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DATA NOTE

Mechanical properties of faecal sludge [version 1; peer review: 3 approved with reservations]

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Abstract
On-site sanitation facilities contribute to the majority of toilet facilities in developing countries as full waterborne sanitation is not feasible or affordable. The characteristics of faecal sludge vary greatly between different locations and types of onsite sanitation facilities and at the same time their understanding is crucial for improvement of the existing faecal sludge management services. The Pollution Research Group (PRG), within the School of Chemical Engineering in the University of Kwa-Zulu Natal have been focussing on the analysis of faecal sludge from different on-site sanitation, such as urine diversion and dehydration toilets, wet and dry ventilated improved pit latrines at household and community levels and unimproved pit latrines. This study was undertaken between 2012 and 2014 and focussed on the characteristics of faecal sludge obtained from different on-site sanitation facilities in the Durban metro area in South Africa. Sampling methods were developed and applied for different depth levels of the pits for each on-site sanitation facility. The analysis followed the PRG standard operation procedures for properties such as: moisture content, total solids, ash content, pH, chemical oxygen demand, density, nutrient contents and thermal properties.

Keywords
Faecal sludge, Faecal Sludge Characteristics, Faecal Sludge Properties, Ventilated Improved Pit Latrines, Community ablution blocks, Urine Diversion Toilets, Unimproved pit latrines.

This article is included in the Water, Sanitation & Hygiene gateway.

Open Peer Review

Approval Status ? ? ?

	1	2	3
version 1 17 Oct 2019	? view	? view	? view

1. **Elizabeth Tilley**, University of Malawi, Blantyre, Malawi
2. **Yu-Ling Cheng**, University of Toronto, Toronto, Canada
3. **Sonia Grego**, Duke University, Durham, USA

Any reports and responses or comments on the article can be found at the end of the article.

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Author roles: Velkushanova KV: Conceptualization, Data Curation, Methodology, Project Administration, Visualization, Writing – Original Draft Preparation; **Zuma L**: Data Curation, Methodology; **Buckley C**: Conceptualization, Data Curation, Formal Analysis, Investigation

Competing interests: No competing interests were disclosed.

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Introduction
The characteristics of faecal sludge in on-site sanitation systems may vary extensively depending on factors such as number of users, toilet use and lifestyle habits of the users, topography, location, urban or rural settlement (Penn *et al*., 2018; Rose *et al*., 2015; Zuma *et al*., 2015). The purpose of this data note is to disseminate the data that was collected through assessing the range of properties that may be encountered, it was proposed that faecal sludge samples are collected and analysed for typical on-site sanitation facilities in the Durban metro area, South Africa. The onsite sanitation facilities were selected in several areas in eThekwini, these included urine diversion and dehydration toilets (UDDTs), wet and dry ventilated improved pit latrines (VIPs) at household and community levels, school VIPs and unimproved pit latrines. The dataset (see *Underlying data* (Velkushanova, 2019)) provides a range and variation of properties for faecal sludge from different onsite sanitation technologies (Table 1). The dataset (Velkushanova, 2019) provides minimum, maximum and average values for all the parameters that were tested on different samples from different onsite sanitation facilities in Durban metro area.

Materials and methods
Sludge sampling
In order to provide a uniform data comparison, a sampling method was developed and applied for selection of 8 samples from different depth levels at the "front" and "back" of the pit for all dry VIPs Figure 1a. Similar approach was followed for the UDDT toilets, where samples were selected from both active and standing vaults Figure 1b. Due to the shallower sludge layers on the School VIPs only four samples were selected from each pit (two from the front and two from the back) and the approach is similar to that of the dry VIPs (Figure 1c). For the Unimproved pit latrines, an approach illustrated in Figure 1d was followed, as there was no superstructure as for the VIP toilets, hence there were no clear boundaries between the faecal sludge disposed in the pit and the surrounding soil. Wet VIPs were those that had a high liquid content within the pit. Samples were selected from the sludge crust concentrated at the top of the pit and from the liquid beneath the sludge layer but no distinction was made between the front and the back of the pit, Figure 1e. The community ablution blocks VIPs did not allow a structured sampling as with the household dry VIPs and UD toilets.

Analytical tests
The selected faecal sludge samples were with capacity of about 1 litre and stored in plastic containers at the laboratory's cold room at 4°C. Therefore analytical tests were carried out, following standard operational procedures, developed within the Pollution Research Group. Parameters such as totals solids, moisture content, suspended solids, volatile solids, ash content, pH, chemical oxygen demand (COD), nutrient contents, density, heat capacity, thermal conductivity and calorific value were measured.

Total solids were measured following oven drying at 105°C for 24 hours. The following method was used:

$$\mathbf{Total solids in sample\,(mg/1)} = \frac{(W_2 - W_1)g \times 100\,000}{V_{sample}\,(ml)} \quad (1)$$

W_2 = weight of residue + filter paper after oven (105°C)

W_1 = weight of filter paper before oven

V_{sample} (ml) = Volume of the sample

Moisture content was estimated using the same method as total solids.

$$\mathbf{MC} = \frac{m_{crucible} + m_{faeces} - m_{exit\,oven}}{m_{faeces}} \quad (2)$$

Where:

MC = Moisture Content

$m_{crucible}$ = mass of a crucible

m_{faeces} = mass of faeces

$m_{exit\,oven}$ = mass of crucible and feaces after drying in the oven

Table 1. Onsite sanitation sampled facilities.

Facility types	Characteristics	Usage level	Number of facilities sampled
Household VIP latrine	Dry	Low use (<5 users/facility)	5
		High use (>5 users/facility)	5
	Wet	Low use	5
		High use	5
Household UDDT toilet		Low use	5
		High use	5
Household unimproved pit latrine	Dry	Low to high use	2
Community ablution block VIP	Dry	High use	9
School VIP toilet block	Wet and dry	High use	4
Total			**45**

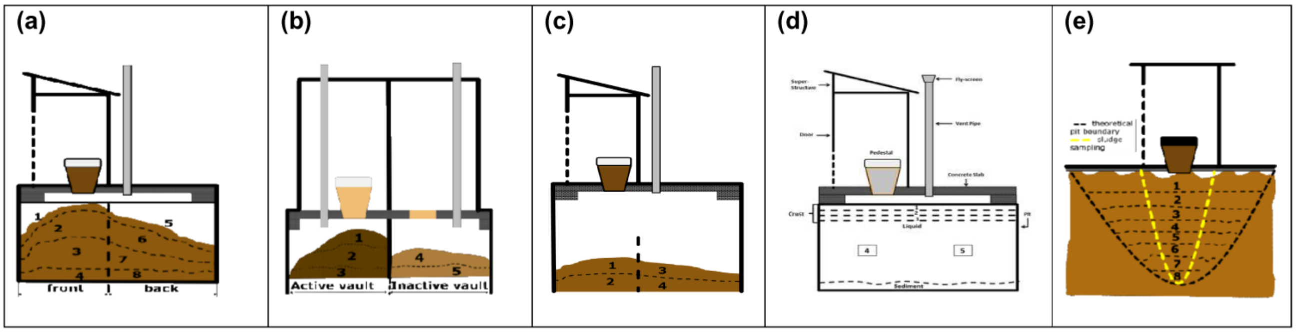

Figure 1. Sampling methods for onsite sanitation technologies in Durban, South Africa. (**a**) Selection of analytical samples from dry ventilated improved pit latrines (VIPs). (**b**) Selection of analytical samples from UDDT toilets. (**c**) Selection of analytical samples from school VIP. (**d**) Selection of analytical samples from unimproved pit latrines. (**e**) Selection of analytical samples from Wet VIP.

Volatile solids were measured following heating using a furnace at 550°C for 20 minutes. The below equation was used:

$$\mathbf{VS} = \frac{\mathbf{m}_{\text{exit oven}} - \mathbf{m}_{\text{exit furnace}}}{\mathbf{m}_{\text{faeces}}} \quad (3)$$

Where:

VS = Volatile solids

m_{faeces} = mass of faeces

$m_{exit\ furnace}$ = mass of faeces and crucible exiting the furnace

$m_{exit\ oven}$ = mass of faeces and crucible exiting the oven

pH was measured using a pH probe to monitor the degradation of the faecal sludge and the sanitising effects of ammonia. pH also indicates the corrosive effect on pit emptying and sludge treatment devices

COD was analysed using the closed reflux titrimetric method. The COD indicates the degradability rate of the sludge contents.

$$\mathbf{COD} = \frac{(\mathbf{Blank} - \mathbf{Titration}) \times \mathbf{molarity\ of\ FAS} \times 8000}{\mathbf{Sample}(\mathbf{mL})} \quad (4)$$

$$\mathbf{COD}\,(\mathbf{gO_2/g\ sample}) = \frac{\mathbf{COD}\,(\mathbf{mg\ O_2/L})}{\mathbf{Dilution\ factor} \times 1000} \quad (5)$$

Where:

FAS = ferrous ammonium sulphate

mg O_2/L = milli grams of Oxygen per litre

gO_2/g sample = grams of oxygen per gram of sample

Density

To measure density,a measure of appropriate volume of 7.5 ml sample is placed oven at 103–105°C overnight.

$$\mathbf{Db}_{\mathbf{wet}}(\mathbf{g/ml}) = \frac{\mathbf{W_2} - \mathbf{W_1}}{\mathbf{V_t}} \quad (6)$$

Where:

$W_2 - W_1$ = Wet mass of sample

V_t = Total volume of sample (7.5 ml)

$$\mathbf{Db}_{\mathbf{dry(g.ml)}} = \frac{\mathbf{W_s}}{\mathbf{V_t}} \quad (7)$$

W_S = Oven dry mass of the sample

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

Nutrient content

Ammonia and phosphate content were measures using Spectroquant tests (Merck) for the purpose of nutrient recovery.

Ammonia content as calculated using the following equations:

$$\mathbf{Wet\ sample\ concentration}\,(\mathbf{g/g}) = \frac{\mathbf{A}}{\mathbf{1000}} \times \frac{\mathbf{V}}{\mathbf{M}} \quad (8)$$

$$\mathbf{Dry\ sample\ concentration}\,(\mathbf{g/g}) = \frac{\mathbf{Wet\ sample\ conc.}\,(\mathbf{g/g})}{\mathbf{Total\ solids}\,(\mathbf{g/g})} \quad (9)$$

Where:

A = Spectroquant reading concentration

V = Volume of dilution (L)

M = Mass of sludge used in sample preperation (g)

Phosphate content was measured in the following equations:

$$\textbf{Wet sample concentration}\ (\text{g/g}) = \frac{\textbf{A}}{\textbf{1000}} \times \frac{\textbf{V}}{\textbf{M}} \quad (10)$$

$$\textbf{Dry sample concentration}\ \ (\text{g/g}) = \frac{\textbf{Wet sample conc. (g/g)}}{\textbf{Total solids (g/g)}} \quad (11)$$

Where:

A = Spectroquant reading concentration

V = Volume of dilution (L)

M = Mass of sludge used in sample preperation (g)

Thermal properties

Thermal conductivity, specific heat capacity and calorific value were measured for the purpose of drying, combustion and evaluating the heating potential. The Thermal conductivity was measured by the thermal conductivity analyser from C-Therm TCi. The calorific value was measured using the bomb Parr 6200 Oxygen Bomb Calorimeter.

Sludge volume index (SVI) is an indication of the sludge settle ability in the final clarifier. It is a useful test that indicates changes in the sludge settling characteristics and quality. The SVI was measured by the equation:

$$\text{SVI}\,(\text{mg/ml}) = \frac{\text{settled sludge volume}\,(\text{mg/L}) \times 1000}{\text{suspended solids}\,(\text{mg/L})} \quad (12)$$

Data availability

Underlying data

Open Science Framework: Mechanical Properties of faecal sludge. https://doi.org/10.17605/OSF.IO/CW5XD [Velkushanova, 2019].

This project contains data on the total solids, moisture content, volatile solids, pH, chemical oxygen demand, density, nutrient contents and thermal properties of faecal sludge collected in Durban, South Africa, 2012–2014.

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PubMed Abstract | Publisher Full Text

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Publisher Full Text

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Current Peer Review Status: ? ? ?

Version 1

Reviewer Report 05 December 2019

https://doi.org/10.21956/gatesopenres.14173.r28094

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Sonia Grego

Center for WaSH-AID, Duke University, Durham, NC, USA

Faecal sludge is a highly heterogeneous material and data on its properties in different sanitation systems and social context is needed to develop effective management approaches.

This data Note provides a useful dataset collected according to appropriate and well described methodologies. I have comments for rewording and minor revisions regarding additional information that should be easily addressable by the authors.

Title:

- The properties recorded for FS in this Note are physio-chemical in addition to some mechanical properties, so the title could be reworded to better reflect the content of the dataset. I would encourage the authors to modify to something like: "Analysis of fecal sludge from different on-site sanitation facilities" or similar.

Abstract:

- "The analysis followed the PRG standard operation procedures for properties such as..." - the SOPs of this study follow mostly recognized standards so I would describe it as: "the analysis followed standard methods and applied consistently PRG standard operating procedures".

Introduction:

- "The purpose of this data note is to disseminate the data that was collected through assessing the range of properties that may be encountered, it was proposed that faecal sludge samples are collected and analysed for typical on-site sanitation facilities in the Durban metro area, South Africa."

There must be a typo or a copy and paste error in this sentence because it does not flow well. Please rephrase.

Also, is eThekwini a Durban metro area? If so, please clarify.

- "The dataset (see *Underlying data* (Velkushanova, 2019)) provides a range and variation of properties for faecal sludge from different onsite sanitation technologies"

I would rephrase as "The dataset (see *Underlying data* (Velkushanova, 2019)) reflects the large variability found in the properties of faecal sludge from different onsite sanitation technologies"

<u>Materials and methods:</u>

- Sludge sampling: This paragraph illustrates a key point of the study and leverages extensively figure 1, which is very useful to the description of this study. Unfortunately figure 1 contains labels in font too small to be read, particularly d and e. Either the fonts or the figure need to be enlarged.

- Analysis: The method description would benefit from the addition of the reference method being followed (e.g. APHA 2540 for total solids, etc.)

- Nutrient content: Please add the model number of the Spectroquant reader and if available the test reagents part number.

The Note would benefit from a final paragraph describing the results reported in the datasheet:

- To summarize for the reader that a number of samples (ranging from xx to yy) were analyzed for each and that for each parameter the min, max and average values are reported in the data sheet.
- Comment on the total number of pits reported. I note that table 1 lists 45 facilities samples, but the number of rows of data reported in the data is higher than 45, please clarify.

Is the rationale for creating the dataset(s) clearly described?

Yes

Are the protocols appropriate and is the work technically sound?

Yes

Are sufficient details of methods and materials provided to allow replication by others?

Partly

Are the datasets clearly presented in a useable and accessible format?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: onsite sanitation systems, wastewater and faecal sludge analysis, engineered systems for waste treatment and diagnostics.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 14 November 2019

https://doi.org/10.21956/gatesopenres.14173.r28095

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Yu-Ling Cheng
Centre for Global Engineering and the Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, ON, Canada

A data set is contributed that reports a broad range of physical and chemical characteristics of fecal sludge collected from a variety of on-site sanitation facilities. As the authors note, information regarding the characteristics of sludge from on-site sanitation would be valuable for developing and operating services and processes for fecal sludge management. So at the high level, the first point I would make is that this data set is valuable because it reports this range of properties. However, the usefulness of the dataset, valuable as it already is, can be significantly enhanced if the authors provide some interpretation of the data.

Specific questions and comments:

1. Were any trends observed between sludge characteristics and types of sanitation facilities?

2. The number of users for each facility was reported. How does the number of users affect sludge characteristics? I can reason number of users can indirectly influence depth, and possibly residence time (e.g. if more users means faster filling and therefore more frequent emptying), but without knowing more details, it is unclear how to interpret the connection.

3. The ash content seems to be very high; with facility-based average values ranging from 0.42 to 0.70 g per g of dry solid mass. Is there any explanation for this?

4. Density measurement as described by equations 6 and 7 is dry solid mass/total wet volume. This seems to be an unusual definition. It is neither the density of the wet fecal sludge, nor the density of the dry mass. Furthermore, you would expect density defined in this manner should be lower than dry solid density, but the reported density values (columns AU through AW) are relatively high - in the range of about 1350 to 1450 kg/m3. The one outlier is data from unimproved pit latrines at about 921 kg/m3. It is possible that the high reported density is related to the high ash content as noted in point 3 above - though the ash content for unimproved pit latrines was as high as other facilities.

5. Is calorific value based on dry or wet fecal sludge mass? And is it the higher or lower calorific value?

6. Volatile solids were determined gravimetrically after heating in an oven at 550 C for 20 minutes. Was this done in an oxygen-lean environment to ensure no combustion? I.e. is the volatile fraction reported the pyrolizable fraction or the combustible fraction?

7. Total solids (columns B, C and D) are reported as percentages. Most of the numbers, except cells B5 through B7 (17.11%, 13.01%, 11.23%) appear to be fractions rather than percentages.

8. Please report the data with the appropriate number of significant figures.

Is the rationale for creating the dataset(s) clearly described?
Yes

Are the protocols appropriate and is the work technically sound?
Partly

Are sufficient details of methods and materials provided to allow replication by others?
Partly

Are the datasets clearly presented in a useable and accessible format?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Chemical engineering, sanitation

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 24 October 2019

https://doi.org/10.21956/gatesopenres.14173.r28093

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Elizabeth Tilley
Department of Environmental Health, Polytechnic, University of Malawi, Blantyre, Malawi

This "data note" summarizes the methods used in a comprehensive FS characterization study conducted across a variety of toilet technologies around Durban, South Africa.

I was excited to read this work as I know the capabilities and scope of the work that the PRG conducts. However, while I recognize the need to rapidly disseminate information in these types of short communications, I felt that there was neither sufficient information on the methods nor on the results. Existentially, the paper struggles with its identity, but could be remedied by either a) creating 2, separate data notes, or b) bulking out this data note into a fuller manuscript that embraces both the technicalities of the methods and the interpretation of the results.

The data set is rich, well-organized, easy to read and I enjoyed examining it myself. However, I would have enjoyed it more if the authors had presented their interpretations and insights to really bring it to life and help me to understand what I was looking at and what key trends I should be focusing on.

Similarly, I felt short-changed by the methods and didn't come away feeling that I could replicate the analyses that the authors had done. Given the heterogeneity of FS (and especially the presence of trash), I was disappointed that there was no information presented about how the actual samples were obtained: grab or composite? Using a spoon or a pump? The sampling strategy was complex and for some toilet types, seemingly impossible! I wish they had told me how they did it.

Very standard methods were written out in full (total solids, moisture, etc.) but the innovative, novel methods were glossed over (thermal conductivity, SVI, calorific value) and not fully explained. The significance of the results, especially in terms of emptying, transport, treatment, etc. becomes even more difficult without a clear understanding of what the parameters indicate.

Specific comments:

Abstract:

- The meaning of "full waterborne" is not clear. Is that "universal sewerage"? or something else? Clarify.

- "different on-site sanitation" **technologies.**

- "such as" implies that there are more included in the study, which there aren't.

Introduction:

- You say that you report the "range and variation", but really just report the range and averages.

Sludge sampling:

- "a sampling method was developed and applied for a selection of 8 samples" made it sound like the sampling was only applied to 8 samples (i.e. 8 toilets), when really 8 samples were taken from each pit. See if you can re-phrase.

- Furthermore, the sample method that "was developed" was not fully explained (as I mentioned above), and given the sampling strategy of targeting different layers and locations, this is one of the most novel and interesting parts of the work.

- Similarly, the figures were difficult to read, especially the numbers that were drawn on the sludge layer.

- "Wet VIPs were those that had a high liquid content": can you better define "high"?

Analytical tests:

- "Therefore analytical tests...": the word "therefore" doesn't make sense. Maybe "thereafter"?

- Again "such as", makes it sound like there were other parameters analyzed and you are simply listing a sub-set.

Table 1:
- Can you clarify how the School toilet was "Wet and dry"? or provide numbers on the number of wet and the number of dry?

Figure 1:
- As above, I would love to see these displayed much larger, and more clearly. On 200% I still can't read the text in figure e.

Analytical tests:
- Using the "pH probe to monitor the degradation of the faecal sludge and the sanitising effects of ammonia" seems like a bit of an overstatement and needs a bit of clarification.

Nutrient content:
- "prep**e**ration" is misspelled on the last line.

Is the rationale for creating the dataset(s) clearly described?
Yes

Are the protocols appropriate and is the work technically sound?
Yes

Are sufficient details of methods and materials provided to allow replication by others?
No

Are the datasets clearly presented in a useable and accessible format?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Environmental engineering, economics,

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.