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**Rheology of sludge in pour-flush toilets: understanding the
requirements for pit emptying technology design**

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Pour-flush (PF) toilets are seen as bridging the gap between basic on-site sanitation and the water-borne sewerage systems that people aspire to. Limited studies have been conducted on the rheological properties of PF sludge, which are a key component in designing and selecting appropriate pit emptying equipment. Samples from active and standing PF leach pits were tested for moisture content and viscosity. The two variables were linked using the fresh faeces viscosity model (Woolley et al., 2014). A second model was used to demonstrate how the volume and moisture of material in standing PF leach pits changed over time. This showed that PF leach pits could be emptied using a pump within two months of active use. Alternatively, PF leach pits can be left for up to five years after which the volume will have reduced to 45 % of the original volume and can be dug out manually.

Introduction

In South Africa, the pour-flush toilet (PF), adapted from traditional Indian design, was tested in the outskirts of the Pietermaritzburg area. Existing ventilated improved pits (VIP) can be converted into PF leach pits by connecting the pedestal to either single or twin on-site leach pits, where the faecal sludge (FS) and flush water is stored and degraded. Some of the material stored in the leach pits will leach into the soil through the porous walls. In the case of twin leach pits, the pipe connection is diverted to the second pit after the first pit is filled and the FS in the first pit degrades. In the case of a single pit, it can be emptied when full or a second pit can be constructed. The PF toilet is seen as bridging the gap between basic on-site sanitation technologies and the water-borne sewerage systems that people aspire to, and the initial results were encouraging with respect to performance and user satisfaction (Still and Louton, 2012).

Limited studies have been conducted on the physical and chemical composition of FS (Buckley et al., 2008; Radford et al., 2014) and to date, the characteristics of PF sludge is documented in neither South Africa nor India. To ensure the success of this technology, understanding the rheology of PF sludge early on is important for design optimisation and management of pit emptying systems. Rheology is the study of material deformity and flow, and is considers the behaviour of non-Newtonian fluids, and the plastic flow of solids. This is more relevant than considering viscosity alone as it take into account the non-Newtonian properties of FS. Some fluids, like water, are Newtonian and shear stress is linearly proportional to the strain rate on the fluid. Non-Newtonian fluids do not conform to this linearity. Some, like custard, are shear-thickening and have a viscosity that increases with shear strain, whilst others, like ketchup, are shear-thinning fluids and have a viscosity that reduces with shear strain. FS can be considered as is a shear-thinning fluid or even, at low moisture contents as a plastic solid (Septien et al., 2017), and therefore rheology provides a more complete picture of flow behaviour over a range of conditions than viscosity at a single value of shear rate.

This study investigates the rheological properties of the FS stored in the PF leach pits. The difference between the active and standing leach pits is examined. The results will aid understanding of the rheological behaviours that informs the selection of appropriate pit emptying equipment.

Materials and methods

Sample collection

Four sites with PF leach pits were selected for sampling and analysis from the pilot scheme on the outskirts of Pietermaritzburg. The sites are referred to Site 1, Site 2, Site 3 and Site 4. Site 1 and Site 2 have twin leach pits, one active (a) and one standing (b); Site 3 and Site 4 each have a single, active leach pit (s).

Samples were collected from the leach pits on four separate occasions over a period of eleven months, with a sample taken from the front and back half of each pit. The aim was to identify changes in sludge composition over time, particularly in the standing leach pits. Sampling Campaign 1 took place in May 2013, Campaign 2 was two months later in July 2013, Campaign 3 was in November 2013 and Campaign 4 in March 2014. The single leach pits (Sites 3 and 4) were not sampled during Campaign 1, as the leach pits originally selected were deemed unrepresentative because of a high water table level that flooded the pits. New leach pits were identified for Sites 3 and 4 and were sampled from Campaign 2 onwards.

Sampling equipment was designed and made at the University of KwaZulu-Natal (UKZN) and tested on-site for its ability to retrieve samples from the leach pit, with alterations made after each sampling campaign to improve the equipment. A tube at the end of a long handle was used to take a 'core' sample of dry soil-like sludge. A plunger was built into the tube to push the sludge out of the tube and into the storage container. A bucket at the end of a long handle was used to scoop out wetter sludge.

Samples were stored in a 2.5 litre bucket with a lid and lined with a plastic bag. The samples were transported to UKZN and stored in a cold room below 4°C.

Solids and moisture content

Total solids, volatile solids, ash (the material that remains after combustion of a sample at 500 °C) and moisture content were measured following the standard methods for water and wastewater analysis (APHA et al., 1995).

Rheology

Static tests to measure the flow properties of the sludge were carried out using an Anton Paar MCR51 rheometer, which operates by shearing a known volume of sludge in a test cell. The torque required to turn the vane at a known speed within the cup of sludge is a function of the viscosity of the sludge. A vane rotated in the sludge within a cup at increasing rotational shear rate in the range 0.0001-1000 s⁻¹. The shear stress and thus viscosity were calculated from the torque. Rheological tests were only carried out during Campaigns 1-3 due to a fault on the instrument when Campaign 4 took place.

Rheological modelling

The rheological properties of PF sludge were compared to the fresh faeces rheology model of Wooley et al. (2014) which linked moisture shear stress and hence viscosity to moisture content using the following equation:

$$\tau = 3 \times 10^{25} \times (MC)^{-12.05} \times \dot{\gamma}^{735.48 \times (MC)^{-1.783}} \quad \text{Equation 1}$$

Where τ is shear stress (Pa), MC is moisture content (g/g wet) and $\dot{\gamma}$ is shear rate (s⁻¹)

This was derived by regressing the rheological data for fresh faeces with moisture contents between 69.3% and 88.7% to develop expressions for K (the consistency coefficient) and n (the flow behaviour index) in terms of the moisture content.

Results

Visual inspection of leach pit contents

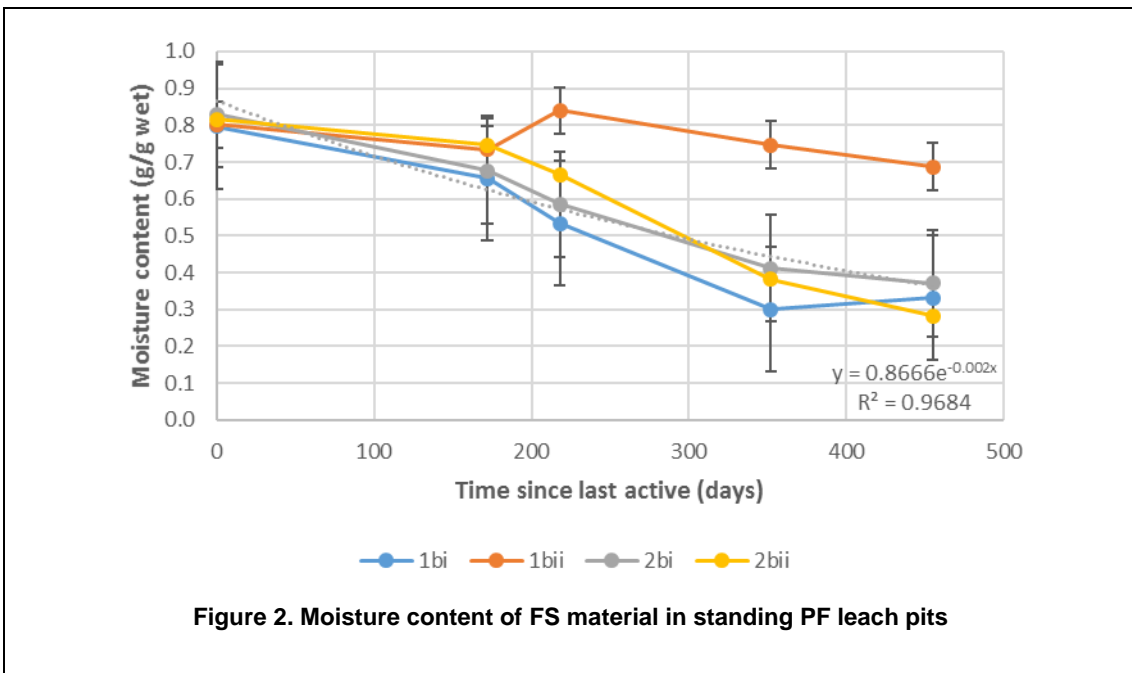
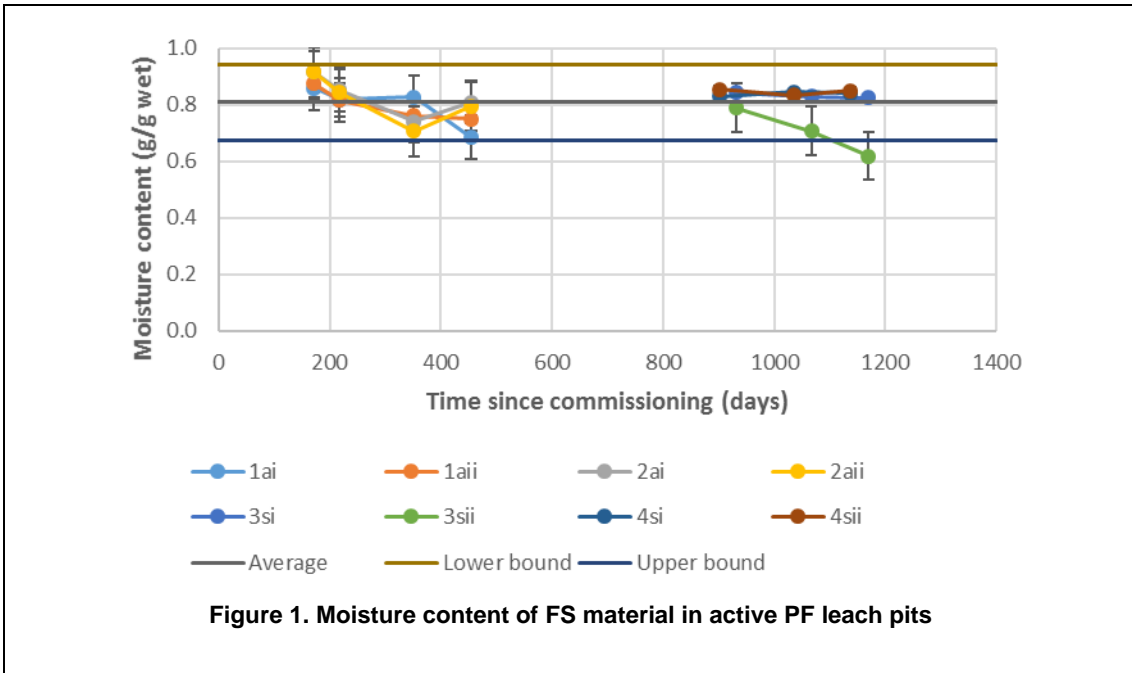
Visual inspection of PF and VIP sludge indicates there is less non-faecal material present (e.g. household waste) in the PF leach pits. The sludge in the PF pits is 'cleaner' than VIP sludge. The narrow size of the pipe in the PF pedestal design limits the amount of non-faecal material that can be disposed of in the leach pit. This reduces the filling rate of the PF leach pit compared to a VIP latrine. The cleaner nature of the PF sludge lends itself to pit emptying via vacuum tanker more easily than VIP sludge. One of the issues with VIP emptying, aside from access to the pit itself, is the large portion of non-faecal matter in the sludge clogging or causing damage to the pit emptying equipment. This risk would be reduced when emptying the PF leach pits.

Moisture content

The moisture content of the sampled pits is shown in Figures 1 and 2. The average moisture content of the active pits, both single and twin was 80.9 %. As these pits have been in use for a relatively short time (less than 18 months), limited pit blinding appears to have occurred. As such, it is likely that the moisture content in the pits will increase over time in the longer-term as reduced infiltration is possible from the active leach pit. There was greater variation in the twin pits than in the single pits. It is assumed that this is because the twin pits had been in use for less time when they were sampled and had not yet reached a state of equilibrium where water entering the pit is equal to that leaching out of the pit. In the standing pits, moisture content decreased over time. An exponential curve was fitted to the data:

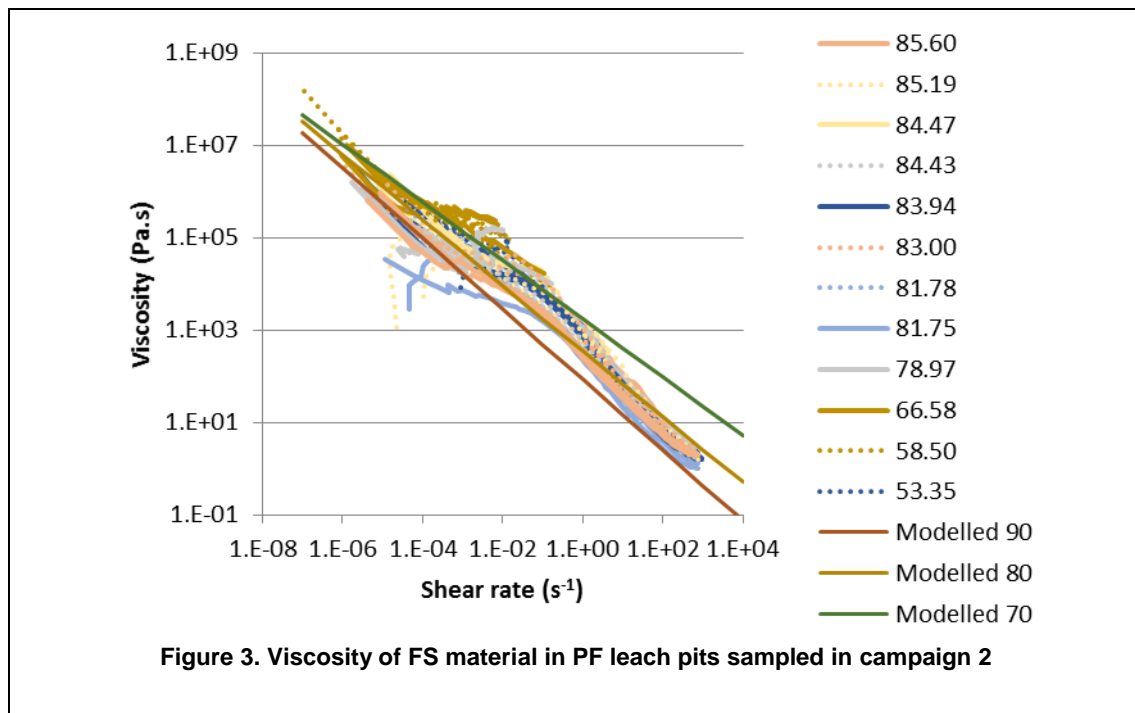
$$MC = 0.8666e^{-0.002t} \quad (R^2 = 0.97) \quad \text{Equation 2}$$

Where *MC* is moisture content (g/g wet) and *t* is time since the pit was active (days)



Rheology

All samples were measured with the rheometer, except the samples from the standing leach pits from Campaign 3 because the shear strength of the sludge exceeded the upper limit of the rheometer. The apparent viscosity was plotted against shear rate for each of the three sampling campaigns where rheological testing was possible. An example viscosity plot from Campaign 2 is shown in Figure 3 with each viscosity curve labelled with moisture content (%). Additionally, the viscosity of fresh faeces with moisture contents of 70, 80 and 90 % as modelled by Wooley et al. (2014) are shown. Approximately a quarter of the samples taken over the three sampling campaigns have a moisture content that falls outside of the bounds of the model. All except two of these samples were taken from standing pits and have moisture contents that are below the lower bound of the model. It can be seen that the fresh faeces model is a good fit to the rheological properties of the content of PF leach pits.



Degradation of FS in standing PF leach pits

Twin leach pits are designed so that FS can be stored and allowed to degrade before emptying. This degradation aims to reduce the volume of the FS to be disposed of and to reduce the pathogen load in the material. In a PF leach pit, water accounts for a significant proportion of the material present. However, as the sides and base of the leach pit are porous, the volume of material in a standing pit will reduce rapidly as the water leaches out.

To assess the change in volume of the pit content over time, the VIP solid degradation model of Brouckaert et al. (2013) was paired with the expected change in moisture content in a standing pit described in Equation 2. The VIP solid degradation model takes into account the dry volume of biodegradable and unbiodegradable material in the pit and does not account for changes in volume of water present:

$$v(t) = v_{u0} + kv_{b0} + (1-k)v_{b0} e^{-rt} \quad \text{Equation 3}$$

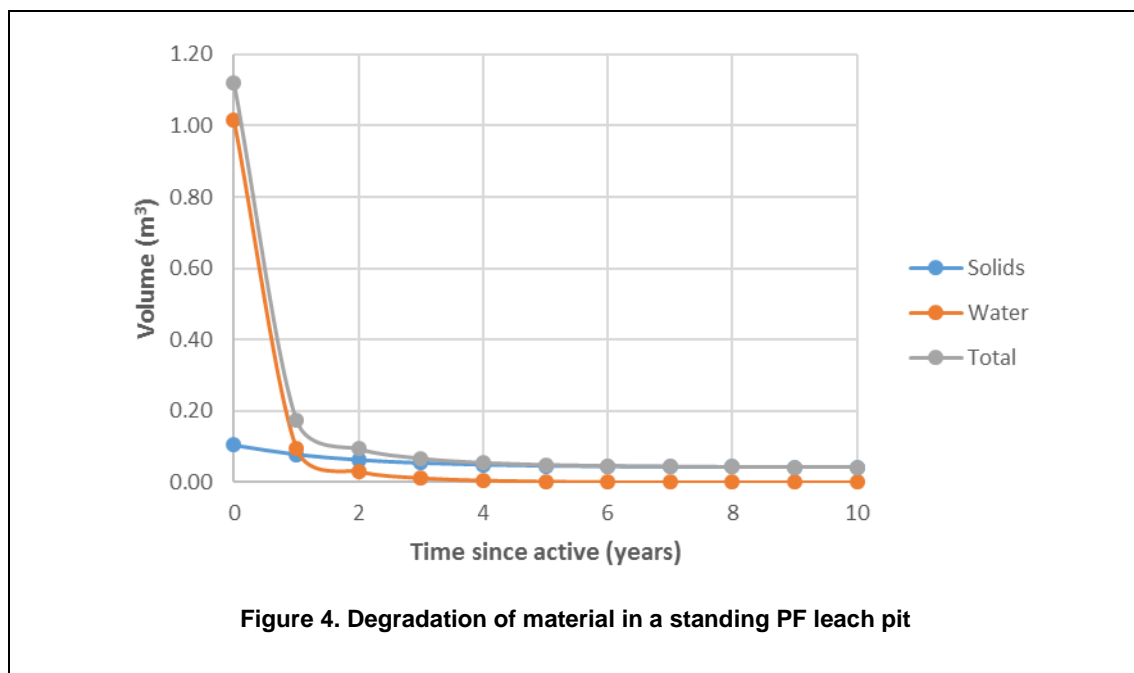
Where $v(t)$ is the volume of material (m^3) in the pit at time t (days), v_{u0} is the volume of unbiodegradable material (m^3) in the pit at $t = 0$, v_{b0} is the volume of biodegradable material (m^3) in the pit at $t = 0$, k is the volume (m^3) of unbiodegradable material produced from degradation of 1 m^3 of biodegradable material and is given a value of 0.1, and r is a rate constant with a value of 0.0015 days^{-1} .

The PF leach pits studied have a total volume of 1.12 m^3 and have an average fill rate of $0.11 \text{ m}^3/\text{year}$. As such, they will hold approximately 10 years of FS before they require emptying. The assumed densities of unbiodegradable material, biodegradable material and water were taken from Brouckaert et al. (2013). The ratio of these components at $t = 0$ were estimated from the average composition of the active pits (both

single and twin) in this study as average ash content, average volatile solids content and average moisture content respectively as shown in Table 1.

Component	Ratio (g/g wet)	Assumed density (kg/m ³)	Volume in full pit (m ³)
Unbiodegradable material (ash)	0.074	2500	0.035
Biodegradable material (volatile solids)	0.060	1000	0.070
Water (moisture content)	0.867	1000	1.015

The degradation of solid material in the FS and the loss of water through leaching are shown in Figure 4. It can be seen that approximately 30 % of the solid material in FS degrades in the first year and that after five years, further reduction in volume of solids is minimal and the remaining material has been reduced in volume by 55 %. The loss of water from the pit is rapid with 90 % of the water leaching out of the pit in the first year. This accounts for a reduction in moisture content from 87 % when the pit ceases to be active, to 42 % after one year.



Discussion

The ability to estimate viscosity of FS is an important aspect of pit-emptying as it helps to determine which technologies are appropriate. Septien et al. (2017) considered the rheology of faecal sludge from VIP latrines and concluded that below a moisture content of 75 %, the exponential increase in friction loss would critically limit the ability to pump FS. The moisture content model based on the data in this paper suggests that 75 % threshold will be crossed 72 days after a pit ceases to be active. As such, there is a window of approximately 2 months after a leach pit is no longer in use, during which it should be feasible to pump material out of the pit. It should also be feasible to pump material out of a pit that is still active. After approximately 2 months of standing, it would be necessary to add water to the pit if it were to be emptied using a pump, which is a less than ideal use of water, particularly in drought-prone regions across much of sub-Saharan Africa. Alternatively, the sludge can be left in a standing pit for up to five years and dug out manually. A visual inspection of the material in standing pits in this study suggested that liquid and plastic

limit of drier sludge may be more applicable than rheological testing in order to understand how the more soil-like material will behave.

As the active pits in this study had been in use for less than 18 months, it is not clear if the rheological properties of the sludge present in the pit will change over a longer time. Due to the presence of flush water, it is likely that PF leach pits will contain a more homogenous FS than VIPs of similar age. However, sampling from different locations in PF leach pits would allow this assumption to be properly assessed.

Conclusion

The results shown in this paper demonstrate that the viscosity of FS in PF leach pits can be modelled as a function of moisture content using the fresh faeces model of Woolley et al. (2014). Viscosity and other rheological properties are an important characteristic of FS for designing and selecting pit-emptying technologies. By modelling the change in moisture content over time in a standing pit, it is possible to identify the window of opportunity during which a full pit can be emptied using a pump. In this case, that window of opportunity for standing pits is within 2 months of the pit being active. However, these results are based on the analysis of a small number of PF leach pits and environmental factors including rainfall and soil conditions are likely to significantly influence the leaching rate from pits and hence the moisture content of the FS.

Whilst a wider study of PF leach pits would be required to ensure the accuracy of the results shown here, it seems likely that PF leach pits are easier to empty than VIP latrines due to the addition of flush water and the limited non-faecal matter in the sludge. A longer-term study would be required to ascertain if the behaviour of the active PF leach pits changes significantly over their lifetime.

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