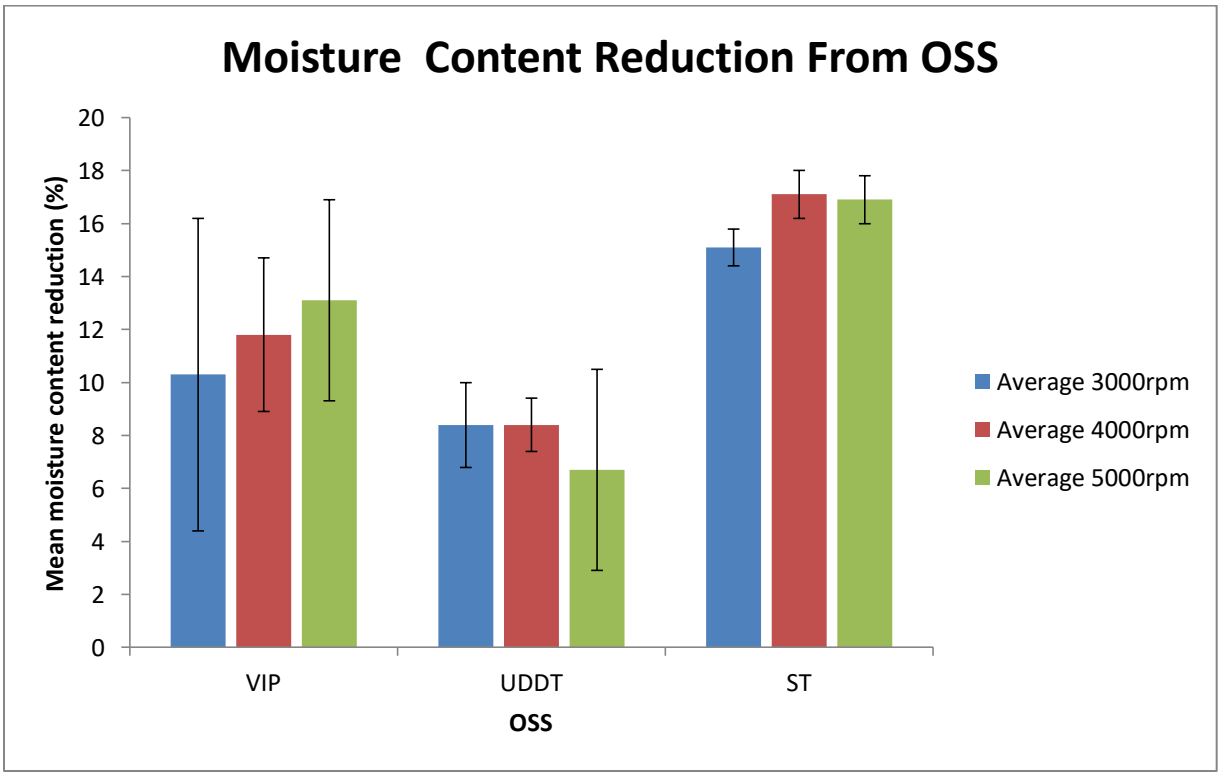

Figure 13: Uncertainty in the average moisture content reduction of FS from different OSS

The comparison above also shows that the maximum value of mean moisture reduction was from the septic tank system, the VIPs, and the UDDTs sanitation system. Between the VIP and UDDT faecal sludge samples, the percent reduction in moisture was higher for the VIP samples than the UDDT samples at almost all time intervals and centrifugation speed apart from the 20 and 40 minutes interval at 3000rpm.

The samples also show that an increase in centrifugation time yields more moisture for every rotation speed but only up to a particular time. The moisture yield reduces with increasing time. The UDDT and ST samples also show a trend where at any time duration of centrifugation, an increase in rotation speed results in increased moisture reduction, which peaks at 4000rpm but then decreases.

4.2. Evaluating the Relation between Sludge Physical Properties and Faecal sludge Settleability and Filterability

4.2.1. Density and porosity of analysed faecal sludge samples

Bulk density (Dbwet) is mass per unit volume and a measure of wetness, volumetric water content, and porosity. The reference mass of the material is taken after oven drying. Particle density or solid density (Db dry) represents only the weight of dry material per unit volume of the material solids; the pore space is not included in the volume measurement. On the other hand, a material's porosity (PS) refers to the pore space portion of the material volume occupied by air and water.

Table 14 and Table 15 in the Appendix B indicate the measured values and subsequent calculations using an Excel spreadsheet for the faecal sludge samples.

For the VIP and UDDT samples: the average bulk density (Dbwet) was calculated at 1.15 gcm3 ± 0.05, and the average dry bulk density/particle density (Dbdry) was calculated at 1.88 gcm3 ± 0.05.

Since the septage density values are similar to those of wastewater and activated sludge and assuming the septage sample consists of only two parts, water and solids; the porosity of ST1 and ST2 were calculated applying the mass balance equation illustrated by Li & Ganczarczyk, (1987) as follows:

$$\eta = \frac{\rho s - \rho f}{\rho s - \rho w} \qquad \text{(Equation 3)}$$

Where the porosity η is the septage porosity, ρs is the density of solid material in the septage with a typical constant value of 1.4 g/ml; ρf is the bulk density (Dbwet) of the septage, and ρw is the density of water.

The density and porosity data for the VIP and UDDT samples are presented in Table 7. Although septage density from the two sampled septic tank systems (ST1 and ST2) has the same density value, density and porosity differ from one onsite system to another between similar systems. The VIP, UDDT, and ST samples have a mean bulk density of 1150kg/m^3, 1150kg/m^3, and 1000kg/m^3, respectively. The VIP samples' mean bulk density is higher than the 1001kg/m^3 reported by (Radford & Sugden, 2014) from VIP samples in Kampala. The VIP and UDDT samples have a lower bulk density than the density range of 1356- 1443kg/m^3 and 1450kg/m^3 from samples in Durban (Strande et al., 2014).

Table 7: Density and porosity from VIP, UDDT and ST samples

Sample	Bulk density (Dbwet) (kg/m3)	Average Bulk density (Dbwet) (kg/m3)	Particle density (Dbdry) (kg/m3)	Average Particle density (Dbdry) (kg/m3)	Porosity	Average Porosity
VIP1	1100	1150	1800	1850	0.4	0.4
VIP2	1200		1900		0.4	
UDDT1	1100	1150	1900	1900	0.4	0.4
UDDT2	1200		1900		0.4	
ST1	1000	1000	Not determined		1	1
ST2	1000				1	

Septage from the ST units is similar to the density of activated sludge and within the density range of 1000– 1030kg/m^3 of primary sludge and is similar to density of water. The VIP and UDDT samples had a similar mean dry density of 1860kg/m^3, which is higher than wastewater sludge dry density of 1200-1600kg/m^3 (Dammel & Schroeder, 1991; Rowe & Abdel-Magid, 1995; (Tchobanoglous et al., 2003; and Quevauviller et al., 2007).

Li and Ganczarczyk (1987) likens sludge porosity to soil porosity as the individual particles sizes and shape influence porosity in the sludge. As such, a sample with spherical primary particles will have a porosity of 0.4-0.5, whereas a sample of a needle-shaped primary particle would have a porosity of 0.9. It is thus inferred that the particles in the VIP and UDDT samples are likely to be spherical and those in ST samples to be needle-shaped/ filamentous. The sludge porosity could also influence the moisture content values. The porosity of ST1 and ST2 samples is one since it is mostly composed of water with suspended and dissolved solids. The initial moisture content values illustrate this in Table 3, recorded at 98.1%wt and 99%wt for ST1 and ST2, respectively.

4.2.2. PSD of analysed faecal sludge

Particle-size distribution (PSD) is a porous media most fundamental physical property. The sizes of particles present, and their relative abundance, have a significant influence on most porous media physical properties. The particle-size analysis consists of isolating various particle sizes or size increments and then measuring the abundance of each size. The medium solid phase's material includes discrete particles of different shapes and sizes and amorphous compounds such as colloidal organic matter (Wallach, 2019).

The PSD generated data is presented in Table 16 Appendix B. The results are manipulated in Excel spreadsheet by arranging the particle sizes from largest to smallest (that is 3500μm - 0.01μm) and calculating the percent volume (% volume) for every particle size. Graphs of samples from same OSS were plotted to visualize the particle sizes with the highest % volume as represented in Figures 14, 15 and 16. The data was then manipulated to show the percent volume distribution of particle sizes in the following ranges: <1μm, 1-10μm, 100-1000μm, and lastly 1000-3500μm as illustrated in Table 8.

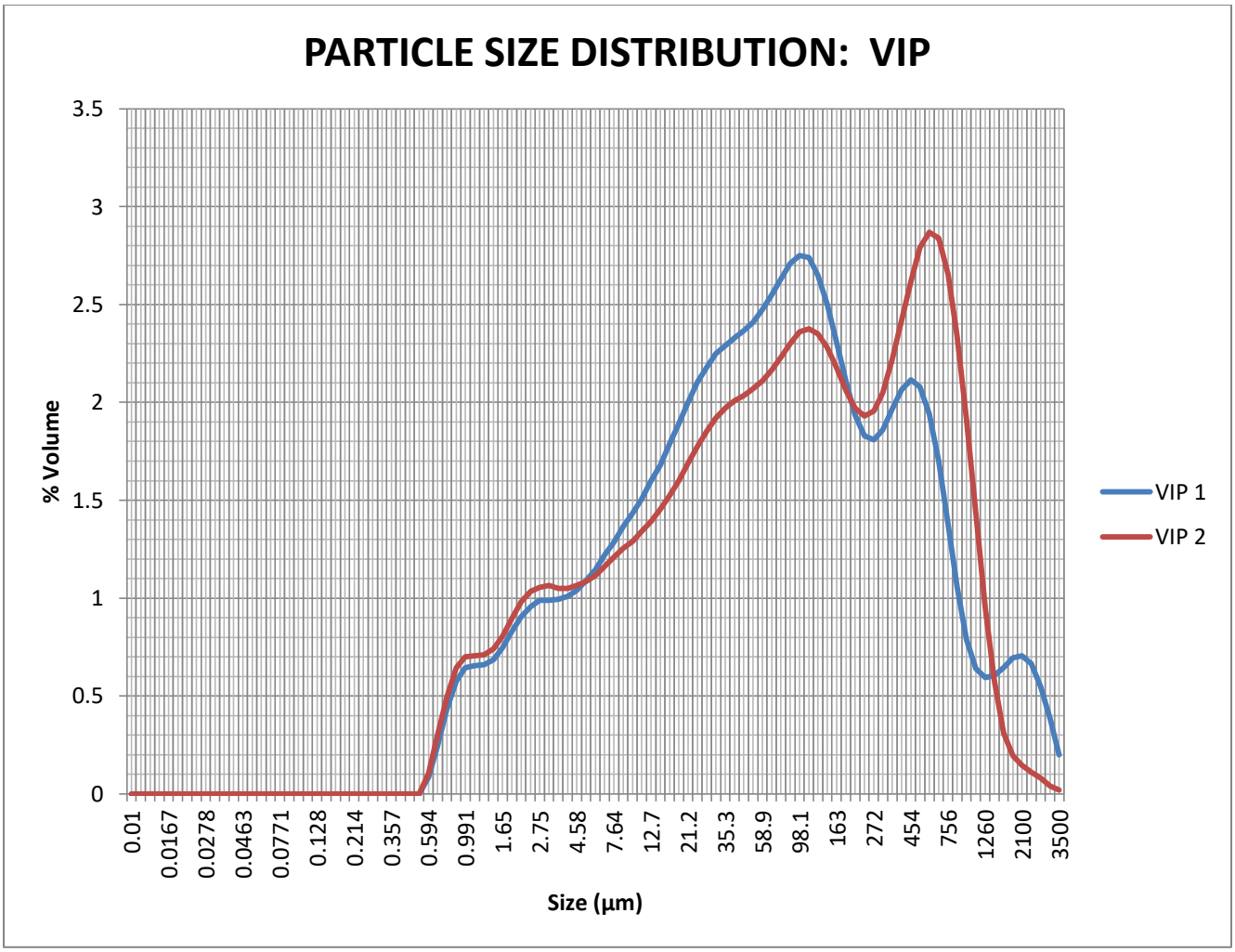

Figure 14: PSD of VIP1 and VIP2 samples

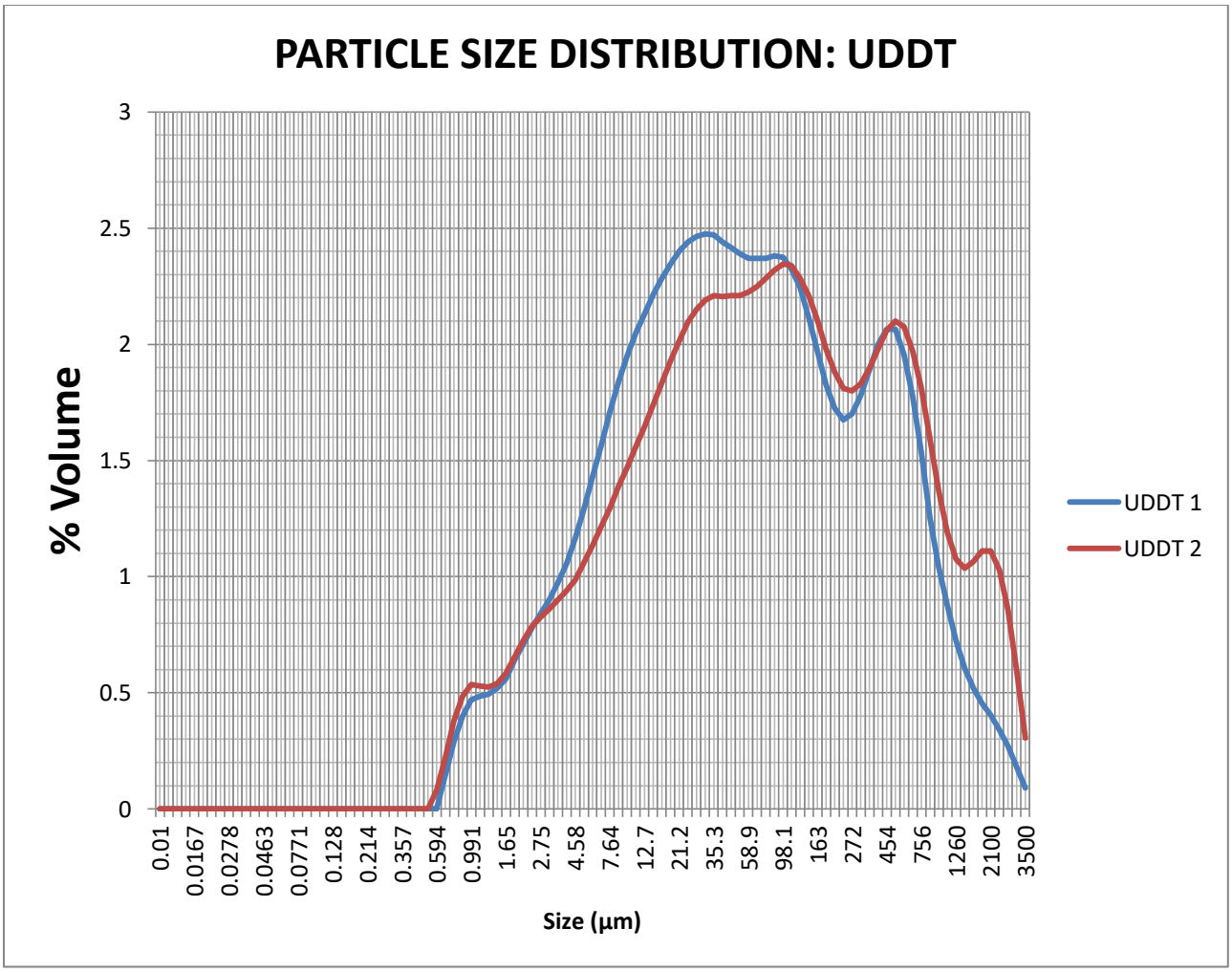

Figure 15: PSD of UDDT1 and UDDT2

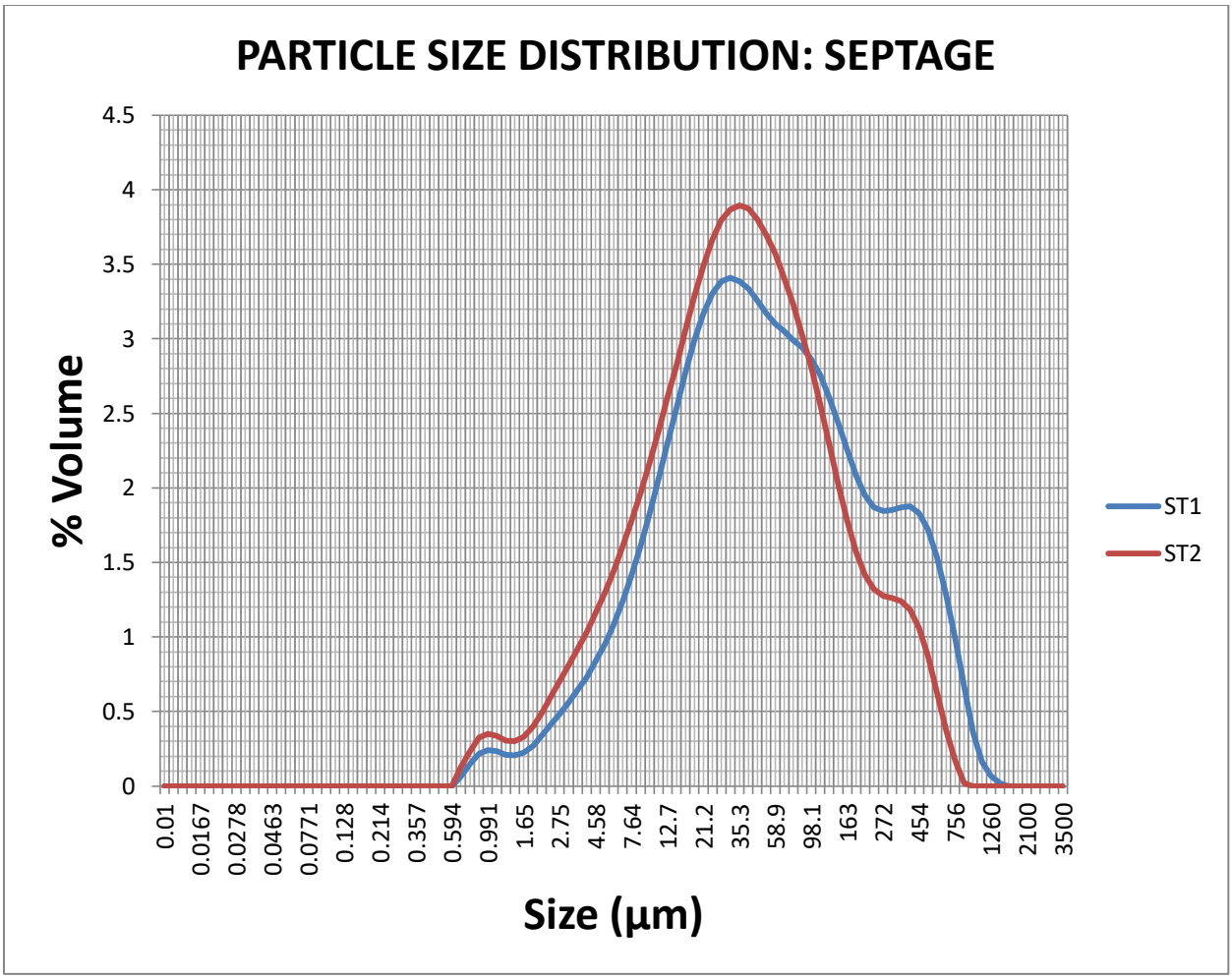

Figure 16: PSD for ST1 and ST2

Table 8 shows the percentage, by volume, between 0.59- 3500µm of the faecal sludge samples. However, the distribution in septage samples was between 0.68-1440µm and 0.68-859µm for ST1 and ST2, respectively.

Table 8: PSD range by % volume from VIP, UDDT, and septic tank

Samples	Volume (%)				
	Size (µm)				
	< 1	**1-10**	**10-100**	**100-1000**	**1000-3500**
VIP1	1.99	18	39.51	34.83	5.68
VIP2	2.25	18.27	33.8	41.82	3.87
UDDT1	1.31	18.91	42.39	32.94	4.47
UDDT2	1.7	16.42	37.42	35.09	9.37
ST1	0.67	13.28	54.02	31.79	0.26
ST2	1.04	17.65	60.28	21.04	0

Particles < 0.59µm were not detected in any of the samples. The peak particle size for volume distribution is about 98.1µm, 666µm, 28.3µm, 454µm, 31.1µm and 33.5µm for VIP1, VIP2, UDDT1, UDDT2, ST1, and ST2, respectively as illustrated in Figure 17. However, in number distribution, most particles are in the range of 10-1000µm.

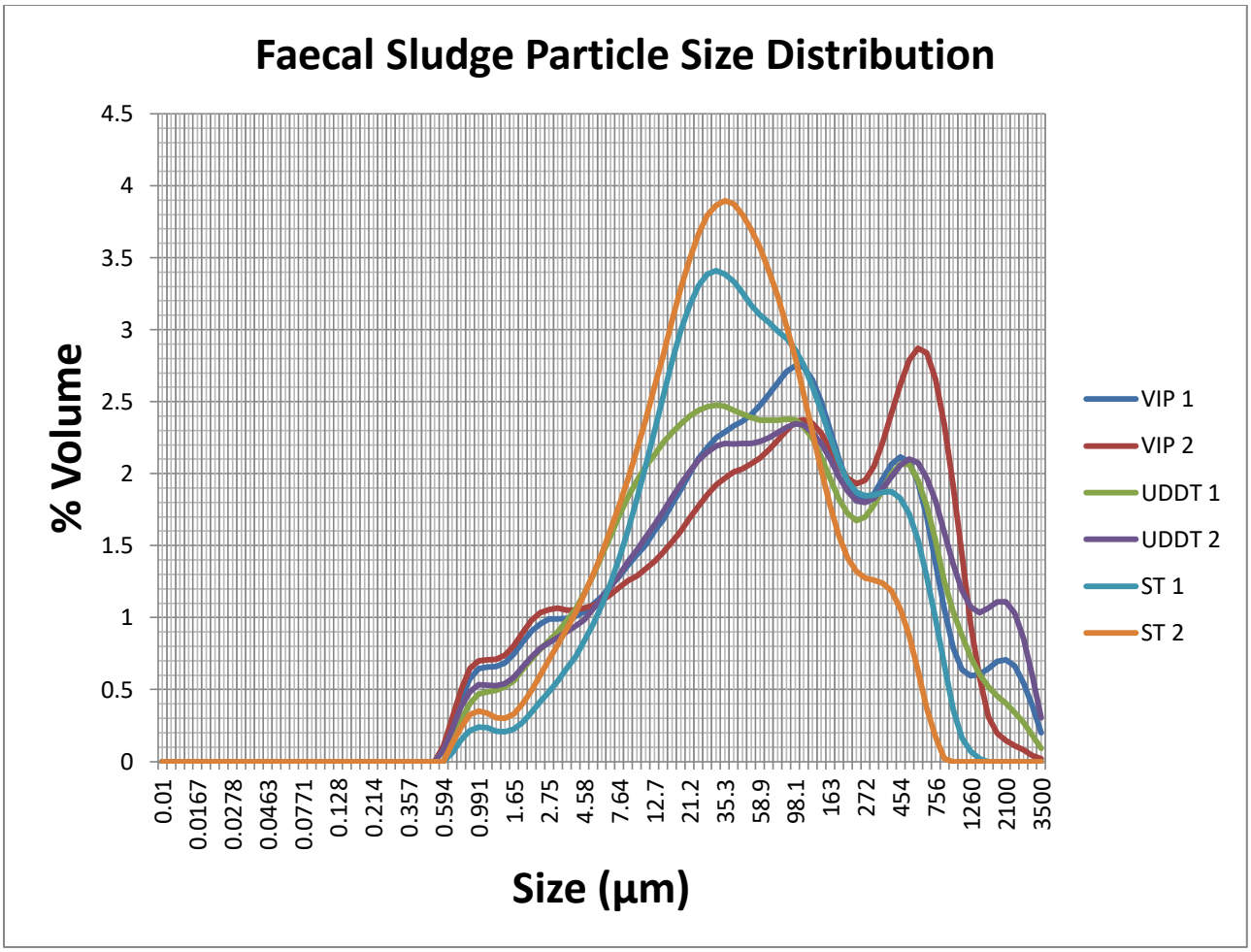

Figure 17: Faecal sludge particle size distribution by percentage volume

The particle size and mineral composition largely determine the nature and behavior of a medium (that is, its internal geometry and porosity, its interactions with fluids, as well as its compressibility and strength) (Wallach, 2019). Sludge with high organic matter content decays more rapidly, increasing the quantity of finely dispersed and colloidal particles and bound water, decreasing water separation from the sludge and poor dewaterability. In contrast, a sludge with a high proportion of large particles (>10 µm) represents a stabilized sludge that easily dewaters (Houghton et al., 2002). Particles larger than 10µm in size in total constitute approximately 79.5% to 86.1% by volume of the analysed FS samples. The analysed FS samples are hence regarded as stabilized because of the high %volume of large particles in each sample;

4.2.3. Analysis of the effect of physical properties of faecal sludge on the settleability and filterability

The correlation and regration were calculated based on alpha value of 0.05 and n of 6 (as illustrated in Tables 17, 18, 19, 20 and 21 of Appendix B). The results are summarised in Table 9 below.

Table 9: Correlation and significance between FS physical properties and the settleability and filterability of faecal sludge

	Evaluation indices for dewatering			
	r		**p**	
FS physical properties	**SVI**	**SRF**	**SVI**	**SRF**
Density	-0.4	0.47	0.43	0.35
Porosity	0.35	-0.37	0.5	0.47
Volume (%) (10-3500 µm)	-0.12	-0.09	0.83	0.87

The relationship between the density of the faecal sludge samples and the SVI values was negative, moderate in strength, and not statistically significant ($r(4) = -0.4$, $p > 0.05$). The relationship between the porosity of the samples and the SVI values was positive, weak in strength, and not statistically significant ($r(4) = 0.35$, $p > 0.05$). The results show a linear relationship between porosity and SVI values which translates to poor settleability of the sludge as porosity increases. On the other hand, an increase in FS density leads to a decrease in SVI values, which indicates good settleability.

A non-significant positive correlation was obtained between density and SRF values ($r(4) = 0.47$, $p > 0.05$). The correlation coefficient was 0.47, indicating a moderately strong relation. This correlation indicates that as faecal sludge density increases, the SRF values also increase, making the sludge more resistant to filtration. Conversely, there is a non-significant negative, weak relationship between the porosity and SRF values ($r(4) = -0.37$, $p > 0.05$). Therefore, as the porosity of faecal sludge increases, its resistance to filtration decreases and becomes easily filterable.

There is a weak, non-significant, negative correlation between the percent volume of large particles in faecal sludge to SVI values ($r(4) = -0.12$, $p > 0.05$). This correlation indicates that as the percentage of large particle size increases, the SVI values decrease, pointing to good sludge settleability. On the other hand, there is a statistically insignificant, very weak negative relationship between the percent volume of large particles in faecal sludge to SVI values ($r(4) = -0.09$, $p > 0.05$). The SRF values decrease with increasing percent volume of large particle size, hinting at a reduced resistance to filtration and ease of filtration. It can thus be inferred that faecal sludge with large particles is less resistant to dewatering.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The main objective of this research project was to investigate the dewatering characteristics of faecal sludge in the context of faecal sludge water boundness. Faecal sludge moisture release and dewaterability were examined by SVI/ DSVI, SRF, and centrifugation. In addition, sludge physical properties – density, porosity, and PSD- were used to study their effect on faecal sludge dewatering. VIP, UDDT, and septic tanks represent the most common onsite sanitation systems, particularly in urban and peri-urban areas of the developing world, for example, South Africa.

As a study conducted in a somewhat recent field, the literature and methodology borrowed from wastewater and sludge treatment and soil science concepts. Because of the semi-solid nature of the VIP and UDDT samples, dilution was required before the DSVI/ SVI and SRF tests were carried out.

It was confirmed that there is a variation in the ease of dewatering faecal sludge from the different onsite sanitation systems and in different units of the same system, which literature owes to several factors such as user habit. The VIP sludge had better settling characteristics than the UDDT sludge. Septage from the septic tank had better settleability than wastewater sludge reported in the literature but poor settleability than VIP and UDDT faecal sludge.

Although all the samples had poor filtering characteristics, the septage performed better, with UDDT faecal sludge having the least filtering characteristics value. The centrifugation analysis showed that the average maximum value of moisture reduction was from the septic tank system, followed by the VIP, and lastly, from the UDDT. The comparisons indicate that septage can easily release moisture by sedimentation, filtration, or centrifugation.

Although septage density from the two sampled ST systems has the same density value, density and porosity differ from one onsite system to another and between similar systems. Because of its high moisture content, the septage has a porosity value of 1. Septic tank sludge can therefore be easily dewatered than VIP and UDDT due to the considerably higher amount of unbound moisture added to the system. The analysed samples also had a high volume by the percentage of particles larger than 10μm, indicating stabilized sludge as reported in the literature that is easily dewatered. Still, they could also be due to other factors like the local use of sand in UDDT.

A correlation between FS physical properties to settleability and filterability in this study indicates that: (i) FS settleability decreases with increasing porosity but increases with increasing FS density. (ii) While FS filterability decreases with increasing density, it increases with increasing porosity. (iii) Lastly, settleability and filterability increase with an increasing volume percentage of large particles (>10 μm).

To be concluded, the work in this thesis represents an addition in the understanding of faecal sludge dewatering, especially in the variation of faecal sludge dewatering evaluation indices from different onsite sanitation systems; and the effect of sludge physical properties on the settleability and filterability of faecal sludge.

5.2. Recommendations

This study presented a series of results that can apply in both small and large-scale faecal sludge treatment. However, the methodology needs to be improved. For example, there is a need to develop a standard sample preparation procedure for measuring semi-solid faecal sludge from a VIP and UDDT for physical analysis.

The primary assumption of this study was that the faecal sludge sample characteristics had not changed despite the storage duration. Testing on fresh samples was not possible because of the movement restriction as Covid-19 preventive measures. Therefore, running the test on fresh samples is recommended to represent a sample delivered at a faecal sludge treatment plant in real-time.

This study was confined to analysing FS samples' dewatering and water retention characteristics from different sanitation systems. It is recommended that these characteristics be analysed for composite samples in the future- that is, a sample constituted from all the three onsite sanitation systems. The reason for analysing a composite mixture is that a faecal sludge treatment plant can treat all faecal sludge types. A correlation between the total solids and type of solid (organic and inorganic) and dewatering is also recommended. The additional data will help develop models to predict optimum dewatering methods for individual sludge and a composite/mixture of sludge.

Different methods presented in the literature review were interesting for the study. Still, due to time limitations, some were not applied. However, they were in the initial proposal: capillary suction time (CST), freeze-drying, and hydraulic conductivity test rig/ water retention cell. These methods are

more direct in quantifying the amount of bound and unbound moisture removed in sludge and soils and are recommended for future studies.

It could be interesting to study the relationship between the dewatering performance of faecal sludge to the toilet and containment system design to find complete efficiency in the faecal sludge sanitation value chain.

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7. APPENDICES

Appendix A: Laboratory Procedures

i. Density and porosity test procedure

8.7.1.2 Density – volume displacement method[57]

Bulk density is a measure of mass per unit volume. It is used as a measure of wetness, volumetric water content, and porosity. Factors that influence the measurement include the organic matter content, porosity, and material structure. Particle density, or solid density, represents only the weight of dry material per unit volume of the material solids; the pore space is not included in the volume measurement. The porosity of a material is the pore space portion of the material volume occupied by air and water. Both density parameters, bulk and particle (solid), are commonly used, depending on the purpose of the measurement. For example, particle density might be more suitable for calculations on drying beds, while the bulk density will have more relevance for emptying and transportation.

8.7.1.2.1 Introduction

Wet bulk density is determined using the same techniques as presented in Method 8.7.1.1. Dry bulk density is determined by oven-drying a known volume of sample and measuring the mass of the dry sample. Particle density is determined using the volume displacement technique. Pore space is then calculated from these values.

8.7.1.2.2 Safety precautions

- General health and safety (H&S) procedures specific for conducting the laboratory analysis of faecal sludge are presented in Section 8.2. Before conducting this method, it is important to be familiar with Section 8.2.3 to ensure safety measures are properly carried out.
- Appropriate personal protective equipment (PPE) should be used; specific details are covered in Section 8.2.3.1.
- Wear gloves suitable for withstanding high temperatures when placing and removing crucibles from the oven.
- Use appropriate mechanical tools, such as metal tongs, to remove crucibles and trays after drying in the oven to avoid direct contact with hot surfaces.

8.7.1.2.3 Required apparatus and instruments

- Porcelain crucibles
- Desiccator with dry desiccant
- Drying oven
- Analytical balance with four decimal places
- 100 mL measuring cylinder
- 7.5 mL measuring scoop or 10 mL measuring cylinder (depending on sludge type)
- Tube to hold the sample that fits inside the 100 mL measuring cylinder
- Glass weighing dish
- Laboratory tissue

- Knife, to trim excess sludge from the measuring scoop
- Heat-resistant gloves
- Thermometer (for the quality control procedure)
- Set of standard calibration weights (for the quality control procedure)
- Distilled water (for the quality control procedure).

8.7.1.2.4 Quality control

General information on quality assurance and quality control (QA/QC) is provided in Section 8.3. Information on standards, operating conditions, and interferences that are specific to this method include:

- The analytical balance and oven must be checked and calibrated weekly.
  - Check the temperature throughout the oven area by placing a calibrated thermometer on each shelf. After 30 min, check the temperature at each level against the oven setting. Using the same method, also check for temperature differences between the front and back of the oven. Adjust the oven setting if necessary. If temperatures are uneven on the shelves, check the insulation.
  - To calibrate the analytical balance, place a standard calibration weight on the balance and weigh. Adjust the balance manually if necessary. Do this with the whole range of weights from the calibration set. Make sure to include a standard weight of a mass similar to the mass of the expected sample + crucible.
- Make sure the desiccant in the desiccator is not saturated, otherwise samples may absorb water while cooling down in the desiccator. Routinely dry the desiccant in the oven at 105 °C (or at a different temperature, depending on the manufacturer's instructions), prior to the colour indicating that the desiccant is nearly saturated.
- Always keep the lid of the desiccator on and use a lubricant on the rim to ensure airtight sealing. Do not overload the desiccator.
- Before every series of density measurements, do a check with distilled water. Follow the measuring procedure with distilled water, and compare the density with the density of water: $\rho_{water} = 0.998203$ g/cm³ for T = 20 °C. A common tolerance limit is 0.0001 g/cm³.

8.7.1.2.5 Sample preparation

- Homogenise the faecal sludge sample thoroughly by stirring with a spoon or stirring rod.
- It is important to prepare the sample for density in the same way as other analysis that is being conducted, especially if the results will be used to convert between weight/weight or weight/volume concentrations (*e.g.* if a blended sample is used for TS measurement and that is the parameter of interest for the density measurement, then density should be measured on the blended sample).
- Exclude larger, inconsistent or floating particles from the sample if it is determined that their inclusion may affect the final result (*e.g.* hair, stones, glass, and maggots).

8.7.1.2.6 Analysis protocol

- Pre-heat the oven to 103-105 °C.
- Place a clean crucible in the oven at a temperature of 103-105 °C for 1 hr prior to use (to remove any moisture). After drying, place the crucible in the desiccator and allow it to cool down to room temperature. Keep the crucible in the desiccator until the next step.
- Weigh the crucible and record the mass (W_1).
- Place the measuring scoop and the glass dish on the balance, and tare the balance. If required, for liquid and slurry sludge types a measuring cylinder might also be used.
- Use the scoop to measure 7.5 mL of the sample, such that the sample completely fills the scoop. Avoid compressing the sample as much as possible.
- Wipe the bottom of the scoop with a laboratory tissue, removing any excess sample.
- Trim any sample from the top of the scoop with the knife, to leave a flat surface flush with the top of the scoop.
- Place the measuring scoop on the glass dish on the scale, and record the mass of the sample contained in the scoop (W_2).
- Transfer all the sample from the scoop into a dried crucible. Rinse the scoop with small volumes of distilled water to dislodge heavy particles. Make sure that all the particles are transferred to the crucible. Add the washings to the crucible.
- Oven-dry the sample at 103-105 °C for at least 24 hr.

- Take the sample out of the oven, and place it in the desiccator to reach room temperature.
- Weigh the dry mass of the sample + crucible using an analytical balance and record the weight (W_3).
- Fill the 100 mL measuring cylinder with 50 mL water.
- Suspend an empty sample-holding tube inside the 100 mL measuring cylinder filled with 50 mL water and record the volume level of water (V_1).
- Carefully transfer all the dry sample from the crucible into the holding tube, ensuring that all the particles are transferred.
- Suspend the tube with the sample in the measuring cylinder with water and record the new level of the water (V_2).

8.7.1.2.7 Calculation

Bulk density

$$\text{Bulk density (wet)} \left(\frac{g}{mL}\right) = \frac{(W_2\text{-}W_1)\,(g)}{Vt\,(mL)}$$

Where:

W_1 = Mass of the crucible (g)

W_2 = Wet mass of sample

V_t = Total volume of sample (7.5 mL).

$$\text{Bulk density (dry)} \left(\frac{g}{mL}\right) = \frac{(W_3\text{-}W_1)\,(g)}{Vt\,(mL)}$$

Where:

W_1 = Mass of the dried crucible (g)

W_3 = Dry residue + crucible after drying at 103-105 °C (g)

V_t = Total volume of the sample, pore volume + solid volume (7.5 mL).

Particle density

Particle density values represents only the weight of dry sample per unit volume of the sample solids; the pore space is not included in the volume measurement.

$$\text{Particle density} \left(\frac{g}{mL}\right) = \frac{(W_3\text{-}W_1)\,(g)}{Vs\,(mL)}$$

Where:

W_1 = Mass of the dried crucible (g)

W_3 = Dry residue + crucible after drying at 103-105 °C (g)

V_1 = Volume in measuring cylinder with holding tube (mL)

V_s = Volume of the solids (ONLY) = V_t-V_1 (mL).

Pore space

Pore space (g/mL) =

Bulk density (g/mL) − Particle density (g/mL)

ii. Particle size distribution test procedure

8.7.1.3 Particle size - laser light scattering method[58]

8.7.1.3.1 Introduction

Characterising particle size distribution can help in designing treatment processes and monitoring process effectiveness. Particle size influences how much organic material is available organic material is for degradation by microorganisms, and how the particle size distribution changes over the course of stabilisation and treatment. Particle size distribution affects settling and dewatering performance, and is also an important characteristic of end products from faecal sludge treatment (*e.g.* dried sludge solid fuels or feedstock for larvae rearing).

Several standard methods for characterising the particle size of water and wastewater exist, and these are discussed in Method 2560 Particle Counting and Size Distribution in the Standard Methods for the Examination of Water and Wastewater (Rice *et al.*, 2017). These include manual sequential sieving and filtration, the use of electronic measurement devices (including electronic sensing zone instruments, light-blockage instruments, and light-scattering instruments), and direct sizing and counting using microscopy. Manual sieving and filtration are slow, labour-intensive, and has a lower level of accuracy, but does not require expensive instrumentation. Electronic measurement of particle size is typically the method of choice if instruments are accessible. However, when large aggregates of particles (> 500 µm) are to be analysed, direct microscopic methods are advised (Rice *et al.*, 2017).

Step-by-step procedures for measuring particle size will vary depending on the selected method, the available equipment, and the characteristics of the incoming faecal sludge samples. One example of electronic measurement of particle size is the laser light scattering method used by the UKZN PRG laboratory in Durban, South Africa that is described here. This method is specifically written to be used with a Malvern Mastersizer 3000 particle size analyser[D], and follows the Malvern Mastersizer 3000 User Manual (Malvern Instruments, 2017) and Method 2560D in Rice *et al.* (2017). The Malvern Mastersizer 3000 measures particle size by shooting a laser beam through a dispersed sample, and measuring the angle and intensity of light scattered off the particles. Mie and Frauhofer theories are used to calculate the particle sizes based on the scattering pattern. A wet dispersion unit is used with faecal sludge samples to circulate samples through the measurement cell. The size range of the Mastersizer 3000 is 0.01-3,500 µm.

8.7.1.3.2 Safety precautions

- General health and safety (H&S) procedures specific for conducting the laboratory analysis of faecal sludge are presented in Section 8.2. Before conducting this method, it is important to be familiar with Section 8.2.3 to ensure safety measures are properly carried out.
- Appropriate personal protective equipment (PPE) should be used; specific details are covered in Section 8.2.3.1.

8.7.1.3.3 Required chemicals

- Particle size standards (for the Mastersizer 3000, Malvern recommends the Malvern QAS3002 Quality Audit Standard).

8.7.1.3.4 Required apparatus and instruments

- Mastersizer 3000
- Mastersizer wet dispersion unit
- Beaker.

8.7.1.3.5 Quality control

General information on quality assurance and quality control (QA/QC) is provided in Section 8.3 .Information on standards, operating conditions, and interferences that are specific to this method include:

- Calibration is performed using standard suspensions or dry powders of spherical particles of known size (*e.g.* standards provided by the manufacturer or NIST standard particles). Rice *et al.* (2017) recommend using at least three different-sized particle standards to calibrate a particle sensor. Follow the manufacturer's instructions to set up a calibration strategy.
- Sample blanks, handled identically to the faecal sludge samples, should be analysed daily. Generally, blanks should not show more than 5% of the counts in any size channel compared to the samples. See Section 7 Quality Control in 2560A (Rice *et al.*, 2017) for a detailed discussion of quality control for particle size analysis, or refer to the manufacturer's instructions.
- Large particles, solid waste, stones, and hair should be removed before testing, as they can harm the instrument. This can be achieved by passing the sample through a sieve before analysis. Sieve size and other pre-treatment steps should be selected based on the upper measurement limit of the specific instrument and the manufacturer's instructions.
- Minimise particle contamination (*e.g.* from airborne particles, contaminated dilution water, or contaminated glassware). Keep the samples in a closed container, ensure the dilution water is particle-free and run blanks to ensure this, and ensure the glassware is thoroughly cleaned and particle-free before use. For information about producing particle-free dilution water, see 2560A in Rice *et al.* (2017).
- Faecal sludge samples may require dilution prior to analysis. It is important to avoid breaking up aggregates or flocs during the sample preparation, so dilutions should be made carefully using pipettes with wide openings. Wide openings can be made by cutting off the tips of the pipettes. The sample should be added to the dilution water (not water added to the sample) in order to reduce shear on the sample. Be careful to use slow, low-intensity mixing. Avoid mechanical stirring and ultrasonication. For more sample preparation tips, see Section 3 Sample collection and handling in 2560A, Rice *et al.* (2017).
- Minimise the time between sample collection and measurement, as particles may agglomerate over

time, changing the particle size distribution. Dilution can also influence agglomeration – make dilutions immediately before analysis.
- If samples must be stored before analysis, refrigerate them (4 °C), but make sure that they are brought back to room temperature before analysis.

8.7.1.3.6 Sample preservation

Samples should be analysed as soon as possible after collection, to prevent changes in particle size distribution due to agglomeration. If the samples must be stored before analysis, store them in a refrigerator (4 °C) and do not dilute them before storage.

8.7.1.3.7 Sample preparation

- Remove all the particles larger than the upper limit of the instrument by sieving.
- If the sample is semi-solid or solid, dilute the sample in particle-free water and gently mix to produce a slurry. Add to a beaker.
- If the sample is liquid or slurry, dilution may not be necessary. Gently mix the sample to ensure homogeneity, then add a portion of the sample to a beaker.

8.7.1.3.8 Analysis protocol

Instrument setup

- Switch on the instrument.
- Switch on the computer and start the Mastersizer software.
- Wait 30 min for the instrument to stabilise before using the instrument.

Measurement

- Select the instrument protocol for measuring the specific sample type (*e.g.* faecal sludge from VIP latrines) and allow the instrument to initialise. A background light measurement will then be taken.
- When prompted, add the sample a small amount at a time until the obscuration is within the correct range (displayed on the computer screen). Note: if the sample is too concentrated, it will immediately exceed the obscuration range - if this happens, the sample will need to be diluted and measured again.
- Run the sample measurement protocol.
- After measurement is completed, clean the system by following the prompts on the user interface.

8.7.1.3.9 Calculation

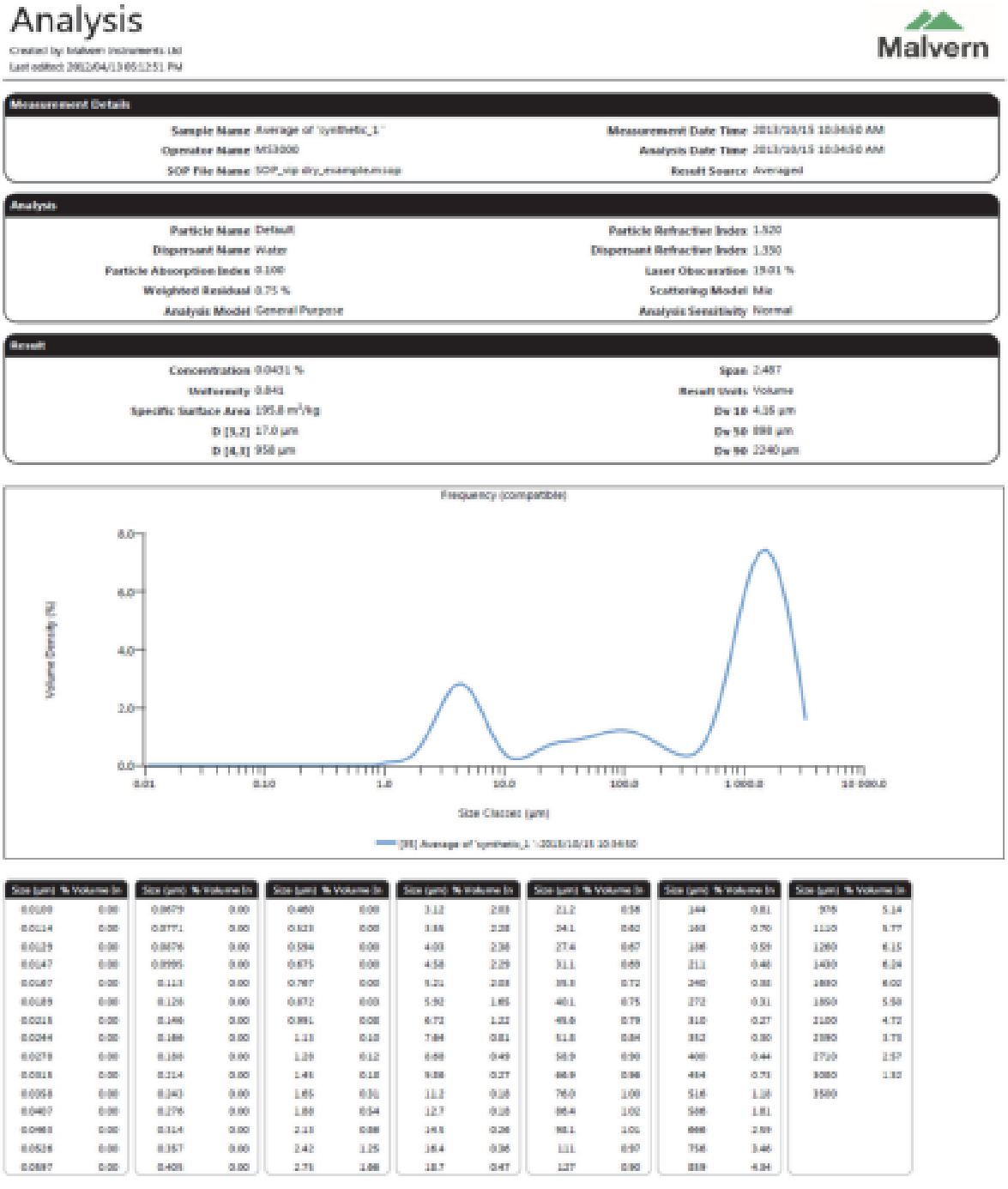
No calculation required – direct reading is based on the overall percentage of particle volume and does not require adjustment based on dilution.

8.7.1.3.10 Data set example

Faecal sludge at UKZN PRG was analysed (unpublished data, Figure 8.14), with the results interpreted as follows:

- Weighted residual - an indication of how well the calculated data was fitted to the measurement data. A good fit is indicated by a residual of less than 1%, while a residual over 1% may indicate the use of an incorrect refractive index and adsorption values for the sample.
- Dv 50, Dv 10 and Dv 90 are standard percentile readings from the analysis.
  - Dv 50 - the particle diameter in µm at which 50% of the sample volume is smaller and 50% is larger. This value is also known as the Mass Median Diameter (MMD) or the median of the volume distribution. The v in the expression Dv 50 shows that this refers to the volume distribution. Following the same naming convention, Ds refers to the surface area distribution, Dl is the length distribution, and Dn is the number distribution.
  - Dv 10 - the particle diameter below which 10% of the sample volume lies.
  - Dv 90 - the particle diameter below which 90% of the sample volume lies.
- D [4, 3] - the volume-weighted mean or Mass Moment Mean Diameter.
- D [3, 2] - the surface-weighted mean, also known as the Surface Area Moment Mean Diameter.
- Span - is the measurement of the width of the distribution. The narrower the distribution, the smaller the span becomes.
- Concentration - the volume concentration. This is calculated using the Beer-Lambert law.
- Obscuration - an ideal range of obscuration is usually between 3 and 20%, depending on the sample and dispersion unit used.
- Distribution - shows the type of distribution the analysis has used. Options include volume, surface area, length, or number. The Mastersizer 3000 measurement is fundamentally a

measurement of volume distribution; the transformation of the results into a surface area, length, or number distribution may amplify any error in the original result, especially at the fine end of the size distribution.



Analysis

Created by: Malvern Instruments Ltd
Last edited: 2012/04/13 05:12:51 PM

Malvern

Measurement Details

Sample Name	Average of 'synthetic_1'	Measurement Date Time	2013/10/15 10:34:50 AM
Operator Name	MS3000	Analysis Date Time	2013/10/15 10:34:50 AM
SOP File Name	SOP_vip dry_example.msop	Result Source	Averaged

Analysis

Particle Name	Default	Particle Refractive Index	1.520
Dispersant Name	Water	Dispersant Refractive Index	1.330
Particle Absorption Index	0.100	Laser Obscuration	19.01 %
Weighted Residual	0.75 %	Scattering Model	Mie
Analysis Model	General Purpose	Analysis Sensitivity	Normal

Result

Concentration	0.0431 %	Span	2.487
Uniformity	0.841	Result Units	Volume
Specific Surface Area	195.8 m^2/kg	Dv 10	4.38 µm
D [3,2]	17.0 µm	Dv 50	898 µm
D [4,3]	958 µm	Dv 90	2240 µm

Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In
0.0100	0.00	0.0679	0.00	0.460	0.00	3.12	2.03	21.2	0.58	144	0.81	976	5.14
0.0114	0.00	0.0771	0.00	0.523	0.00	3.55	2.28	24.1	0.60	163	0.70	1110	5.77
0.0129	0.00	0.0876	0.00	0.594	0.00	4.03	2.36	27.4	0.67	186	0.59	1260	6.15
0.0147	0.00	0.0995	0.00	0.675	0.00	4.58	2.29	31.1	0.69	211	0.48	1430	6.24
0.0167	0.00	0.113	0.00	0.767	0.00	5.21	2.03	35.3	0.72	240	0.38	1630	6.02
0.0189	0.00	0.128	0.00	0.872	0.00	5.92	1.65	40.1	0.75	272	0.31	1850	5.58
0.0215	0.00	0.146	0.00	0.991	0.00	6.72	1.22	45.6	0.79	310	0.27	2100	4.72
0.0244	0.00	0.166	0.00	1.13	0.10	7.64	0.81	51.8	0.84	352	0.30	2390	3.73
0.0278	0.00	0.189	0.00	1.28	0.12	8.68	0.49	58.9	0.90	400	0.44	2710	2.57
0.0315	0.00	0.214	0.00	1.46	0.18	9.86	0.27	66.9	0.98	454	0.73	3080	1.33
0.0358	0.00	0.243	0.00	1.65	0.31	11.2	0.16	76.0	1.09	516	1.16	3500	
0.0407	0.00	0.276	0.00	1.88	0.54	12.7	0.16	86.4	1.22	586	1.81		
0.0463	0.00	0.314	0.00	2.13	0.88	14.5	0.26	98.1	1.41	666	2.59		
0.0526	0.00	0.357	0.00	2.42	1.35	16.4	0.36	111	0.97	756	3.46		
0.0597	0.00	0.405	0.00	2.75	1.88	18.7	0.47	127	0.90	859	4.34		

Figure 8.14 Example of data generated during the particle size analysis (source: unpublished data, UKZN PRC).

iii. Mixed liquor suspended solids in sludge volume index (SVI) test procedure

8.6.1.3 Total suspended solids and total dissolved solids – oven drying method[5]

8.6.1.3.1 Introduction

The TSS method is used to determine the efficiency of treatment technologies, such as settling tanks and biological filters. The measured volume of a thoroughly-mixed sample is vacuum-filtered through a dried, pre-weighed glass fibre filter. The filters and residue are then dried to a constant weight at 103-105 °C. The increase in weight of the filter represents the total suspended solids. Total dissolved solids are the TS minus the TSS.

For faecal sludge, clogging of the filters is a common problem. For this reason, this method is only suitable for liquid and slurry samples. If clogging occurs, the method can be adapted by dilution of the sample and/or choosing a larger pore size (maximum up to 2.0 µm), but needs to be carefully documented.

8.6.1.3.2 Safety precaution

- General health and safety (H&S) procedures specific for conducting laboratory analysis of faecal sludge are presented in Section 8.2. Before conducting this method, it is important to be familiar with Section 8.2.3 to ensure safety measures are properly carried out.
- Appropriate personal protective equipment (PPE) should be used; specific details are covered in Section 8.2.3.1.
- Always conduct the total suspended solids analysis in a room with sufficient airflow and an exhaust system.
- Wear gloves suitable for withstanding high temperatures when removing crucibles from the oven.
- Use appropriate mechanical tools, such as metal tongs, to remove crucibles and trays after drying in the oven to avoid direct contact with hot surfaces.

8.6.1.3.3 Apparatus and instruments

- Analytical balance with four decimal places
- Büchner funnel with a rubber bung and fitting conical filtration flask
- Vacuum pump with a rubber tubing
- Glass fiber filters (GF/C grade) ranging in size from 0.45 µm to 2.0 µm depending on the thickness of the sludge and clogging of the filters. It is important to use GF/C grade to withstand 550 °C and that the filter diameter matches the Büchner funnel diameter.
- Desiccator with dry desiccant
- Aluminium weighing boats or porcelain crucible
- Drying oven
- Graduated cylinder
- Forceps
- Pencil
- Stainless steel tray (optional, to move the crucibles in and out of the oven)
- Heat-resistant gloves
- Thermometer (for the quality control procedure)
- Set of standard calibration weights (for the quality control procedure)

8.6.1.3.4 Quality control

General information on quality assurance and quality control (QA/QC) is provided in Section 8.3. Information on standards, operating conditions and interferences that are specific to this method includes:

- The analytical balance and oven must be checked and calibrated weekly.
- Check the temperature throughout the oven area by placing a calibrated thermometer on each shelf. After 30 min, check the temperature at each level against the oven setting. Using the same method, also check for temperature differences between the front and back of the oven. Adjust the oven setting if necessary. If temperatures are uneven on the shelves, check the insulation.
- To calibrate the analytical balance, place a standard calibration weight on the balance and weigh. Adjust the balance manually if necessary. Do this with the whole range of weights from the calibration set. Make sure to at least use a standard weight of a mass similar to the mass of the expected sample + crucible.
- Make sure the desiccant in the desiccator is not saturated, otherwise samples can absorb water

while cooling down in the desiccator. Routinely dry the desiccant in the oven at 105 °C (or at a different temperature, depending on the manufacturer's instructions), prior to the colour indicating that the desiccant is nearly saturated.

- Always keep the lid of the desiccator on and use a lubricant on the rim to ensure airtight sealing. Do not overload the desiccator.
- The volume or mass of the wet sample used should be chosen so that the drying will yield a residue between 2.5 and 200 mg of the dried sample (in general around 30 mL for the volumetric method, or 10-20 g for the gravimetric method, but this will depend on the type of sludge).
- For solid, semi-solid and slurry samples: limit the sample to no more than 10-20 g faecal sludge, otherwise the sample will take too long to dry and can form a moisture-trapping crust on top. If crust formation is occurring, samples should be placed in the oven at a lower temperature initially and the temperature gradually increased until 103-105 °C is reached.
- For liquid samples, the volume of the sample can be higher as the TS content is much lower. The proportion of the weight of the sample to the weight of the porcelain or aluminium crucible should also be taken into account, so that weight differences in the sample can be measured accurately.
- Make sure samples are fully cooled in a desiccator to ambient temperature prior to weighing.
- Sludges that contain highly mineralised water with a significant concentration of calcium, magnesium, chloride and/or sulphate can be hygroscopic and require prolonged drying, proper desiccation, and rapid re-weighing.
- Exclude larger, inconsistent or floating particles from the sample if it is determined that their inclusion can affect the final result (*e.g.* hair, stones, glass and maggots).
- Glass fibre filters are delicate, especially when wet, and care should be taken not to rip or damage them during filtration and handling. If a filter is damaged during filtration, particles might not be captured or pieces of the filter could be washed away, which will lead to measurement errors. Filters need to be prepared as described in Section 8.6.1.3.7.

8.6.1.3.5 Sample preservation

Samples should be analysed as soon as possible. If samples cannot be analysed immediately, they should be stored in a refrigerator at 4 °C for no longer than 48 hours. Before starting the analysis, let the samples return to ambient temperature. Do not freeze the samples.

8.6.1.3.6 Sample preparation

- Thoroughly mix all the samples using a stainless steel rod (or other appropriate tool) in order to have representative samples. For liquid samples, invert the closed sample bottle with the sample about 3 times.
- When measuring total dissolved solids, in addition to following this method, TS should be measured (following Method 8.6.1.1 or Method 8.6.1.5).

8.6.1.3.7 Analysis protocol

Equipment preparation

- Pre-heat the oven to 103-105 °C.
- Rinse the Büchner funnel with distilled water.
- Place the Büchner funnel with the rubber bung (stopper) on top of the filtration flask to seal the apparatus.
- Attach the filtration flask to a vacuum pump.
- If analysing multiple samples or replicates at the same time, mark each crucible/aluminium weighing boat with a unique identification number/letter. Number the crucible with a pencil or scratch the number into the aluminium weighing boat and note down which sample and replicate is in which number crucible to be able to distinguish between samples later.
- Pre-wash the glass fibre filter: place a filter onto the funnel (rough side up), apply the vacuum, and rinse three times with an aliquot of distilled water.
- Place the washed filter in a crucible or aluminium weighing boat and place in the oven at a temperature of 103-105 °C for 1 hr, prior to use (to remove any moisture). Afterwards, place the crucible with the filter in the desiccator and allow it to cool to room temperature. Always keep the rough side of the filter up.
- Note: if measuring volatile suspended solids after the total suspended solids, prepare the filter + crucible at 550 °C for ≥15 min in a muffle furnace instead of in the oven prior to use to remove any

potential residual organic material from previous measurements. Only porcelain crucibles should be used (see Method 8.6.1.2).

Procedure

- Weigh the filter + crucible or aluminium weighing boat on a balance and record its mass (W_1).
- Place the filter into a Büchner funnel, with the rough side up.
- Measure out a 30 mL sample volume using a graduated cylinder. Note: choose the sample volume to yield between 2.5 and 200 mg residue. For slurry sludge, measure 20 mL sample using a graduated cylinder. (Use less sample volume if the dried residue is more than 200 mg or use a smaller pore size if the dried residue is lower than 2.5 mg).
- Wet the filter with distilled water to seal the edges of the filter to the surface of the funnel.
- Turn on the vacuum pump.
- Pour the sample onto the filter, keeping the sample in the middle of the paper.
- Wash the graduated cylinder with distilled water until thoroughly rinsed (at least 2-cylinder volumes). Ensure all the particles are washed onto the filter.
- Pour rinse water onto the filter. For liquid and slurry samples >5 % TS, wash with at least two successive volumes of 10 mL distilled water and pour the rinse into the filter. Allow complete drainage between washings, and continue suction until all the traces of water are removed.
- If the sample is clogging the filter during filtration, dilute the sample using an appropriate dilution factor (*e.g.* 1:5 or 1:10) and filter the diluted sample. Note: the dilution factor needs to be reported and accounted for when calculating the total suspended solids concentration.
- If clogging still occurs even with the dilutions (*i.e.* if filtration takes >10 min to complete), then the next size larger pore size filter should be used. It is very important to document this and report it in the methods. In general, the smallest pore size possible in the range 0.45 µm to 2.0 µm should be used.
- When filtration is complete, remove the filter with forceps gently along the edge of the filter paper and then lift slowly (or first with a spatula and then forceps).
- Remove the paper with a pair of forceps, taking care not to tear the paper.
- Carefully place the filter in its marked crucible or aluminium weighing boat, rough side (containing the sample) facing up.
- Place in the oven at 103-105 °C for at least 2 hr, until constant weight is achieved. To do this, cool and weigh the sample as described below, place the sample back in the drying oven for 1 hr and then cool and weigh again. Repeat the steps of drying, cooling and weighing until a constant weight is obtained, or until weight change is less than 0.5 mg. The length of drying time needs to be evaluated for each specific type of sample, and revisited periodically.
- Remove from the oven, place in the desiccator and cool to room temperature.
- Weigh the crucible or weighing boat with the filter on the analytical balance and record the mass (W_2).

8.6.1.3.8 Calculation

Total suspended solids (g/L) =

$$\frac{(W_2(g)-W_1(g))}{V_{sample}(L)} (\times \text{DF if using dilution factor})$$

W_1 = Weight of filter + crucible/aluminium weighing boat before drying (103-105 °C) (g)

W_2 = Weight of residue + filter + crucible/aluminium weighing boat after drying (103-105 °C) (g)

V_{sample} = Volume of sample used (L)

DF = Dilution factor

Total dissolved solids (g/L) =

Total solids (g/L) = Total suspended solids (g/L)

8.6.1.3.9 Data set example

A faecal sludge sample was collected from a ventilated improved pit latrine in Durban, South Africa. It was analysed in six replicates using Method 8.6.1.3. The average TSS (g/L) was 0.37. The results for TSS are presented in Table 8.6 (source: unpublished data UKZN PRG).

Table 8.6 Total suspended solids obtained by oven drying methods.

Sample no.	Filter paper mass (g) (W_1)	Residue + filter mass after drying (g) (W_2)	Sample volume (L)	Total suspended solids (g/L)
1-a	0.4146	0.4289	0.0300	0.4767
1-b	0.4186	0.4313	0.0300	0.4233
1-c	0.4289	0.4446	0.0300	0.4298
1-d	0.4287	0.4427	0.0300	0.4292
1-e	0.4137	0.4264	0.0300	0.4233
1-f	0.4268	0.4276	0.0300	0.0267
Average				0.3682
SD				0.1685

iv. Specific resistance to filtration (SRF) test procedure

1.2.5 Buchner funnel apparatus for determination of specific resistance to filtration

A simple version of the apparatus (Fig. 6) can be constructed from standard laboratory equipment[4]. It consists of a 70 mm dia. Buchner funnel connected to an evacuated measuring cylinder or burette into which the filtrate flows. The required degree of vacuum (usually 49 kPa) is achieved by adjustment of the variable leak into the vacuum reservoir which is evacuated at a constant rate by a water-operated vacuum pump. A more complex technique for setting the degree of vacuum utilizes a mercury manostat[4].

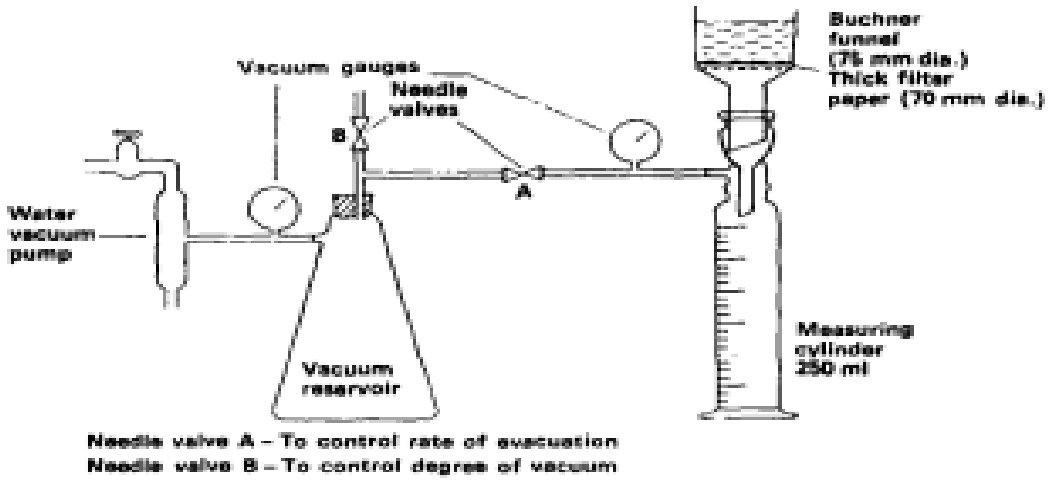


Fig. 6. Simplified apparatus for determining specific resistance to filtration

The degree of vacuum (49 kPa) is first set by adjustment of valve B with valve A closed. The filter medium (which may be a Whatman No. 17, or 3 layers of Whatman No. 1, 70 mm dia. filter paper) is placed in the funnel and wetted with a little water. With the funnel connected to the measuring cylinder, valve A is opened slightly to remove the surplus water and to ensure the filter medium fits closely to the bottom of the funnel. About 300 ml of the sludge are then transferred between beakers to ensure adequate mixing, and a sub-sample of 100 ml is taken for subsequent total dry solids determination. At least 100 ml of the remainder of the sludge sample are then poured into the Buchner funnel. With valve A already slightly open, gauge 1 should immediately indicate that a pressure difference is being applied to the sludge, and filtrate should be allowed to flow into the measuring cylinder. (When there is no indication of a change in pressure it is probably due to a leak in the system; this should be remedied.) Valve A is then gradually opened further so that the required degree of vacuum is reached within about 30 s. During

this period some adjustment of valve B may be necessary to maintain the required degree of vacuum, particularly if the rate of filtration is rapid.

The rate of filtration is then measured by recording the total volume of filtrate collected after various time intervals. The intervals of time do not necessarily have to be constant but may be progressively increased to compensate for the gradual decrease in the filtration rate. Typically between 5 and 10 volume and time measurements are adequate. Throughout the period of observations it is necessary to ensure that the pressure of filtration remains constant.

Finally, after valve A has been closed and the residual vacuum in the system released, a sample of filtrate is taken for the determination of total solids concentration. This figure will approximate to the dissolved solids concentration of the sludge, which on subtraction from the sludge total solids will approximately equal the sludge suspended-solids concentration.

On removing the Buchner funnel for cleansing, check that there is a surplus of sludge covering the filter cake. If there is none it is necessary for the determination to be repeated, but using an increased volume of sludge. This may necessitate the fitting of a cylindrical extension piece to the top of the Buchner funnel.

An example of a calculation to determine the specific resistance to filtration is given in Appendix 1.

Determination of Specific Resistance to Filtration

The relation between time (θ) and the volume of filtrate (V), after the initial time and flow of filtrate have been subtracted (see example) should be such that on plotting $\frac{\theta}{V}$ against V on linear graph paper a straight line can be drawn through the points. (If a straight-line relationship cannot be obtained, despite trying a number of different zero positions of θ and V, an average specific resistance cannot be calculated.) The slope of this line (b) is then directly proportional to the average specific resistance (r) according to the equation:

$$r = \frac{2A^2Pb}{\eta c}$$

where A is the filtration area

P is the filtration pressure

η is the viscosity of the filtrate (assumed to be the same as that of water)

c is the mass of dry suspended solids per unit volume of liquid in the sludge being filtered

b is the slope of the plot of $\frac{\theta}{V}$ against V.

If A is expressed in units of cm^2

P " " " " " kPa

b " " " " " s/ml^2

η " " " " " poise

c " " " " " g/ml

then the value of r may be calculated in units of m/kg (i.e. SI units) by using the following equation:

A set of experimental data is given below. In this example the time (θ) and volume (V) data start when pressure was first applied. These values have been recalculated by discounting the volume of filtrate collected during the first 60 s. Thus from each time θ, 60 s is subtracted to give $\theta_n = \theta - 60$. Similarly, 13 ml (i.e. the volume of filtrate in the first 60 s) is subtracted from the corresponding filtrate volume V to give $V_n = V - 13$. From the tabulated values of V_n and θ_n, the ratios $\frac{\theta_n}{V_n}$ are calculated. The ratios are plotted against the corresponding values of V_n, as shown in Fig. A.

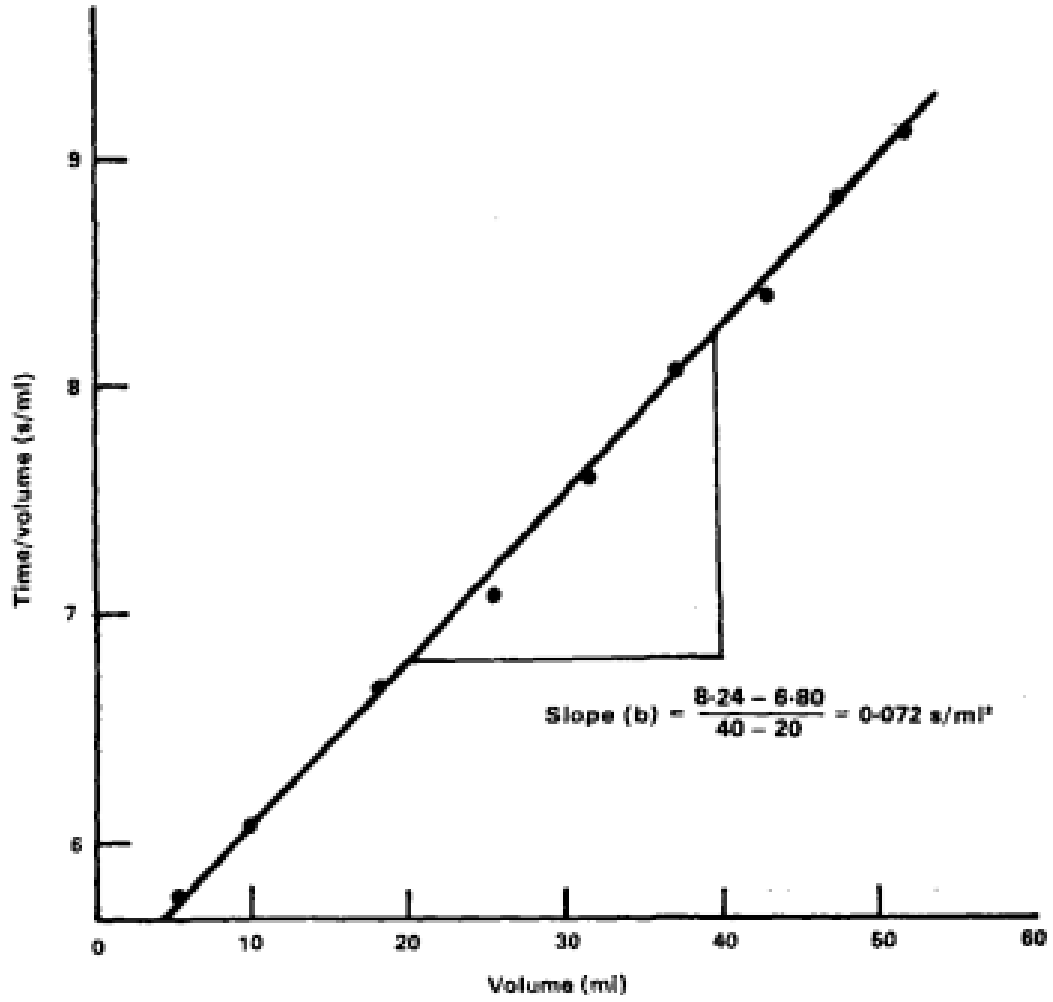


Fig. A. Plot of Buchner-funnel filtration data to obtain specific resistance to filtration

NUMERICAL EXAMPLE

Filtration Data

Experimental data		Derived data		
Time (s) θ	Filtrate (ml) V	Time (s) θ_n	Filtrate (ml) V_n	Ratio θ_n/V_n
0	0			
30	7·2			
60	13·0	0	0	
90	18·2	30	5·2	5·77
120	22·9	60	9·9	6·06
180	31·0	120	18·0	6·67
240	38·4	180	25·4	7·09
300	44·8	240	31·6	7·59
360	50·3	300	37·3	8·04
420	56·1	360	43·1	8·35
480	60·7	420	47·7	8·81

Other Data

Total solids content of sludge = 3·58%
Total solids content of filtrate = 0·35%
$\therefore$ Suspended solids (by difference) = 3·21%

$$\therefore \quad c = \frac{SS}{100-SS} = \frac{3{\cdot}21}{100-3{\cdot}21} = 0{\cdot}0332 \text{ g/ml}$$

Temperature of sludge = 20·4°C
Pressure of filtration = 369 mm of mercury vacuum (= 49 kPa)
Area of filtration = 38·5 cm²

The slope of the line (b) = 0·072 s/ml²

Then with $2A^2 = 2964$
$P = 49$
$b = 0{\cdot}072$
$\eta = 0{\cdot}01$
$c = 0{\cdot}0332$

$$r = \frac{2964 \times 49 \times 0{\cdot}072}{0{\cdot}01 \times 0{\cdot}0332} \times 10^5 \text{ m/kg}$$

v. Moisture content analysis test procedure

8.6.1.5 Total solids and moisture content – thermal balance (moisture analyser) method[8]

8.6.1.5.1 Introduction

A moisture analyser is designed to determine relative moisture content in small samples of various substances, by measuring the change of weight due to water evaporation during convective drying. This method is applicable for all types of sludge – liquid, slurry, semi-solid and solid; however, samples with a higher moisture content will have a longer drying and measurement time. Method 8.6.1.1 and Method 8.6.1.5 are equally suitable to determine TS and moisture content, and should be selected depending on the availability of equipment.

8.6.1.5.2 Safety precautions

- General health and safety (H&S) procedures specific for conducting laboratory analysis of faecal sludge are presented in Section 8.2. Before conducting this method, it is important to be familiar with Section 8.2.3 to ensure safety measures are properly carried out.
- Appropriate personal protective equipment (PPE) should be used; specific details are covered in Section 8.2.3.1.
- Always conduct the TS analysis in a room with sufficient airflow and an exhaust system.
- Do not place any flammable substances on or near the moisture analyser.

8.6.1.5.3 Apparatus and instruments

- Aluminium weighing boats
- Thermal balance (moisture analyser)

8.6.1.5.4 Quality control

General information on quality assurance and quality control (QA/QC) is provided in Section 8.3. Information on standards, operating conditions and interferences that are specific to this method includes:

- Before using a moisture analyser, make sure the instrument was left on for a sufficient period of time (see Section 8.6.1.5.7).
- Minimise external environmental influences such as air draught, vibrations or direct sunlight.
- Ensure the analyser is levelled. This is essential for testing liquid samples, which must be at uniform level in the sample container.
- Exclude larger, inconsistent or floating particles from the sample if it is determined that their inclusion could affect the final result (*e.g.* hair, stones, glass and maggots).
- Disperse visible floating oil and grease with a blender or stainless steel mixing rod before withdrawing a sample portion for analysis.

8.6.1.5.5 Sample preservation

Samples should be analysed as soon as possible. If samples cannot be analysed immediately, they should be stored in a refrigerator at 4 °C for no longer than 7 days. Before analysis, let the samples return to ambient temperature. Do not freeze the samples.

8.6.1.5.6 Sample preparation

Thoroughly mix all the samples using a stainless steel rod (or other appropriate tool) in order to have representative samples. If desired, samples can also be blended (see Section 8.4.2).

8.6.1.5.7 Analysis protocol

Equipment preparation

- Switch the instrument on. Wait until the analyser completes its self-examination and finishes heating up. 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. The program must be set to end when the sample mass changes less than 0.05% of mass per minute.
- Check that the temperature is 105 °C for moisture analysis.

Procedure

- Press 'Start Program' and follow prompts on the display screen; this can vary per model and brand.
- Open the lid of the moisture analyser, place the clean and empty weighing boat on the weighing cradle.
- Close the cover gently and tare the boat weight; the LCD screen should now show weight as '0'

and a flashing icon to indicate that the machine is ready for loading the sample.

- Lift the lid of the moisture analyser and then evenly spread 1-3 g of the wet sample on the weighing boat.
- 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 the sample weight and its moisture content.
- Record the moisture reading (before lifting the lid); this is the end of the drying procedure.
- Press 'Stop' and lift the lid to end the current testing.

Appendix B: Data Analysis using Excel spreadsheet

i. Sludge volume index (SVI) and Diluted sludge volume index (DSVI) data collection and calculations

Table 10: SVI data for ST samples; and DSVI data for VIP and UDDT samples

Samples	Replication	Volume (ml)	Filter mass (g)	Residue + Filter mass after oven (g)	Mass of Residue (g)	Suspended solids (g/L)	Mean SS (g/L)	Settled sludge volume (ml/L)	SVI/ DSVI (ml/g)
ST1	1	20	0.4157	0.6596	0.2439	12.20	11.15	400	35.9
	2	20	0.4149	0.6169	0.202	10.10			
ST2	1	20	0.412	0.591	0.179	8.95	8.39	225	26.8
	2	20	0.4099	0.5664	0.1565	7.83			
VIP1	1	5	0.4108	0.6148	0.204	40.80	36.89	700	19.0
	2	5	0.4095	0.5744	0.1649	32.98			
VIP2	1	5	0.4082	0.5914	0.1832	36.64	36.01	675	18.7
	2	5	0.4093	0.5862	0.1769	35.38			
UDDT1	1	5	0.4108	0.5181	0.1073	21.46	20.58	525	25.5
	2	5	0.4129	0.5114	0.0985	19.70			

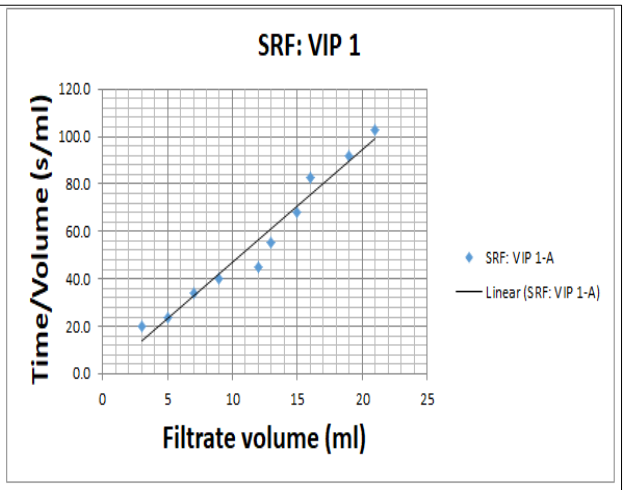
UDDT2	1	5	0.4108	0.5087	0.0979	19.58	15.67	550	35.1
	2	5	0.4076	0.4664	0.0588	11.76			

ii. Specific resistance to filtration (SRF) data collection and calculations

Figure 18: Collected data and SRF calculations for VIP1

Experimental Data		Derieved Data		
Time (s) θ	Filtrate (ml) V	Time (s) θ n (θn = θ	Filtrate (ml) Vn	Ratio θ n/Vn
0	0			
30	1			
60	2	0	0	
120	5	60	3	20.0
180	7	120	5	24.0
300	9	240	7	34.3
420	11	360	9	40.0
600	14	540	12	45.0
780	15	720	13	55.4
1080	17	1020	15	68.0
1380	18	1320	16	82.5
1800	21	1740	19	91.6
2220	23	2160	21	102.9

NOTES		
Temperature of sludge (oC)		14
Pressure of		49
Area of filtration		63.6173
Filter pore size		1.7
Filtered volume		100
Slope	4.739759	
r =	**3E+14**	**m/kg**

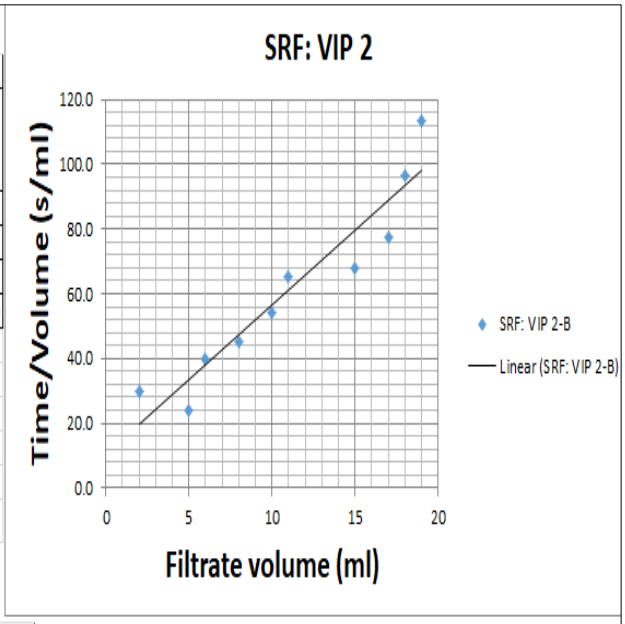


	Mass of crucible (g)	Mass of crucible + sample (g)	Mass of sample (g) A	Mass of crucible + sample (g) (after oven drying)	Mass of solids (g) B	Total Solids content (%)	Suspended solids %	C= (SS)/ 100-SS
Original sample	44.9433	72.7007	27.7574	46.4205	1.4772	5.321824		
Filtrate	39.9273	57.631	17.7037	39.9576	0.0303	0.171151	5.150673	0.054304

Figure 19: Collected data and SRF calculations for VIP2

Experimental Data		Derieved Data		
Time (s) θ	Filtrate (ml) V	Time (s) θ n (θn = θ	Filtrate (ml) Vn	Ratio θ n/Vn
0	0			
30	1			
60	3	0	0	
120	5	60	2	30.0
180	8	120	5	24.0
300	9	240	6	40.0
420	11	360	8	45.0
600	13	540	10	54.0
780	14	720	11	65.5
1080	18	1020	15	68.0
1380	20	1320	17	77.6
1800	21	1740	18	96.7
2220	22	2160	19	113.7

NOTES	
Temperature of sludge (oC)	15
Pressure of filtration	49
Area of filtration (cm2)	63.6173
Filter pore size	1.7
Filtered volume (mL)	100
Slope	4.605798219
r=	3.07E+14 m/kg

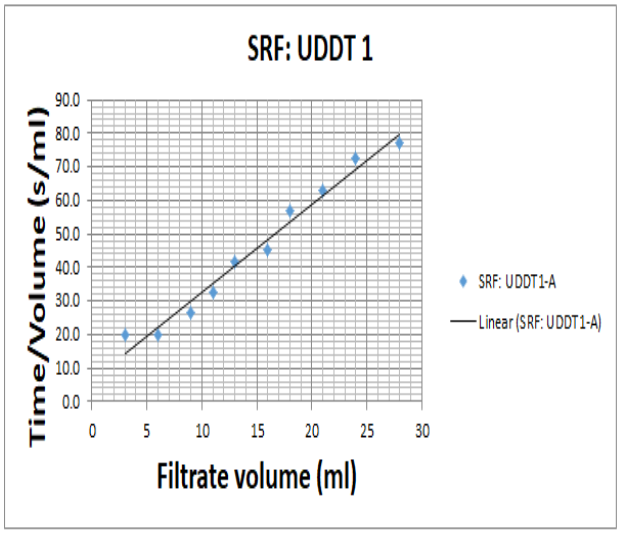


	Mass of crucible (g)	Mass of crucible + sample (g)	Mass of sample (g) A	Mass of crucible + sample (g) (after oven crying)	Mass of solids (g) B	Total Solids content (%)	Suspended solids %	C= (SS)/ 100-SS
Original sample	36.8421	62.8782	26.0361	38.3493	1.5072	5.788885		
Filtrate	42.5202	60.6011	18.0809	42.552	0.0318	0.175876	5.613009	0.059468039

Figure 20: Collected data and SRF calculations for UDDT1

Experimental Data		Derieved Data		
Time (s) θ	Filtrate (ml) V	Time (s) θ n (θn = θ	Filtrate (ml) Vn	Ratio θ n/Vn
0	0			
30	5			
60	7	0	0	
120	10	60	3	20.0
180	13	120	6	20.0
300	16	240	9	26.7
420	18	360	11	32.7
600	20	540	13	41.5
780	23	720	16	45.0
1080	25	1020	18	56.7
1380	28	1320	21	62.9
1800	31	1740	24	72.5
2220	35	2160	28	77.1

NOTES		
Temperature of sludge (oC)		15
Pressure of filtration		49
Area of filtration		63.6173
Filter pore size		1.7
Filtered volume		100
Slope	2.598412	
r	3E+14	m/kg

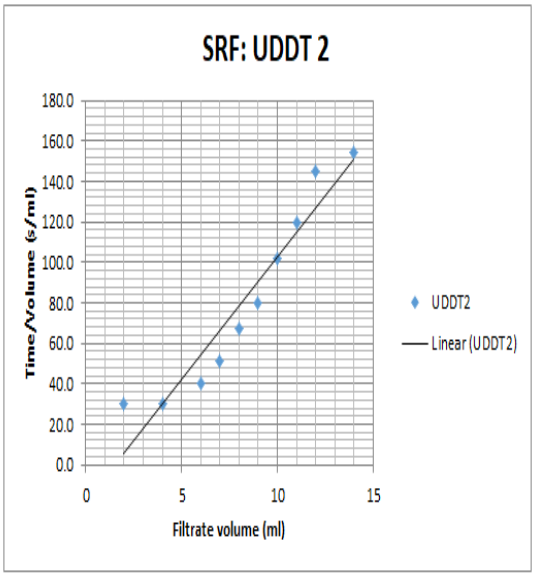


	Mass of crucible (g)	Mass of crucible + sample (g)	Mass of sample (g) A	Mass of crucible + sample (g) (after oven drying)	Mass of solids (g) B	Total Solids content (%)	Suspended solids %	C= (SS)/ 100-SS
Original sample	69.6334	94.3662	24.7328	70.4219	0.7885	3.188074	3.046177	0.0314188
Filtrate	65.4292	89.2493	23.8201	65.463	0.0338	0.141897		

Figure 21: Collected data and SRF calculations for UDDT2

Experimental Data		Derieved Data		
Time (s) θ	Filtrate (ml) V	Time (s) θ n (θn = θ -60)	Filtrate (ml) Vn	Ratio θ n/Vn
0	0			
30	2			
60	3	0	0	
120	5	60	2	30.0
180	7	120	4	30.0
300	9	240	6	40.0
420	10	360	7	51.4
600	11	540	8	67.5
780	12	720	9	80.0
1080	13	1020	10	102.0
1380	14	1320	11	120.0
1800	15	1740	12	145.0
2220	17	2160	14	154.3

NOTES		
Temperature of sludge (oC)		10
Pressure of filtration		49
Area of filtration (cm2)		63.6173
Filter pore size		1.7
Filtered volume (mL)		100
Slope	12.05750556	
r	6.14E+14	m/kg

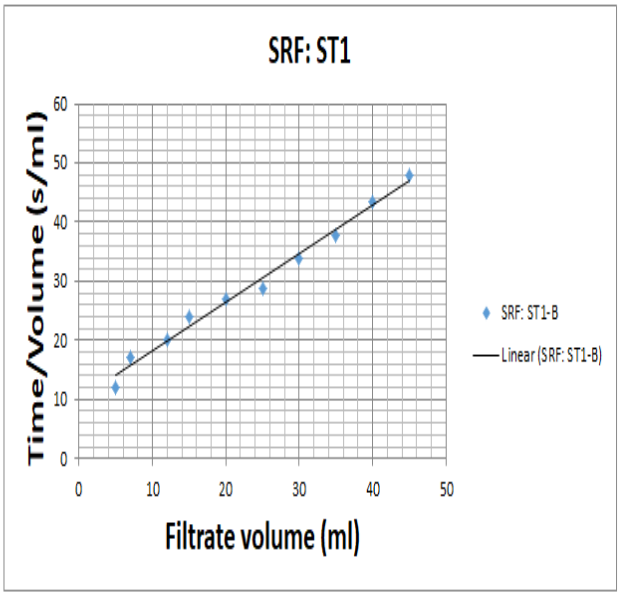


	Mass of crucible (g)	Mass of crucible + sample (g)	Mass of sample (g) A	Mass of crucible + sample (g) (after oven drying)	Mass of solids (g) B	Total Solids content (%)	Suspended solids %	C= (SS)/ 100-SS
Original sample	33.4933	58.479	24.9857	35.3574	1.8641	7.460668	7.222517	0.077847738
Filtrate	41.6341	52.0057	10.3716	41.6588	0.0247	0.23815		

Figure 22: Collected data and SRF calculations for ST1

Experimental Data		Derieved Data		
Time (s) θ	Filtrate (ml) V	Time (s) θ n (θn = θ	Filtrate (ml) Vn	Ratio θ n/Vn
0	0			
30	10			
60	15	0	0	
120	20	60	5	12.0
180	22	120	7	17.1
300	27	240	12	20.0
420	30	360	15	24.0
600	35	540	20	27.0
780	40	720	25	28.8
1080	45	1020	30	34.0
1380	50	1320	35	37.7
1800	55	1740	40	43.5
2220	60	2160	45	48.0

NOTES	
Temperature of sludge (oC)	11
Pressure of filtration	49
Area of filtration (cm2)	63.6173
Filter pore size	1.7
Filtered volume (mL)	100
Slope	0.828468123
r	2.17222E+14 m/kg

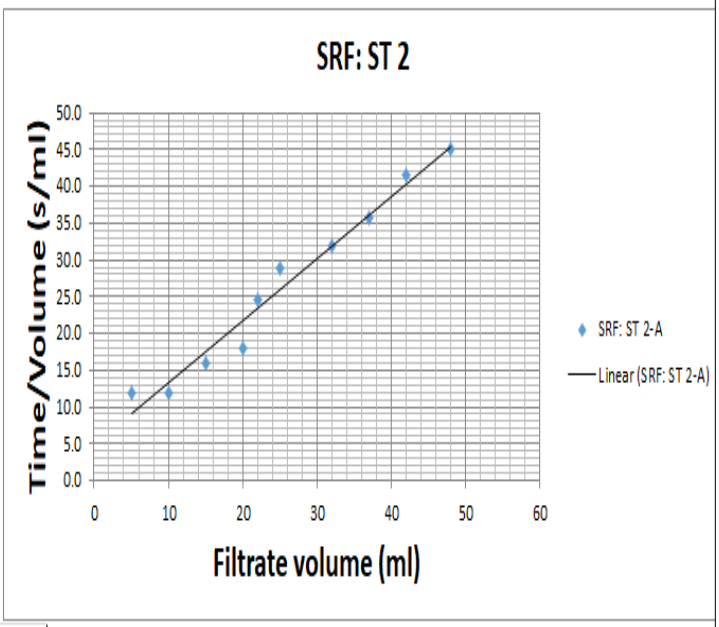


	Mass of crucible (g)	Mass of crucible + sample (g)	Mass of sample (g) A	Mass of crucible + sample (g) (after oven	Mass of solids (g) B	Total Solids content (%)	Suspended solids %	C= (SS)/ 100-SS
Original sample	39.4284	69.4813	30.0529	39.9002	0.4718	1.569898	1.49014607	0.015126873
Filtrate	44.1666	74.8867	30.7201	44.1911	0.0245	0.079752		

Figure 23: Collected data and SRF calculations for ST2

Experimental Data		Derieved Data		
Time (s) θ	Filtrate (ml) V	Time (s) θ n (θn = θ	Filtrate (ml) Vn	Ratio θ n/Vn
0	0			
30	20			
60	25	0	0	
120	30	60	5	12.0
180	35	120	10	12.0
300	40	240	15	16.0
420	45	360	20	18.0
600	47	540	22	24.5
780	50	720	25	28.8
1080	57	1020	32	31.9
1380	62	1320	37	35.7
1800	67	1740	42	41.4
2220	73	2160	48	45.0

NOTES		
Temperature of sludge (oC)		15
Pressure of		49
Area of filtration		63.6173
Filter pore size		1.7
Filtered volume		100
Slope	0.842214	
r	4E+14	m/kg



	Mass of crucible (g)	Mass of crucible + sample (g)	Mass of sample (g) A	Mass of crucible + sample (g) (after oven drying)	Mass of solids (g) B	Total Solids content (%)	Suspended solids %	C= (SS)/ 100-SS
Original sample	33.4931	64.135	30.6419	33.8022	0.3091	1.008749	0.915846	0.009243
Filtrate	41.6339	68.113	26.4791	41.6585	0.0246	0.092903		

iii. Centrifugation data and calculations

Table 11: Percent moisture content of centrifuged faecal sludge samples

MOISTURE CONTENT (%)						
TIME (MIN)	3000RPM					
	VIP		UDDT		ST	
	VIP1	VIP2	UDDT1	UDDT2	ST1	ST2
0	80.825	73.141	78.326	68.856	98.126	98.979
20	80.268	70.555	70.588	63.082	81.971	82.742
40	70.789	70.63	69.598	63.453	82.37	84.867
60	64.179	52.303	68.527	60.474	82.11	84.68
80	67.353	64.848	69.571	61.189	82.375	86.57
100	63.328	64.918	64.125	60.656	82.335	84.528
120	66.75	64.161	70.308	61.111	83.378	83.658
TIME (MIN)	4000RPM					
	VIP		UDDT		ST	
	VIP1	VIP2	UDDT1	UDDT2	ST1	ST2
0	80.825	73.141	78.326	68.856	98.126	98.979
20	65.038	63.23	72.138	61.395	84	81.899
40	71.987	65.81	69.783	60.632	81.549	81.818
60	65.962	56.791	67.867	60.776	81.098	82.212
80	62.544	63.068	69.053	60.369	79.407	81.642
100	65.851	67.997	68.442	63.362	79.77	82.41
120	68.57	65.689	71.895	56.325	79.496	82.135
TIME (MIN)	5000RPM					
	VIP		UDDT		ST	
	VIP1	VIP2	UDDT1	UDDT2	ST1	ST2
0	80.825	73.141	78.326	68.856	98.126	98.979
20	70.672	71.137	73.386	66.43	82.586	83.043
40	70.496	58.166	71.209	65.164	81.715	82.601
60	67.069	59.481	77.835	63.346	79.587	82.984
80	67.867	52.913	68.944	64.868	79.046	81.391
100	69.767	57.576	58.089	62.465	79.536	83.696
120	67.241	54.131	66.393	64.002	80.752	83.172

Table 12: Percent moisture reduction of centrifuged faecal sludge samples

MOISTURE CONTENT REDUCTION (%)						
TIME (MIN)	**3000RPM**					
	VIP		**UDDT**		**ST**	
	VIP1	**VIP2**	**UDDT1**	**UDDT2**	**ST1**	**ST2**
20	0.6	2.6	7.7	5.8	16.2	16.2
40	10.0	2.5	8.7	5.4	15.8	14.1
60	16.6	20.8	9.8	8.4	16.0	14.3
80	13.5	8.3	8.8	7.7	15.8	12.4
100	17.5	8.2	14.2	8.2	15.8	14.5
120	14.1	9.0	8.0	7.7	14.7	15.3
TIME (MIN)	**4000RPM**					
	VIP		**UDDT**		**ST**	
	VIP1	**VIP2**	**UDDT1**	**UDDT2**	**ST1**	**ST2**
20	15.8	9.9	6.2	7.5	14.1	17.1
40	8.8	7.3	8.5	8.2	16.6	17.2
60	14.9	16.4	10.5	8.1	17.0	16.8
80	18.3	10.1	9.3	8.5	18.7	17.3
100	15.0	5.1	9.9	5.5	18.4	16.6
120	12.3	7.5	6.4	12.5	18.6	16.8
TIME (MIN)	**5000RPM**					
	VIP		**UDDT**		**ST**	
	VIP1	**VIP2**	**UDDT1**	**UDDT2**	**ST1**	**ST2**
20	10.2	2.0	4.9	2.4	15.5	15.9
40	10.3	15.0	7.1	3.7	16.4	16.4
60	13.8	13.7	0.5	5.5	18.5	16.0
80	13.0	20.2	9.4	4.0	19.1	17.6
100	11.1	15.6	20.2	6.4	18.6	15.3
120	13.6	19.0	11.9	4.9	17.4	15.8

Table 13: Calculation of the mean % moisture content reduction of centrifuged samples from identical OSS at measured time intervals

	3000RPM								
	VIP			UDDT			ST		
TIME (MIN)	VIP1	VIP2	Mean VIP	UDDT1	UDDT2	Mean UDDT	ST1	ST2	Mean ST
20	0.6	2.6	1.6	7.7	5.8	6.8	16.2	16.2	16.2
40	10.0	2.5	6.3	8.7	5.4	7.1	15.8	14.1	14.9
60	16.6	20.8	18.7	9.8	8.4	9.1	16.0	14.3	15.2
80	13.5	8.3	10.9	8.8	7.7	8.2	15.8	12.4	14.1
100	17.5	8.2	12.9	14.2	8.2	11.2	15.8	14.5	15.1
120	14.1	9.0	11.5	8.0	7.7	7.9	14.7	15.3	15.0
	4000RPM								
	VIP			UDDT			ST		
TIME (MIN)	VIP1	VIP2	Mean VIP	UDDT1	UDDT2	Mean UDDT	ST1	ST2	Mean ST
20	15.8	9.9	12.8	6.2	7.5	6.8	14.1	17.1	15.6
40	8.8	7.3	8.1	8.5	8.2	8.4	16.6	17.2	16.9
60	14.9	16.4	15.6	10.5	8.1	9.3	17.0	16.8	16.9
80	18.3	10.1	14.2	9.3	8.5	8.9	18.7	17.3	18.0
100	15.0	5.1	10.1	9.9	5.5	7.7	18.4	16.6	17.5
120	12.3	7.5	9.9	6.4	12.5	9.5	18.6	16.8	17.7
	5000RPM								
	VIP			UDDT			ST		
TIME (MIN)	VIP1	VIP2	Mean VIP	UDDT1	UDDT2	Mean UDDT	ST1	ST2	Mean ST
20	10.2	2.0	6.1	4.9	2.4	3.7	15.5	15.9	15.7
40	10.3	15.0	12.7	7.1	3.7	5.4	16.4	16.4	16.4
60	13.8	13.7	13.7	0.5	5.5	3.0	18.5	16.0	17.3
80	13.0	20.2	16.6	9.4	4.0	6.7	19.1	17.6	18.3
100	11.1	15.6	13.3	20.2	6.4	13.3	18.6	15.3	16.9
120	13.6	19.0	16.3	11.9	4.9	8.4	17.4	15.8	16.6

iv. Sludge density and porosity data and calculation

Table 14: Septic tank density and porosity test data

Sample	Replicates	Mass of crucible, W1 (g)	Mass of crucible + Wet sample, W2 (g)	Mass of Wet sample, W3 (W2-W1) (g)	Total Volume of Sample (Vt) *ml*	Bulk density (Dbwet), W3/Vt g/ml; gcm3	Average Bulk density (Dbwet) gcm3	Porosity
	1	35	44.9	9.9	10	1	1	1
ST1	2	43.2	53.2	10	10	1		
	1	38.8	48.7	9.9	10	1	1	1
ST2	2	48.9	59	10.1	10	1		

Table 15: VIP and UDDT density and porosity test data

Sample	Mass of wet sample (g)	Vol. of core A (cm3)	Bulk density (Dbwet) (g/cm3)	Mass of dry sample (g)	Vol. of core B (cm3)	Bulk density / Particle density (Dbdry) (g/cm3)	Porosity (Ps) (1-(Db wet/Db dry))
VIP1	107.1	95.0	1.1	94.6	52.9	1.8	0.4
VIP2	112.5	95.0	1.2	102.1	52.9	1.9	0.4
UDDT1	106.5	95.0	1.1	98.1	52.9	1.9	0.4
UDDT2	112.0	95.0	1.2	98.9	52.9	1.9	0.4

v. PSD programme generated data

Table 16: Data generated during the particle size analysis of VIP, UDDT, and ST samples

	% Volume					
Size (µm)	VIP 1	VIP 2	UDDT 1	UDDT 2	ST 1	ST 2
0.01	0	0	0	0	0	0
0.0114	0	0	0	0	0	0
0.0129	0	0	0	0	0	0
0.0147	0	0	0	0	0	0
0.0167	0	0	0	0	0	0
0.0189	0	0	0	0	0	0
0.0215	0	0	0	0	0	0
0.0244	0	0	0	0	0	0
0.0278	0	0	0	0	0	0
0.0315	0	0	0	0	0	0
0.0358	0	0	0	0	0	0
0.0407	0	0	0	0	0	0
0.0463	0	0	0	0	0	0
0.0526	0	0	0	0	0	0
0.0597	0	0	0	0	0	0
0.0679	0	0	0	0	0	0
0.0771	0	0	0	0	0	0
0.0876	0	0	0	0	0	0
0.0995	0	0	0	0	0	0
0.113	0	0	0	0	0	0
0.128	0	0	0	0	0	0
0.146	0	0	0	0	0	0
0.166	0	0	0	0	0	0
0.188	0	0	0	0	0	0
0.214	0	0	0	0	0	0
0.243	0	0	0	0	0	0
0.276	0	0	0	0	0	0
0.314	0	0	0	0	0	0
0.357	0	0	0	0	0	0
0.405	0	0	0	0	0	0
0.46	0	0	0	0	0	0
0.523	0	0	0	0	0	0
0.594	0.085	0.105	0	0.08	0	0
0.675	0.245	0.3	0.145	0.22	0.06	0.125
0.767	0.435	0.495	0.29	0.38	0.15	0.235
0.872	0.575	0.645	0.4	0.485	0.215	0.325
0.991	0.645	0.7	0.47	0.535	0.24	0.35
1.13	0.655	0.705	0.485	0.53	0.235	0.335
1.28	0.66	0.71	0.495	0.525	0.21	0.305
1.45	0.685	0.74	0.52	0.54	0.205	0.3
1.65	0.745	0.805	0.56	0.585	0.225	0.33
1.88	0.83	0.895	0.64	0.655	0.27	0.4
2.13	0.905	0.98	0.71	0.725	0.34	0.49
2.42	0.955	1.035	0.78	0.785	0.415	0.6
2.75	0.99	1.055	0.84	0.825	0.485	0.705
3.12	0.99	1.065	0.9	0.86	0.56	0.81
3.55	0.995	1.05	0.975	0.9	0.645	0.92
4.03	1.01	1.05	1.055	0.94	0.725	1.03
4.58	1.04	1.065	1.165	0.985	0.835	1.16
5.21	1.09	1.085	1.29	1.06	0.95	1.295
5.92	1.145	1.115	1.43	1.135	1.085	1.445
6.72	1.22	1.16	1.565	1.215	1.24	1.61

7.64	1.285	1.21	1.71	1.295	1.415	1.78
8.68	1.365	1.255	1.84	1.39	1.61	1.965
9.86	1.435	1.29	1.95	1.47	1.825	2.165
11.2	1.505	1.34	2.05	1.56	2.055	2.375
12.7	1.6	1.39	2.13	1.645	2.295	2.605
14.5	1.68	1.455	2.215	1.74	2.54	2.825
16.4	1.79	1.525	2.285	1.835	2.78	3.065
18.7	1.89	1.6	2.345	1.93	2.995	3.29
21.2	2	1.69	2.4	2.015	3.17	3.49
24.1	2.105	1.775	2.44	2.095	3.305	3.665
27.4	2.18	1.855	2.465	2.15	3.385	3.795
31.1	2.25	1.92	2.475	2.19	3.41	3.865
35.3	2.29	1.97	2.47	2.21	3.385	3.895
40.1	2.33	2.01	2.44	2.205	3.335	3.875
45.6	2.365	2.035	2.415	2.21	3.255	3.8
51.8	2.41	2.07	2.39	2.21	3.17	3.695
58.9	2.475	2.11	2.37	2.225	3.1	3.57
66.9	2.55	2.165	2.37	2.25	3.05	3.405
76	2.63	2.23	2.37	2.285	2.99	3.235
86.4	2.71	2.3	2.38	2.32	2.94	3.025
98.1	2.75	2.36	2.375	2.345	2.86	2.805
111	2.74	2.375	2.325	2.34	2.755	2.555
127	2.65	2.35	2.245	2.285	2.605	2.29
144	2.5	2.28	2.115	2.21	2.435	2.025
163	2.305	2.175	1.97	2.105	2.255	1.78
186	2.105	2.06	1.825	1.98	2.085	1.57
211	1.935	1.97	1.725	1.88	1.95	1.415
240	1.83	1.93	1.675	1.81	1.87	1.32
272	1.81	1.955	1.7	1.8	1.845	1.275
310	1.86	2.05	1.78	1.83	1.85	1.26
352	1.965	2.22	1.89	1.895	1.87	1.24
400	2.065	2.42	2	1.98	1.875	1.185
454	2.115	2.62	2.065	2.06	1.83	1.06
516	2.08	2.79	2.065	2.1	1.72	0.875
586	1.94	2.87	1.955	2.075	1.54	0.63
666	1.7	2.84	1.775	1.97	1.28	0.37
756	1.375	2.655	1.535	1.81	0.99	0.17
859	1.06	2.34	1.25	1.59	0.67	0.02
976	0.79	1.915	1.04	1.37	0.36	0
1110	0.64	1.435	0.875	1.19	0.165	0
1260	0.595	0.95	0.725	1.075	0.07	0
1430	0.605	0.585	0.605	1.035	0.02	0
1630	0.645	0.31	0.52	1.065	0	0
1850	0.695	0.195	0.455	1.11	0	0
2100	0.705	0.145	0.405	1.11	0	0
2390	0.665	0.11	0.34	1.03	0	0
2710	0.545	0.08	0.27	0.855	0	0
3080	0.385	0.04	0.18	0.595	0	0
3500	0.2	0.02	0.09	0.305	0	0

vi. Correlation and regression analysis:

i. Correlation and regression analysis of Density and porosity to SVI and SRF

Table 17: Correlation analysis of Density and porosity to SVI and SRF

Sample		Density	Porosity	SVI	SRF
VIP	1	1100	0.4	35.9	3.5
	2	1120	0.4	26.8	3.1
UDDT	1	1100	0.4	19.0	3.3
	2	1120	0.4	18.7	6.1
ST2	1	1000	1.0	25.5	2.2
	2	1000	1.0	35.1	3.6

	Density	*SVI*
Density	1	
SVI	-0.39808	1

	Density	*SRF*
Density	1	
SRF	0.484105	1

	Porosity	*SVI*
Porosity	1	
SVI	0.348481	1

	Porosity	*SRF*
Porosity	1	
SRF	-0.4415	1

Table 18: Regression analysis of Density and porosity to SVI

Regression analysis of Density and porosity to SVI								
SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.398080369							
R Square	0.15846798							
Adjusted R Square	-0.051915025							
Standard Error	7.663174262							
Observations	6							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	44.23319106	44.23319106	0.753235652	0.434420943			
Residual	4	234.8969591	58.72423977					
Total	5	279.1301502						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	82.35688665	64.04450574	1.285932114	0.267858653	-95.45916782	260.1729411	-95.45916782	260.1729411
Density	-0.051724217	0.059597562	-0.867891498	0.434420943	-0.217193575	0.113745141	-0.217193575	0.113745141
SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.34848115							
R Square	0.121439112							
Adjusted R Square	-0.09820111							
Standard Error	7.829955822							
Observations	6							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	33.89731748	33.89731748	0.55290015	0.498437896			
Residual	4	245.2328327	61.30820817					
Total	5	279.1301502						

Table 19: Regression analysis of Density and porosity to SRF

Regression analysis of Density and porosity to SRF								
SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.484105106							
R Square	0.234357754							
Adjusted R Square	0.042947192							
Standard Error	1.304959445							
Observations	6							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	2.08500672	2.085007	1.224372	0.330569234			
Residual	4	6.811676613	1.702919					
Total	5	8.896683333						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-8.431693548	10.90611799	-0.77312	0.482601	-38.7119315	21.84854436	-38.71193145	21.84854436
Density	0.011229839	0.010148849	1.106513	0.330569	-0.01694788	0.039407562	-0.016947884	0.039407562
SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.441496784							
R Square	0.19491941							
Adjusted R Square	-0.006350738							
Standard Error	1.338146766							
Observations	6							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	1.734136265	1.734136	0.968447	0.380782971			
Residual	4	7.162547068	1.790637					
Total	5	8.896683333						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	4.700891977	1.225200033	3.836836	0.01851	1.299191344	8.10259261	1.299191344	8.10259261
Porosity	-1.839121151	1.868841535	-0.9841	0.380783	-7.02785708	3.349614781	-7.027857083	3.349614781

ii. Correlation and regression analysis of PSD to SVI and SRF

Table 20: Correlation analysis of PSD to SVI and SRF

Samples		Volume (%) Size (µm) 10-3500	Evaluation indices SVI	SRF
VIP	1	80.0	35.9	3.5
	2	79.5	26.8	3.1
UDDT	1	79.8	19.0	3.3
	2	81.9	18.7	6.1
ST	1	86.1	25.5	2.7
	2	81.3	35.1	3.6

	Size/SVI	
	Size	*SVI*
Size	1	
SVI	-0.11581	1

	Size/SRF	
	Size	*SRF*
Size	1	
SRF	-0.08506	1

Table 21: Regression analysis of PSD to SVI and SRF

Regression analysis of PSD to SVI and SRF								
SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.115805467							
R Square	0.013410906							
Adjusted R Square	-0.233236367							
Standard Error	8.297390583							
Observations	6							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	3.743388228	3.743388	0.054373	0.827068328			
Residual	4	275.3867619	68.84669					
Total	5	279.1301502						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	55.53104673	123.0911013	0.451138	0.675266	-286.2246389	397.2867323	-286.2246389	397.2867323
Size	-0.352345405	1.511046087	-0.23318	0.827068	-4.547681917	3.842991107	-4.547681917	3.842991107
SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.085055593							
R Square	0.007234454							
Adjusted R Square	-0.240956933							
Standard Error	1.372686784							
Observations	6							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0.054923974	0.054924	0.029149	0.872724276			
Residual	4	7.537076026	1.884269					
Total	5	7.592						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	7.185374327	20.36369461	0.352852	0.742008	-49.35330591	63.72405456	-49.35330591	63.72405456
Size	-0.042679287	0.249981361	-0.17073	0.872724	-0.736738814	0.65138024	-0.736738814	0.65138024