Faecal sludge simulants to aid the development of desludging technologies

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ABSTRACT

This paper presents a review of currently available data from the literature on the undrained shear strength, bulk density, stickiness and debris content of faecal sludge. Those data have been used to develop two different simulants that replicate the full range of shear strengths and densities reported for faecal sludge. Comprehensive specifications are also presented for the debris or solid waste found in latrines to more closely replicate the challenge of pumping faecal sludge. Finally, a design guide has been produced to capture these results and support quantitative performance testing of desludging pumps. The simulants have already been used as part of the Bill & Melinda Gates Foundation's Faecal Sludge Omni-Ingestor project and by Water for People's SaniHub in developing improved desludging pumps. The wider use of these simulants could accelerate the development of pit emptying technologies and help standardize the quantitative evaluation of their performance.

Key words | desludging pumps, faecal sludge simulant, pit emptying

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INTRODUCTION

The provision of safe and effective faecal sludge management is one of the greatest current challenges globally, with an estimated 1.8 billion people using pit latrines and a further 1.1 billion without any sanitation facility (Graham & Polizzotto 2013). This totals almost 3 billion potential latrine users, or 40% of the world's population, which could grow further as urban populations in developing countries are forecast to double in size to over 5 billion by 2050 (UN-DESA 2012). Increasing population densities due to rapid urbanization mean there is often no space to dig a new pit when latrines are full, forcing residents to resort to manual pit emptying or open defecation.

The Faecal Sludge Omni-Ingestor (FSOI) project aims to provide safe, low-cost pit emptying services by increasing the proportion of on-site sanitation systems that can be mechanically emptied. The project is therefore developing technology to pump and pre-process faecal sludge from on-site sanitation systems, making it suitable for treatment and resource-recovery applications (Beaumont 2014).

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Historically, the development of improved desludging pumps has been hindered by the lack of a safe, replicable material for use in early-stage testing and for evaluating the performance of different systems under controlled conditions. In addition to replicating the mechanical properties of faecal sludge, a simulant should present minimal health, safety and environmental risks, be cheap, manufactured from widely available materials and relatively durable to allow storage and reuse in multiple tests. This paper describes the development of two such simulants, comparing their properties with those of faecal sludge.

LITERATURE REVIEW

A thorough literature review was undertaken to collect data for a meta-analysis of the key properties controlling 'pumpability' of faecal sludge: undrained shear strength and bulk density (Radford & Fenner 2013).

Undrained shear strength determines whether sludge will start to flow under a given suction. Faecal sludge data recorded at a reference shear strain rate of 1/s are presented in Figure 1 below. A further 15 ventilated improved pit latrine samples tested by UKZN (2013) are not included as they exceeded the torque limit of the laboratory rheometer (equivalent to a shear strength of 1,760 Pa) at a shear strain rate below 1/s. All water contents are calculated on the basis of total wet mass throughout this paper. Although the maximum strength of faecal sludge remains unknown, extrapolation of rheological data based on the shear strain rate behaviour of weaker samples suggests a maximum shear strength of approximately 10 kPa for sludge with total solids contents of up to 40%. This strength was selected as the upper limit for the simulant, representing heavily consolidated dry faecal sludge.

Bulk density is important for suction-based emptying systems as it determines the static head required to lift the sludge out of the pit, thus limiting the maximum emptying depth. Faecal sludge density data are presented in Figure 2 below from a range of on-site systems including ventilated improved pit latrines (VIP), urine diversion dry toilets (UDDT), school toilets (SCH), unimproved pit latrines (PIT), community ablution blocks (CAB), pour-flush toilets (PF) and septic tanks (SEPT). The sludge in these systems varies in consistency from liquid (e.g., septic tanks) to soil-like (e.g., UDDTs) and the wide range in properties within individual toilets is demonstrated by plotting the mean, minimum and maximum values reported for multiple samples, where available.

There is no overall correlation between bulk density and water content, likely due to non-uniform samples containing varying amounts of low density fat and grease, and high

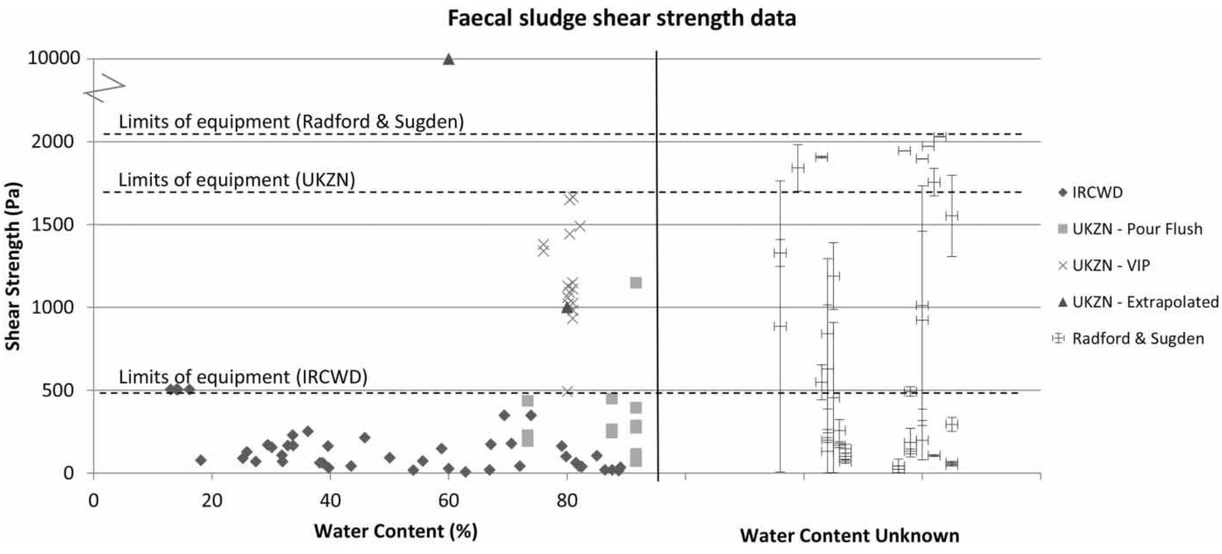


Figure 1 | Faecal sludge shear strength data (Bösch & Schertenleib 1986; UKZN 2013; Gasser 2014; Radford & Sugden 2014).

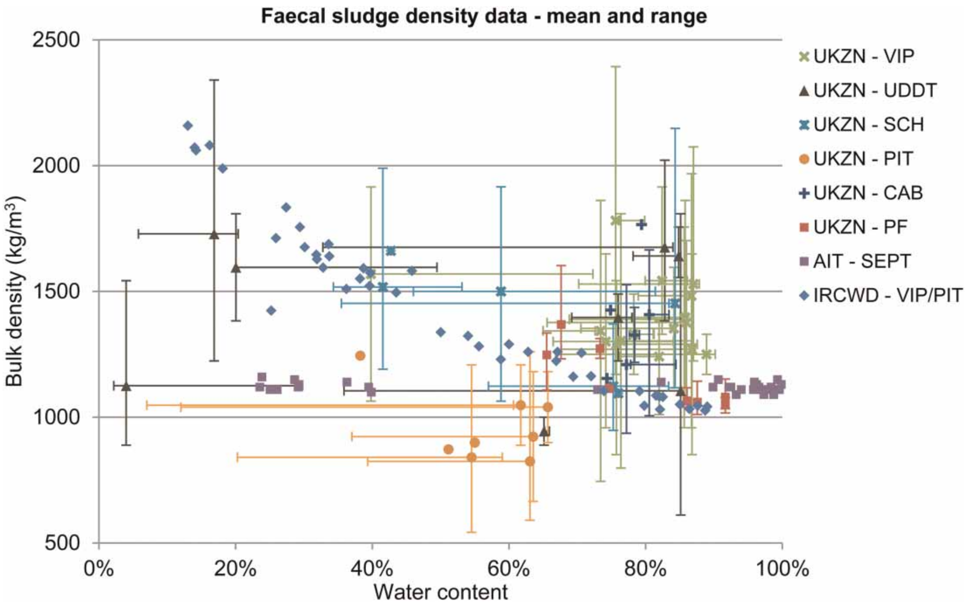


Figure 2 | Faecal sludge density data (Bösch & Schertenleib 1986; AIT 2012; UKZN 2014a).

density sand and grit. However, two broad clusters are evident in the data, the first consisting of unimproved pit latrines ('UKZN – PIT') and septic tank sludge ('AIT – SEPT') with a mean density of 1,100 kg/m^3. The other data, including VIPs, UDDTs, school toilets and community ablution blocks, have an average density of 1,400 kg/m^3. The IRCWD data include both VIPs and unimproved pit latrines, therefore spanning both groups, as do the pour flush data which include samples from active and sealed vaults.

Anecdotal evidence suggests that sludge 'stickiness' is also important, leading to blockages and delays as sludge adheres to equipment (Harrison & Wilson 2012). No faecal sludge stickiness data were found in the literature, however Thewes (1999) presents a correlation between stickiness and consistency index for high-plasticity clays and Zumsteg & Puzrin (2012) developed a simple empirical stickiness test which was adapted to use a low-cost food processor in place of a Hobart mortar mixer (UKZN 2014b) and used on both the simulants and faecal sludge.

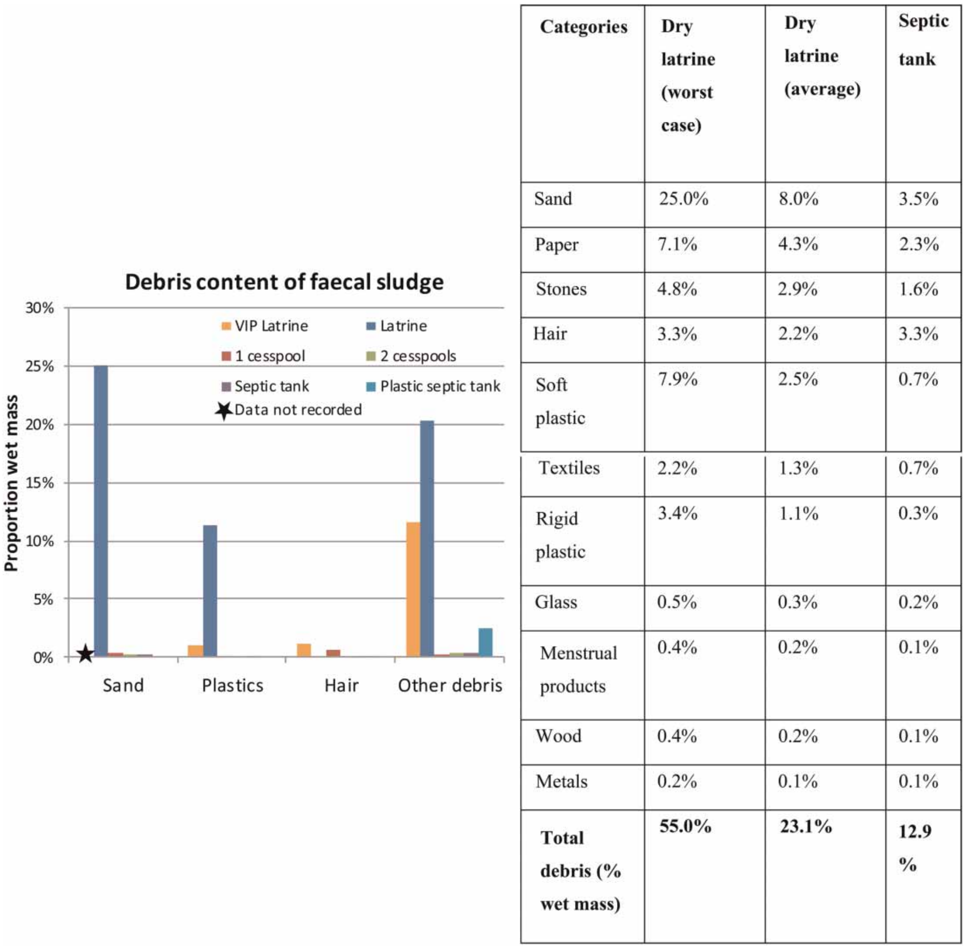
In addition to pumping high-solids faecal sludge, the pumps must handle the high proportion of solid waste or debris contained in many on-site sanitation systems. Debris data were therefore also collected from the literature and are summarized in Figure 3 below.

'Average' and 'Worst case' debris specifications for septic tanks and dry latrines were developed from this data and are summarized in Figure 3. The 'Average' specification is representative of a typical pit and consists of 25 different materials across the 11 categories shown in Figure 3. In contrast, the 'Worst case' specification is intended for accelerated stress-testing of pump prototypes and includes almost 100 materials.

A desktop review of existing simulants for faecal sludge identified nine compositions using kaolin, bentonite, topsoil, compost, maize meal and wheat flour (Beaumont 2012; Byrne 2012). A simple combination of kaolin clay and topsoil was selected as the most replicable and durable according to the available data. Milorganite, an organic fertilizer derived from sewage sludge, was identified as a potential alternative simulant material with the advantage of being a standardized material available throughout the USA for use in the FSOI project.

METHODS

The undrained shear strength of each simulant was tested at a range of water contents. The proportion of kaolin was varied in that simulant to investigate the effect of solid



Categories	Dry latrine (worst case)	Dry latrine (average)	Septic tank
Sand	25.0%	8.0%	3.5%
Paper	7.1%	4.3%	2.3%
Stones	4.8%	2.9%	1.6%
Hair	3.3%	2.2%	3.3%
Soft plastic	7.9%	2.5%	0.7%
Textiles	2.2%	1.3%	0.7%
Rigid plastic	3.4%	1.1%	0.3%
Glass	0.5%	0.3%	0.2%
Menstrual products	0.4%	0.2%	0.1%
Wood	0.4%	0.2%	0.1%
Metals	0.2%	0.1%	0.1%
Total debris (% wet mass)	**55.0%**	**23.1%**	**12.9 %**

Figure 3 | Debris content of faecal sludge as percentage wet mass, and resulting specifications for debris in simulants (Kone & Dodane 2008; AIT 2012; UKZN 2012).

composition on simulant properties. In the Milorganite 10% of the solids and water were replaced with salt and vinegar, respectively, to reduce odour. Undrained shear strength was measured using a mini-ball penetrometer (Kuo 2011) as described by Underdown (2013) at four different shear strain rates, with four repeats each. The strength at the reference rate of 1/s was calculated from the resulting strength–strain rate correlation. Each simulant's bulk density was measured according to BS 1377-2 (BSI 1990).

Embedded water content, that portion of water bound within the solids rather than added as a liquid, was identified in the literature review as having significant impact on simulant properties. This was investigated by producing a series of strength–water content correlations for topsoil that had been pre-dried by varying amounts.

To control for stickiness the Atterberg limits of the simulants were measured according to BS 1377-2 (BSI 1990) and used to calculate their consistency indices. The modified empirical stickiness test (UKZN 2014b) was also used to test both faecal sludge and the simulants. Laboratory tests also measured the mass of water absorbed per unit weight of each type of debris and determined how best to mix in the materials without fouling or binding a mechanical mixer.

RESULTS

The full range of shear strengths reported for faecal sludge was successfully replicated in the kaolin–topsoil simulant by simply varying its water content. A normalized water content, shown in Equation (1), was defined as a function of kaolin content (K), proportion embedded water (E) and total water content (WC_T) to account for varying embedded water contents (WC_E). This normalization increased the coefficient of correlation from 79 to 98% for the three embedded water contents tested:

$$\mathrm{WC}_N = \mathrm{WC}_T \cdot \left[1 - \frac{0.05 \cdot E}{0.01 \cdot (1-K) \cdot (1-\mathrm{WC}_T) + E \cdot \mathrm{WC}_T}\right] \qquad (1)$$

where $E = (1-K) \cdot \dfrac{\mathrm{WC}_E}{\mathrm{WC}_T} \cdot \dfrac{(1-\mathrm{WC}_T)}{(1-\mathrm{WC}_E)}$

The kaolin–topsoil simulant was batched from five different topsoils and three kaolin clays in the UK, Uganda and USA for testing prototype desludging pumps. It was found that although a strong correlation holds between shear strength and water content in all cases, that correlation is specific to the materials used, as demonstrated in Figure 4 below.

The proportion of kaolin was also varied for a given source of materials and it was found that higher kaolin contents require a lower water content for a given strength.

The full range of strengths was also achieved using the Milorganite simulant, as shown in Figure 5 below, although an erroneous water content was recorded for the strongest sample due to poor temperature control resulting in the partial loss of volatiles. A freshly opened bag of Milorganite was found to have an embedded water content of 9%, therefore normalized water content was used as defined in Equation (1) above.

The granulated nature of the Milorganite means that its stickiness, and to a lesser extent strength, increase both with time and with additional shearing as the granules break down. It also means that the Milorganite simulant cannot be incrementally diluted and tested immediately, but rather needs to soak for at least a day prior to use.

Repeated Atterberg limit tests on a single faecal sludge sample produced highly variable results, with liquid limits of 124 and 157% and plastic limits in the range 49–67%. This is likely due to the presence of grit and hair, and the data were discounted as too unreliable. The empirical stickiness test however proved quick and simple, producing more consistent data with results in the range 3–10% at water contents of 50–70%. This range of stickiness was replicated in both simulants; however, only six samples of faecal sludge were tested and further data are required before these simulants can be considered truly representative of faecal sludge stickiness. The food processor used was also torque-limited to testing samples with a reference shear strength of under 1,200 Pa.

The debris tests successfully mechanically mixed all debris materials into the simulant, at the high proportions

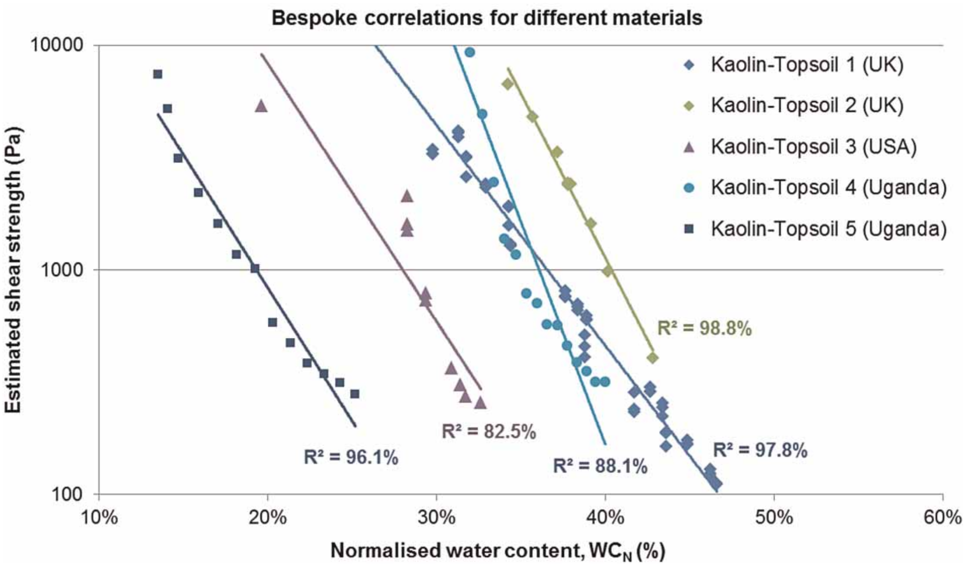


Figure 4 | Kaolin–topsoil strength correlations, with 60% kaolin by dry mass.

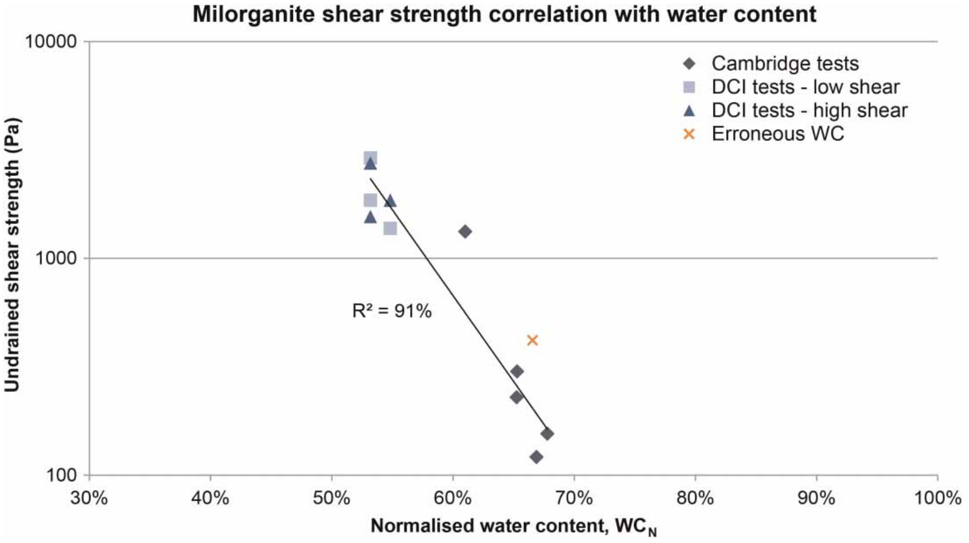


Figure 5 | Milorganite shear strength–water content correlation.

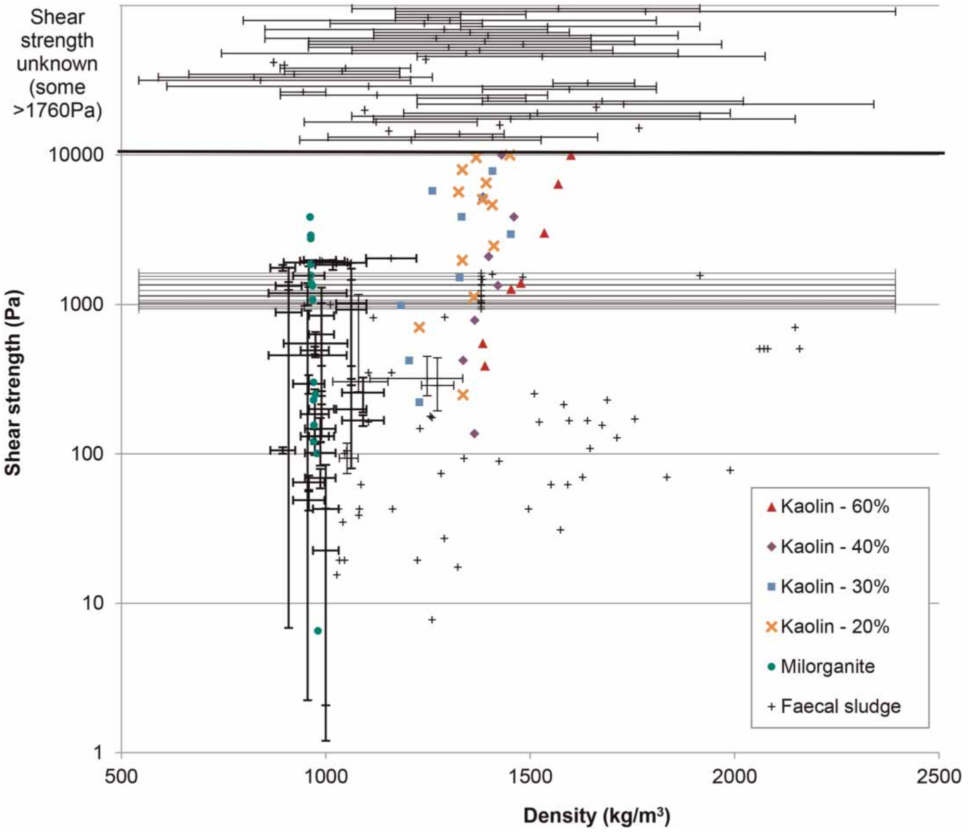


Figure 6 | Physical characterization of faecal sludge and pumping simulants (Bösch & Schertenleib 1986; Gasser 2014; UKZN 2014a).

reported in faecal sludge, with the exception of hair extensions and plastic bags which should be added in layers by hand.

DISCUSSION

The strength and density of the two simulants are compared with faecal sludge in Figure 6 below. Density data from samples with unknown shear strength have also been included for completeness. It is evident that both simulants reproduce the full range of shear strengths reported for faecal sludge but have significantly different densities. The Milorganite simulant has a mean density of 980 kg/m^3, comparable to unimproved pit latrine and septic tank sludge (1,100 kg/m^3, Figure 2) whereas the kaolin–topsoil simulants have mean densities in the range 1,360–1,450 kg/m^3, comparable to the other toilet systems (1,400 kg/m^3, Figure 2). The Milorganite is considered a better simulant for faecal organic matter and is therefore recommended for use when debris, including sand, will be separately added to the simulant. The kaolin–topsoil simulant, in contrast, replicates faecal sludge containing small-sized inorganics and should be used where additional debris of this type will not be added to the simulant.

Table 1 | Qualitative comparison of kaolin–topsoil and Milorganite pumping simulants

Criterion	**Kaolin–topsoil**	**Milorganite**
Usability	Requires mixing of two solid components, topsoil may require pre-sieving to remove lumps which can be time-consuming	Easy to batch – simply add water to dry Milorganite. No large lumps, hence no sieving required. Need to leave 24 hour to soak
Predictability	Highly consistent strength–water content relationship for given materials, varies between materials	Strength increases after soaking and then gradually with time and additional shearing as granules break down
Homogeneity	Can be difficult to remove lumps during mixing, particularly for large volumes	Uniform strengths after soaking and remixing, except for <25% TS where solids settle out of suspension
Availability	Recipe can be adapted to available materials	Widely available in the USA, difficult to obtain elsewhere
Odour	Negligible odour when freshly mixed	Strong earthy smell when freshly mixed, addition of salt and vinegar helps prevent odour developing over time

Sludge stickiness was not satisfactorily measured by either Atterberg limit testing (highly variable results), or the empirical stickiness test (limited to strengths below 1,200 Pa), and an alternative procedure should be sought. The use of a Hobart mortar mixer would overcome the challenges associated with the latter method, but is likely too expensive for widespread testing of faecal sludge. The laboratory protocol based on the Jenike shear test developed by Peeters *et al.* (2011) for mapping the sticky phase of wastewater activated sludge could provide a simple and low-cost alternative.

A qualitative comparison of the two simulants was also made on the basis of five criteria, shown in Table 1 below. On this basis, the Milorganite was selected for FSOI testing in the USA, primarily due to the ease of producing large batches of simulant and the fact it is a standardized material that all vendors across the country could obtain. Conversely the kaolin–topsoil simulant was selected by Water for People's SaniHub in Uganda using cheap, locally available materials. The results presented in Figure 4 suggest that a single universal 'recipe' for simulant that can be used globally is probably an unrealistic objective, particularly if using low-cost, locally sourced materials.

A simple MS Excel-based design guide has been produced to capture the results reported here and guide the user through the process of producing a simulant 'recipe' for testing desludging pumps. It includes the debris specifications described above and calculates the additional water required to compensate for absorption into the debris. The design guide is flexible and includes these data but with the capacity for the user to enter additional data if used as a tool to develop new simulants from different materials. It is currently being converted into a web-based tool and will be made freely available online (http://FSMtech.org).

The simulants presented here could help to accelerate the development of desludging pumps by identifying problems at an early stage through enabling testing with a safe, replicable material. It is also hoped that this will support efforts to standardize the quantitative evaluation of desludging technologies, improving the quality and consistency of data collected and ensuring that investments are prioritized for the most promising systems. However, widespread studies are still required to characterize the 'pumpability' of faecal sludge, measuring *in situ* shear strength, empirical stickiness, total solids, density and debris content.

CONCLUSION

Data have been presented from the literature on key properties affecting the 'pumpability' of faecal sludge. Undrained shear strengths of up to 2 kPa (at a reference shear strain rate of 1/s) have been reported; however, all data are limited by the capacity of the equipment used, with extrapolation of rheological data suggesting an upper limit of approximately 10 kPa for sludge with 40% total solids.

Faecal sludge bulk densities ranging from 540 to 2,400 kg/m^3 have been presented, with no apparent correlation to water content and very significant differences between samples taken from a single toilet system. Generally, however, there appear to be two clusters of data, consisting of unimproved pits and septic tanks with a mean density of 1,100 kg/m^3 and all other systems at 1,400 kg/m^3.

Stickiness has been anecdotally reported as a key property influencing 'pumpability'; however, no data were identified in the literature for faecal sludge stickiness. Atterberg limit tests produced highly variable results and an empirical stickiness test using a food processor was torque-limited to just 1,200 Pa. Further work is therefore required to develop a suitable test and collect stickiness data for faecal sludge, with one possible methodology suggested based upon a protocol developed for wastewater activated sludge derived from the Jenike shear test.

Debris data have been presented on a percentage wet mass basis from three studies, but further data are required, especially from wet pit latrines and septic tanks. Future studies should also report the prevalent solid waste management practices as these are likely to have a strong influence on the total amount and types of solid waste disposed into the pits.

Two classes of simulant have been developed that replicate the pumping behaviour of faecal sludge, spanning the full predicted range of shear strengths and matching the two density clusters. Further refinement of the simulants will be required as additional data are collected, particularly in reviewing their effectiveness at replicating the stickiness of faecal sludge.

This work has also demonstrated that a single, universal simulant recipe based upon cheap, locally available materials is probably not a realistic aim due to variations in material properties. Instead, a simulant design tool has been developed to guide users through the process of developing suitable simulants, and this will be made freely available online.

The simulants presented here are already being used to quantitatively evaluate the performance of different desludging pumps and should help to prioritize investment into development of the most promising systems. However, further studies are also required to characterize the 'pumpability' of faecal sludge and collect consistent data sets spanning the full ranges of undrained shear strength, bulk density, sludge stickiness and debris contents.

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REFERENCES

AIT 2012 *Assessment of Faecal Sludge Rheological Properties*. Asian Institute of Technology, Pathumthani, Thailand.

Beaumont 2012 *032 Vendor Simulant Formulas*. Beaumont, Kailua, USA.

Beaumont 2014 FSM Technology. http://fsmtech.org/ (acessed 10 October 2014).

Bösch, A. & Schertenleib, R. 1986 *Emptying on-site excreta disposal systems* (IRCWD Report 03/85). IRCWD (now EAWAG – Sandec), Zurich, Switzerland.

BSI 1990 *BS 1377-2:1990 Soils for civil engineering purposes – Part 2: classification test*. British Standards Institution, London, UK.

Byrne, A. 2012 *Sanitation in developing countries – emptying pit latrines*. MSc thesis, Trinity College Dublin, Dublin, Ireland.

Gasser, V. 2014 *VIP Latrine Sludge – Rheology and Water Contents*. Unpublished results. ETH, Zurich, Switzerland.

Graham, J. P. & Polizzotto, M. L. 2013 Pit latrines and their impacts on groundwater quality: a systematic review. *Environ. Health Persp.* **121** (5), 521–530.

Harrison, J. & Wilson, D. 2012 Towards sustainable pit latrine management through LaDePa. In: *Second International Faecal Sludge Management Conference FSM2*. SuSanA, *Durban, South Africa*.

Kone, D. & Dodane, P. H. 2008 Faecal sludge management – An approach to bridging infrastructure provision and human excreta management. In: *International Conference on Water in the City and Urban Sanitation 23–24 June 2008*, Marina de Bercy, *Paris, France*.

Kuo, M. 2011 *Deep ocean clay crusts: behaviour and biological origin*. PhD thesis, University of Cambridge, Cambridge, UK.

Peeters, B., Dewil, R., Van Impe, J. F., Vernimmen, L. & Smets, I. 2011 Using a shear test-based lab protocol to map the sticky phase of activated sludge. *Environ. Eng. Sci.* **28**, 81–85.

Radford, J. T. & Fenner, R. A. 2013 Characterisation and fluidisation of synthetic pit latrine sludge. *J. Water Sanit. Hyg. Dev.* **3** (3), 375–382.

Radford, J. T. & Sugden, S. 2014 Measurement of faecal sludge in-situ shear strength and density. *Water SA* **40** (1), 183–187.

Thewes, M. 1999 *Adhäsion von Tonböden beim Tunnelvortrieb mit Flüssigkeitsschilden [Adhesion of clay soil during tunneling with liquid shields]*. PhD thesis, Bergische Universität Wuppertal, Wuppertal, Germany.

UKZN 2012 *Mechanical Properties of Faecal Sludge – Interim Report A*. University of KwaZulu-Natal, Durban, South Africa.

UKZN 2013 *Raw Data Rheology of VIP Faecal Sludge*. Unpublished Results. University of KwaZulu-Natal, Durban, South Africa.

UKZN 2014a *Mechanical Properties of Faecal Sludge – Final Project Report*. University of KwaZulu-Natal, Durban, South Africa.

UKZN 2014b *SOP Stickiness Test v001*. University of KwaZulu-Natal, Durban, South Africa.

UN-DESA 2012 *World Urbanisation Prospects: The 2011 Revision: Highlights*. United Nations, New York, USA.

Underdown, C. 2013 *Characterisation of synthetic pit latrine sludges and their fluidisation potential*. MEng thesis, University of Cambridge, Cambridge, UK.

WHO, UNICEF 2014 *Progress on Sanitation and Drinking-Water: 2014 Update: Joint Monitoring Programme for Water Supply and Sanitation*. World Health Organisation & UNICEF, Geneva, Switzerland.

Zumsteg, R. & Puzrin, A. 2012 Stickiness and adhesion of conditioned clay pastes. *Tunnell. Underground Space Technol.* **31**, 86–96.

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