Faecal sludge pump characterisation

by

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I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

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Technical Abstract

2.5 billion people lack access to adequate sanitation. The proportion of the world's population living in urban areas is projected to grow from its current figure of 54% to 66% by 2050. Much of that growth will mean expansion of urban informal settlements or 'slums'. Lack of government investment and legal problems with land ownership mean that on-site sanitation is often the only option in these areas. Lack of space and resources preclude digging new pits when old ones are full and so it is necessary to de-sludge pits regularly. As such there has been significant interest in developing Pit Emptying Technologies (PETs). Where PETs fail to empty the thicker sludge, or where PETs are not available, pits are emptied manually, with significant associated health risks.

This project forms part of a wider body of work which seeks to take a scientific approach to improving the reach and efficacy of PETs as a replacement to manual emptying. There are three parallel strands which form the work. Firstly we must understand what pits contain, secondly we must know the performance limitations of existing PETs and finally we must understand the business proposition of the pit emptying entrepreneur so that we can utilise that knowledge to match pumps to pits and to develop PETs which deliver more value to the entrepreneur.

This project focuses mostly on the second and third strand but also contributes to some extent to the first strand. Previous work on pit contents has resulted in the development of a faecal sludge simulant with which PETs can be safely tested. This simulant was used to test the range of shear strengths which can be pumped by 3 PETs (Gulper 1, Gulper 2 and Oxfam Diaphragm pump) and to measure the flow rates each PET could achieve at each shear strength. The process of producing the simulant followed the method suggested by previous work, providing an opportunity to critique that process. In light of the results on PET performance and based on the existing data on pit contents, the profitability of using each pump to empty pits in Kampala was calculated. The effect of the shear strength of the sludge in the pit on profitability was analysed.

The maximum pumpable shear strengths of the Gulper 2, Gulper 1 and Oxfam diaphragm pump were found to be 590Pa, 430Pa and approximately 50 Pa respectively. While the Gulper 2 pumped sludge of a higher shear

strength, the flow rates achieved with the Gulper 1 were substantially higher when used on sludge with a strength less than or equal to 282 Pa. The Oxfam diaphragm pump achieved some head when used on sludge with a strength 200Pa and below but the head achieved was insufficient for the sludge level to reach the top of the 'pit'. As the sludge level was close to reaching the pit when tested with a 110Pa simulant it was assumed that the Oxfam Diaphragm pump could pump sludges of 50Pa and below for the purpose of the business model analysis.

A cost model was developed to describe the cost to an entrepreneur of emptying a single pit. Strength and displacement data from 29 pits in Kampala was analysed to give a volumetric strength profile of those pits in terms of the range of shear strengths at which the PETs were tested in this study. The volumetric strength data was combined with the experimentally acquired flow rate data to calculate the proportion of sludge in each pit that each PET could remove and the average flow rate that each PET would achieve when pumping that sludge. The cost model was then used to calculate the cost to the entrepreneur of emptying each of those pits and combined with the payment model used in Kampala to calculate the profit an entrepreneur would make by emptying each of those pits. It was found that the Gulper 2 would make an average profit of US$ 1.7 per pit whereas using the the Oxfam diaphragm pump and the Gulper 1 would result in average losses of US$ 30 and US$ 86 respectively. The reason for the Gulper 2's superior profitability was its ability to empty much larger volumes of sludge from the pit due to its greater reach. The high fixed cost of vehicle hire and fuel and the constraint of only being able to empty 1 pit per day in Kampala make the cost of emptying relatively inelastic. This means that it is important for entrepreneurs to be able to charge a large fee for emptying each pit in order to cover their fixed costs. While the capability of the Gulper 2 to empty thicker sludge does allow it to empty a larger proportion of the sludge in the pit, the slow flow rate at high shear strengths makes it expensive to the entrepreneur to empty high shear strength pits.

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1 Introduction

1.1 Global sanitation context

The provision of affordable sanitation to rapidly growing urban informal settlements poses a difficult and important challenge. The Millennium Development Goal (MDG) for sanitation was for 75% of the global population to have access to 'improved' sanitation by 2015.[1] The reality of 2.5 billion people[2] without access falls more than half a billion short of that MDG. An estimated 105 million people in urban areas[2] have no option but to defecate in the open or into plastic bags because public facilities are too expensive, too far away or too poorly maintained.[3] This number is gradually increasing.[2] Waste from 4.1 billion people, almost 60 % of the population, is discharged to the environment untreated.[4] 2 million deaths[5] a year can be attributed to sanitation-related diseases. Of those, children under 5 years are the most affected group.[5] In addition to the mortality rate, Neglected Tropical Diseases (NDT's) such as schistosomiasis, helminths and trachoma, all of which have a faeco-oral transmission pathway, result in large Disability Adjusted Life Year (DALY) losses in developing countries.[6]

Currently 54%[7]of the world's population is urban and by 2050 66%[7] of the world's population is projected to be urban. The difficulty of providing sustainable urban sanitation to this growing population is demonstrated by the fact that, since 1990, 1.2 billion people in urban areas have gained access to improved sanitation and yet the urban population without access has risen from 541 million to 756 million.[2]

There are often large intra-urban disparities in access to sanitation[2] . The poorest people live in informal urban settlements or 'slums' and tend to have much worse sanitation coverage, with open defecation being more common.[2] The current population living in slums is estimated to be 863 million.[8] Providing sanitation in urban informal settlements brings a unique set of challenges. Uncertainty regarding land tenure often means that it is difficult to install sanitation infrastructure.[9] As such, on-site sanitation is the only option and so pit latrines are installed. It is estimated that 1.8 billion people use pit latrines.[10] Space and resource limitations mean that there is no option to dig a new pit when the first one is full.[11] In these high loading situations, emptying of pit latrines is critically important.[12] Efforts to meet the sanitation MDG's have resulted in large scale projects to provide households with pit latrines[13] as they offer the most affordable and flexible solution to the growing sanitation demands of the urban poor. However, their ease of use, affordability, and simplicity comes with a cost, most heavily borne by the factions of society who find themselves with the stigmatised and unhygienic task of emptying the pits.

1.2 Pit emptying

Manual emptying of pits by informal entrepreneurs is widely practised.[14] Emptiers, often without protective clothing, use scoops and buckets to empty the pit,[11] spending up to six hours waist deep in faecal sludge while doing so.[12] Currently the informal nature of pit emptying work means that sludge is often dumped into local streams, drainage channels or the nearest open field.[12,15,13] Even where discharge into official disposal points in the sewer is permitted, operators tend to be unwilling to travel to reach these points.[15] The role of the pit emptier is frequently stigmatised. Hostility towards pit emptying operators in Kibera (Nairobi) results in pit emptiers working at night to avoid being attacked.[15,13,12] While manual emptying of pits does provide employment, with payment rates higher than the market labour rate,[11] the risk to workers of attack[12] and disease[16] mean that an alternative solution must be found. Vacuum tankers, designed to empty septic tanks,[17] are able to empty watery sludge fast but restricted access[15,16,18] and prohibitive cost[11,12] mean they are inappropriate for use in slums.[14] The lack of appropriate desludging services means that householders postpone emptying their pits until they are dangerously full,[19] or resort to unhygienic practices such as flooding out the pit during the rainy season.[14,19]

The plight of the pit emptiers has motivated efforts to produce affordable, small scale Pit Emptying Technologies (PETs) which can empty pits hygienically and which can access tight spaces.[17] Available technologies include the UN's Vacutug, the MAPET, the Gulper 1, Gulper 2 and the Oxfam Desludeging Diaphragm pump.[13,20,21] Useful studies comparing the performance of these pumps based on their resilience, affordability and access characteristics are available.[22,17,15,13,23] However, due to the lack of a safe testing solution until recently, PETs have been tested on faecal sludge or on a 'ad-hoc' simulant which the tester believes approximates the behaviour of faecal sludge.[24] The great variability of pits between countries makes it hard to compare the results obtained.[25] As such there is a dearth of quantitative information on the relative pumping performance of the different PETs.

1.3 Pit emptying improvement framework

As part of a recent move to approach the problem of pit emptying from a scientific viewpoint, a framework has been established which highlights the important gaps in our knowledge and the utility of reducing them.[26]

1. **What is in the ground?** - The first and most critical step towards effective faecal sludge management is understanding the physical characteristics of faecal sludge. This involves both understanding the physical behaviour of the material and understanding the overall variation with depth in a pit and the variation spatially between different pits in the same geographical area.
2. **What can pumps do?** Greater understanding of the performance limits of pumps is required. Important aspects include the range of pumpable shear strengths, achieved flow rates and the effect of debris. Useability characteristics are also important but are better understood at present.
3. **Implications for practice** - We can overlay the data for pits and pumps and establish the differences between the capability of different pumps to empty different pits. Using this analysis and with some information on typical business models we can investigate what effect these differences might have on the profitability of a business. Using this analysis local entrepreneurs, or those supporting them, can make more informed decisions on which pump to invest in. Designers can also see where marginal gains can be made and can then design technologies to exploit them.

1.4 Project aims

In the main, this project will focus on using the simulant developed by Radford [27] and Underdown [28] to investigate the performance of 3 PETs (Oxfam Diaphragm pump, Gulper 1 and Gulper 2). This characterisation will involve finding the limiting shear strength that is just pumpable for each PET and the flow rate the PETs can achieve at each shear strength. As well as the quantitative data, observations on using each pump and possible improvements will be noted.

The PET performance data will then be applied to different pit emptying business models in order to examine their sensitivity to PET performance.

1.5 Research objectives

- To characterise the performance of 3 PETs in terms of the range of shear strengths they can pump and the flow rates they achieve within that envelope of shear strengths.
- To use those results and existing data on pit composition to analyse the effect of differences in PET performance on the success of various pit emptying business models.

2 Previous work

2.1 Sludge characteristics

2.1.1 Key parameters affecting pit emptying

Undisturbed in-situ shear strength, density, stickiness and debris content have been identified as the parameters which control the ‘pumpability’ of pit latrine sludge. [29] Sludge is treated as a weak soil rather than a stong liquid [27, 28, 24, 25] based on the observation that consolidated sludge does not readily flow. [27] As such undrained shear strength is used to characterise the sludge rather than viscosity. Undrained shear strength controls the suction required to cause sludge to start moving. The density of a certain sludge controls what head can be achieved for a certain suction and so limits the depth which a given suction system can empty to. Stickiness [30] and debris content affect the likelihood of equipment blockages. [29, 18] Throughout this study water content is defined as $WC = \frac{mass of water}{total mass}$ because the correlation between simulant density and water content is linear when plotted on a wet mass basis. [28]

2.1.2 Undrained shear strength of faecal sludge

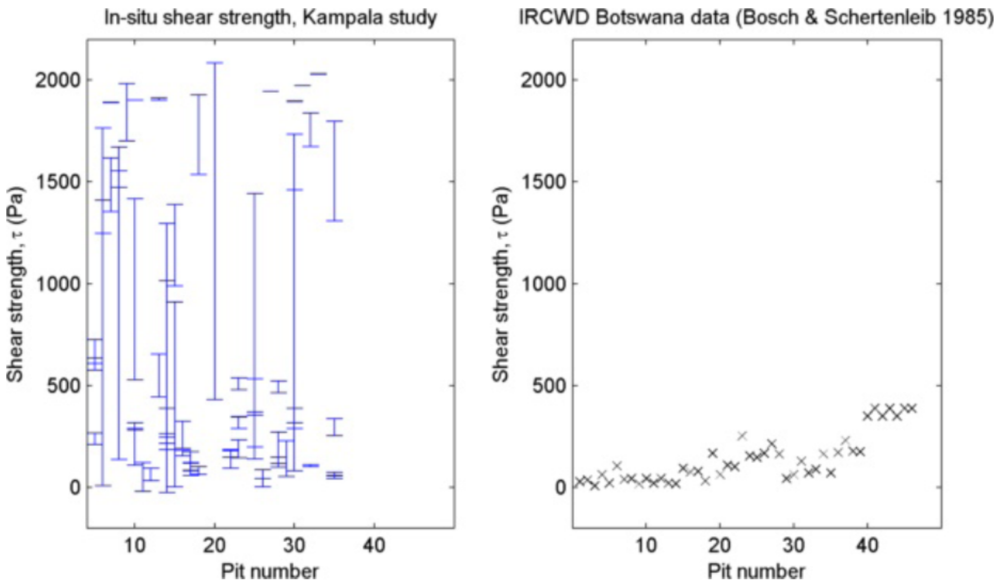

Figure 1: Reported shear strengths in pits in Kampala and Gaborone - *The Kampala study recorded the whole range of shear strengths in each pit while the Gaborone study only recorded the shear strength of one sample from each pit.*
Source: Figure 2 from 'Measurement of faecal sludge in-situ shear strength and density' by Radford and Sugden, [25] licensed under CC BY 4.0.

A study in Gaborone, Botswana carried out by the International Reference Centre for Waste Disposal (IRCWD) in 1985 tested the density and shear strength of samples taken from 47 pits. [18] A more recent study in Kampala [25] tested the density of a sample and the in-situ shear strength profile of 30 pits. In both studies the maximum shear strength measured was limited by the equipment used.

In the Botswana study this limit was around 500Pa and in the Kampala study this limit was around 2000Pa.[25] As a result of these technology limits the maximum strength of faecal sludge is not known. However the results of the two studies, presented in Figure 1, do show that there is a large range of shear strengths in and between pits and that undrained shear strengths range from 0Pa up to at least 2000Pa. The observation that undrained shear strength varies with depth is important when considering PET performance because it will be the sludge strength at the depth of insertion of the PET which will determine how well the PET performs.

2.2 Faecal sludge simulants

Two previous MEng projects[27,28] and subsequent work by Mott MacDonald[29] have resulted in the development of two synthetic sludges which reproduce the full range of undrained shear strengths seen in pit latrine sludge and which have densities in the range observed for faecal sludge.[29] The first, developed by Radford[27] and Underdown,[28] consists of a mixture of kaolin, topsoil and water. The second is based on Milorganite, a fertilizer derived from treated sewage sludge.[29]

The kaolin topsoil simulant has a density of around $1500(kg/m^3)$,[29] similar to the measured densities of sludges found in Ventilated Improved Pit Latrines (VIPs) and Urine Diverting Dry toilet (UDDT).[29] The Milorganite simulant has a density of around 1000 (kg/m^3),[29] making it more representative of sludges found in septic tanks.[31]

The kaolin topsoil simulant displays a highly consistent relationship between shear strength and water content for a given topsoil, although the relationship varies with the topsoil used.[28] This variation is partly because some topsoils contain significant amounts of clay[29] and partly because the water content of topsoil varies and so the amount of water added to the mixture for a given water content varies depending on the topsoil used.[28] In order to account for the variation in shear strength due to variations in topsoil water content, a normalised water content (WC_N) has been defined as a function of the true water content (WC_T), the proportion of kaolin by dry mass K, and the water content of the topsoil

(WC_E), as shown in Equations 1 and 2 [29] .

$$WC_N = WC_T.\Big(1 - \frac{0.05E}{0.01(1-K)(1-WC_T) + E.WC_T}\Big) \quad (1)$$

$$\text{where } E = (1-K).\frac{WC_E}{WC_T}.\frac{1-WC_T}{1-WC_E} \quad (2)$$

2.3 PET performance

Increasing recognition of the importance of pit emptying as part of effective Faecal Sludge Management (FSM) has lead to the development of various PETs. [23] Currently available technologies which have been specifically designed for emptying pit latrines are listed below. In what follows, as in various other studies, [13, 32] the PET's are classified either as semi-mechanised (PETs where the work input is manual) or fully mechanized (PETs which are powered by an engine).

Fully-mechanized PETs

- **UN-HABITAT Vacutug MK II** - A vacuum pump with a 500L tank which is mounted on a self propelled chassis [33].
- **ROM 2** - A vacuum pump and a pressure pump for fluidising sludge which must be mounted on a truck or trailer. [34]
- **Diaphragm Sludge Pump** - A truck mounted diesel driven diaphragm pump. [34]
- **The Pit Excrevator** - A screw pump driven by a hydraulic motor. [35]

Semi-mechanized PETs

- **Gulper 1** - A fixed length, manual, positive displacement pump made predominantly of PVC. [36]
- **Gulper 2**- A manual positive displacement pump whose length can be varied made of steel tube and PVC [36]
- **Oxfam diaphragm pump** - A manually driven diaphragm pump. [21]

2.3.1 Qualitative performance studies

The performance of many of the technologies listed in the previous section has been analysed qualitatively in a variety of studies. The following criteria have been commonly identified as important determinants of success:

1. **Accessibility** [23,15,17,35] - The ability of the PET to travel along narrow streets to reach the latrine and of the emptying apparatus to enter the pit superstructure.

2. **Affordability** [23,37,15,33,35] - This includes both the capital cost of the pump and the cost of operation and maintenance.

3. **Sanitary** [35,23,37,15,13] - The PET must allow hygienic emptying such that neither the operators nor the users are exposed to health risks.

4. **Effectiveness** [35,37,15,23,34] - The PET must be able to empty the sludge found in the area it is used in, and must cope with any rubbish in the pits.

5. **Ease of use** [15,23,37,34] - The PET must be easy for one or two people to set up and operate.

A summary of the performance of each of the semi-mechanized pumps mentioned above against these criteria is given in Table 2 based on a review of the available literature. The table does not include various technologies which have been developed previously which have now fallen into disuse but important lessons can be learnt from the failure of these technologies. The MAPET, which was successfully used in Dar es Salaam for between 8 and 13 years, [33] is no longer operational due to a combination of factors which include a breakdown on institutional support, the reliance on importing a leather piston ring which could not be locally sourced and the difficulty of recovering maintenance and transport costs from emptying fees. [33] Chain based technologies such as the Nibbler and Gobbler have also been tested but difficulties faced during testing have put a stop to development. [33]

PET	Accessibility	Affordability	Sanitary	Effectiveness	Ease of use
Vacutug	Can access most areas apart from where the topography is steep or the streets very narrow.[13,23] Unable to access pits inside houses or back courtyards.[15] Has insufficient vacuum power to empty pits from any distance.[23]	Costs 20% of vacuum tanker but still not all that affordable at $USD8000.[13] Some schemes report that emptying fees can exceed maintenance and operating costs[17] while others report not managing to break even.[23] Slow travelling speed means that distance to site is a critical factor in its ability to break even.[23,11]	No problems reported	Only manages to pump high liquid content sludge, often after the addition of water.[15,33,13] Breaks down frequently.[34] Blockages are common.[15,34] Empties to a limited depth.[15,33] Lack of suction through hose joints limits performance.[15] Has limited storage capacity[23]	Need to consistently remove and reinsert hose to maintain suction.[15,33] Hard to handle[13] and unstable.[34] Requires 4 operators[13]
ROM 2	No problems so far but not yet tested in townships.[34] Can pump from 30m away.[34]	Good fuel economy keeps operating costs down.[34]	No problems reported	Works well after large bits of rubbish have been removed from the pit.[34] Able to cope with small bits of rubbish.[34] Inbuilt fluidiser allows thick sludge to be emptied.[34]	No problems reported
Diaphragm sludge pump	No data	No data	No data	Very sensitive to rubbish. Fine for septic tanks but fails to operate on even fluidised pit latrine sludge.[34]	No data
Pit Excravator	Easily portable but poor manoeuvrability within the latrine superstructure can restrict access.[35]	No data	No data	Doesn't deal well with rubbish and dry sludge but can run backwards to help clear blockages.[35]	No data

Table 1: Qualitative assessment of the performance of fully-mechanized PETs - *Note that ROM 2 was modified during testing and it is the modified performance which is presented here. Note also that the only available data on the Pit Excravator is from the developer of that technology.*

PET	Accessibility	Affordability	Sanitary	Effectiveness	Ease of use
Gulper 1	Higly portable.[13] Difficult to set up and operate in a small superstructure.[33]	Very inexpensive[13] and can be manufactured and repaired locally.[33] Quoted prices vary between 40 and 1400 USD.[33] PVC riser is reported to crack after long term use[33]	Wet sludge tends to splash at outlet.[33]	Faster than manual emptying[23] with quoted flow rates of 30L/min.[33] Tends to get blocked due to rubbish.[33]Only empties down to about 1m so more frequent emptying is required[23] although a longer pump is available.[15]	No need to break the squatting slab.[23] Hard work to use[20]
Gulper 2	Slab must often be broken to get the pump into the pit.[20] Heavier than the Gulper 1 but still small and light enough to be carried.	Costs $215 in Kampala	Has a clean outlet consisting of a flexible hose.[20]	Pumps thicker sludge than the G1.[20] Capable of reaching 3m into the pit.[20]	The inclusion of a lever arm reduces drudgery relative to the Gulper 1.[20]
Oxfam Diaphragm pump	No reported problems.	Low capital cost ($300-850 USD).[33] Rubber diaphragm tends to crack and spare parts are difficult to source[33] (Note that previous development work on the MAPET also found that rubber diaphragms are liable to break[13])	No reported problems	Only capable of extracting low viscosity sludge.[33] Gets blocked by rubbish.[33,37,38] Difficulty in keeping fittings airtight leads to low performance[33]	No data

Table 2: Qualitative assessment of the performance of semi-mechanized PETs

Thye[23] developed a decision making framework to aid in the selection of appropriate technology for faecal sludge management in a community. The proposed framework is as follows:

1. **Access to the pit** - considers the distance that equipment must travel to get to the pit.
2. **Emptying** - This stage is split into two categories
   (a) *Type of sludge in the pit* - a flow chart of questions about local pit type, anal cleansing practice and solid waste disposal are used to attempt to classify the sludge qualitatively.
   (b) *Devices to empty pit* - Based on the qualitative categorisations in part 2a and upon the depth of sludge that needs emptying, different types of technology are suggested.
3. **Method of transport away from the pit** - based on the decisions made in part 1 and on the distance to the disposal point, different transport options to the disposal point are considered.

While the framework is useful for examining the technical applicability of a technology it should be noted that the social acceptability and economic aspects of a technology should be also be considered.[16] As Thye acknowledges,[23] stage 2 is based entirely on qualitative judgement. Recent work to develop tools to characterise pits quantitatively[25, 15] should strengthen the quality of information available at Stage 2a. The lack of quantitative understanding of the effect of the conditions on the performance of PETs,[23] as can be seen by the purely qualitative descriptions of PET effectiveness in Table 2, remains a barrier to good decision making at stage 2b. It is this lack of quantitative understanding which this project seeks to address.

2.3.2 Quantitative performance studies

Since Thye published the decision making framework presented above, a single quantitative study,[39] facilitated by recent simulant development work,[28, 27, 24] has been carried out by Water for People (WfP) on two PETs which they commonly use: the Gulper 1 and the Gulper 2. Their results are shown in Table 3. 2kPa sludge was also tested but neither device could be submerged in it.[20]

		Gulper 1		*Gulper 2*	
Shear strength (Pa)	**Operator**	Time taken to prime (s)	Mass pumped in 30s (kg)	Time taken to prime (s)	Mass pumped in 30s (kg)
100	Person 1 (60 kg)	16	17.5	16	37.3
100	Person 2 (80 kg)	19	18.6	15	45.4
500	Person 1 (60 kg)	125, failed	failed	25	22.5
500	Person 2 (80 kg)	180, failed	failed	20	29.4

Table 3: Initial data on the performance of the Gulper 1 and Gulper 2[20]

The work presented here aims to further fill that gap in quantitative understanding. The initial study by Water for People has proved that the simulant can be successfully used to test PETs. This study aims to validate and build upon the WfP study and to set a precedent for future work on PET performance.

3 Investigating PET performance

3.1 Introduction

The aim of this experimental work is to provide quantitative information on pump effectiveness to add to existing knowledge on the performance of the PETs presented in Table 2. This information should be of use for pump selection and design and will establish a rigorous protocol for the assessment of other pumps. Pump effectiveness will be quantified by describing the flow rate achieved by various pumps at different shear strengths. Only semi-mechanized technologies could be

Figure 2: Left to right - The Oxfam diaphragm pump, the Gulper 1 and the Gulper 2

acquired for testing. The pumps tested were the Gulper 1, the Gulper 2 and the Oxfam desludgeing pump, as shown in Figure 2. In the Oxfam Diaphragm pump a diaphragm between two chambers is pushed back and forwards with a lever to sequentially compress and expand each chamber. Non return valves on the inlet and exit ensure that sludge is sucked in from the pit when the pressure in the chamber is low and exhausted out into the outlet hose when the pressure in the chamber is high. The mode of operation of the Gulper 1 and the Gulper 2 is demonstrated in Figures **??** and **??** respectively.

3.2 Methods

3.2.1 Experimental design

A maximum test strength of 1500Pa was chosen based on the study done by Water for People in Uganda.[39] This study showed that neither the Gulper 1 nor the Gulper 2 could be inserted into the sludge at 2000Pa and so testing sludge at this thickness would be obsolete. In order to maximise efficiency it was decided that the pumps would be tested sequentially at each strength before diluting down to a weaker sludge

The kaolin-topsoil simulant was chosen in preference over the milorganite simulant. The solids settle out of milorganite at high water contents making milorganite unsuitable for shear strengths of less than 500 Pa.[29] Milorganite is also difficult and expensive to procure in the UK. Other sources of dried biosolids were sought out in the UK but a fully dried version could not be located and the batch size for purchasing wet biosolids was excessively large. A composition of 60 % Kaolin and 40 % topsoil by dry mass was chosen as it best replicates the stickiness of faecal sludge according to the (extremely limited) existing data.[26] Work by Underdown[28] derived the empirical relation shown in Equation 3 between true water content and density for a 60% Kaolin by dry mass simulant.

$$\rho = -1323WC + 2104 \tag{3}$$

When the experiment was initially designed it was expected that a penetrometer would be available to measure the undrained shear strength of the simulant in-situ within the testing vessel. This turned out not to be the case due to funding restrictions in the penetrometer development. Work by Mott MacDonald[29]indicates that the Abrams slump test, as used to check the consistency of concrete, effectively measures undrained shear strength for simulant strengths between 2kPa (±600Pa) and 500Pa (±160Pa) but that the accuracy of the test is reduced for strengths below 250Pa. This work suggests that stickiness has no effect on the slump test results, as mixtures of 20%, 30% and 40% kaolin were tested and gave very similar results, but also notes that excessive amounts of material may be left in the cone when testing high stickiness mixtures.[29] Based on the endorsement of this work, the Abrams slump test was used in lieu of a penetrometer. The standard procedure was followed, as set out in BS EN 12350-2:2009 *Testing fresh concrete - Part 2: Slump- test*.[40] A plywood base with a plastic coating was used. Slump readings were converted to values for undrained shear strength according to the correlation determined in the aforementioned work by Mott MacDonald.[29] This conversion was done automatically using the simulant development spreadsheet produced by Mott MacDonald.[41]

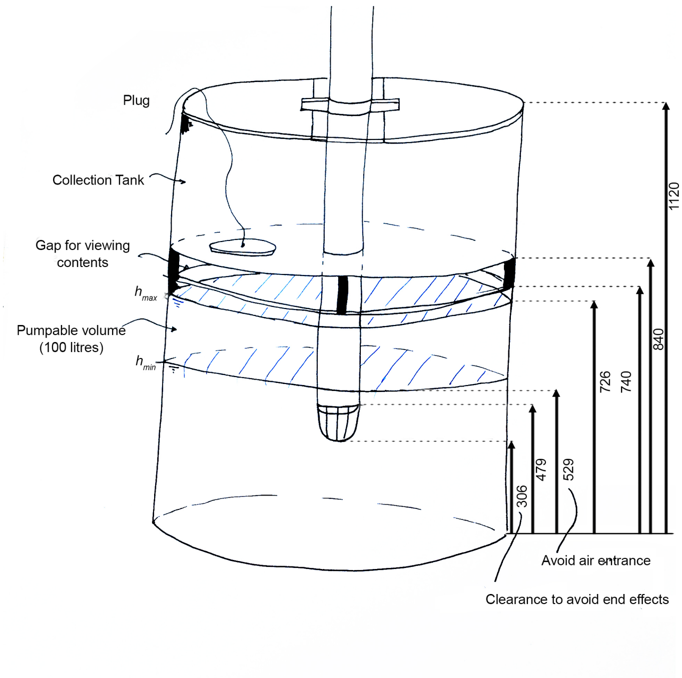

Figure 3: Rig design - *all dimensions are in mm*

3.2.2 Rig design

The rig was designed to enable quick and reliable testing of the pumps. Initial data from Water for People suggested a maximum mass flow rate of 90kg/minute, [20] achieved when using the Gulper 2 on 100Pa simulant. 100Pa simulant has a density of approximately $1300kg/m^3$ [29] making the achieved volumetric flow rate 69 litres/minute. PETs must be primed before testing and this requires approximately 16 litres of sludge. These figures suggest a required pumpable volume of 85 litres. However the as yet untested Oxfam diaphragm pump may achieve a higher flow rate than the Gulper 1 and Gulper 2 did in previous testing and so the rig was designed to contain a pumpable volume of 100 litres. A minimum clearance of 300 mm between the bottom of the pump and the tank was specified to avoid end effects altering the inflow into the device. A minimum sludge cover of 50 mm above the inlet of the pipe was specified to prevent air being sucked in to the pump.

For ease of use the collection tank into which the sludge will be pumped was placed on the lid of the tank with a removable bottom such that, after a run, the sludge could be dropped back down into the main tank, thus recycling the sludge. A pipe in the centre of th top tank allowed the PET to pass into the bottom tank while keeping the collected sludge in the top tank. A gap between the bottom tank and the collection tank was specified so that the surface of the sludge in the bottom tank could be observed. A circular tank was selected on the basis of its small plan area. The initial batch size required to test at 1500Pa was calculated to be approximately 540kg.

3.2.3 Correlating water content and undrained shear strength

Figure 4: Slump testing: Simulant at 68000Pa, 1300Pa and 300Pa

Before the pumps could be tested, it was necessary to correlate the undrained shear strength of the sludge with its water content for the particular soil used in the study. Following procedure set out in the Mott Macdonald simulant design guide,[41] 25 kg of very strong sludge was mixed and then diluted until it would release from a slump cone. This was then further diluted and the water content and shear strength of the sludge were recorded at 14 levels of dilution. Water content tests were carried out according to standard procedure and undrained shear strength measurements were found using the Abrams slump cone as described above. However, even high water content sludge failed to release from the cone during initial experiments, and so the cone was lubricated with vegetable oil before each test. Examples of successful slump tests are shown in Figure 4 while examples of slump tests whose results had to be discarded are shown in Figure 5.

Figure 5: Failed slump tests showing, from left to right: a) the cone being pulled to one side due to the stickiness of the sludge on release, b) voiding due to poor compaction and c) both problems simultaneously

3.2.4 PET performance

The topsoil was sieved through a course grating to remove large lumps of soil which would not mix well. The correlation between water content and shear strength was used to ascertain that a water content of 40.8% was required to achieve a target shear strength of 1500Pa. That water content, Equations 1 and 2 and the value of the soil embodied water content were used to calculate the quantities of topsoil, kaolin and water required to produce 543 kg of 1500Pa simulant. Batches of 9.5kg of topsoil, 11kg of kaolin and 10kg of water were mixed in a cement mixer and then tipped into a tank where they were mixed further using a plaster stirrer. This relatively small batch size was determined by the unmixed volume which could fit into the cement mixer. Eighteen such batches were mixed to give 549kg of simulant. The resultant simulant had a water content of 38.5 % and an undrained shear strength of 1800Pa. The decision was taken to start testing at this strength.

The outer diameter of the outlet of the Gulper 2 is 90mm, not a standard size for ribbed hose in the UK. As such 100mm hose was used and a jubilee clipped was used to attach it firmly to the outlet. This pipe broke frequently due to the stress on the hose resulting from being jubilee clipped onto a smaller diameter pipe. Plastic sheet was added to the outlet of the Gulper 1 to ensure that the pumped simulant all fell into the bucket it was being pumped into. The pumps were tested in turn.

Figure 6: The mixed simulant in the tank, mixing the simulant for testing, testing the Gulper 2 .

After a test was complete the lid of the tank was removed and the simulant diluted to the next target undrained shear strength. These target shear strengths were determined depending on the PET performance at the previous shear strength with the aim of determining with some precision maximum pumpable shear strength of each PET. When a PET began to function, the time taken to prime and the mass which the PET could pump in one minute was measured. The mass flow rate test was repeated two or three times depending on the difference between the first two readings. The simulant was pumped into buckets rather than the top tank as had been planned. This was because the volumes pumped were insufficient to give an accurate volume reading in the top tank and so buckets were filled and weighed instead. When a PET filled a bucket in less than a minute the testing duration was reduced. Pumps were cleaned thoroughly with a hose between tests to ensure that the valves didn't stick on subsequent tests.

3.3 Results and Discussion

3.3.1 Correlating water content and undrained shear strength

The embodied water content of the soil was found to be 24.4%. Nominally the sludge should release from the slump cone at an undrained shear strength of around 10,000 Pa.[29] In these experiments the sludge first released when it had an undrained shear strength of 68,000Pa. Further dilution produced a sludge which would not release until the shear strength fell to 2500Pa. This behaviour was put down to the stickiness of the simulant due to its high kaolin content. As all of the sludge used was to be weaker than 2500Pa, the correlation was made from this point. The resulting correlation is shown in Figure 7. The high r^2 value confirms that water content is an excellent predictor of simulant shear strength, with 94 % of the variance in the shear strength data being explained by variance in the water content data.

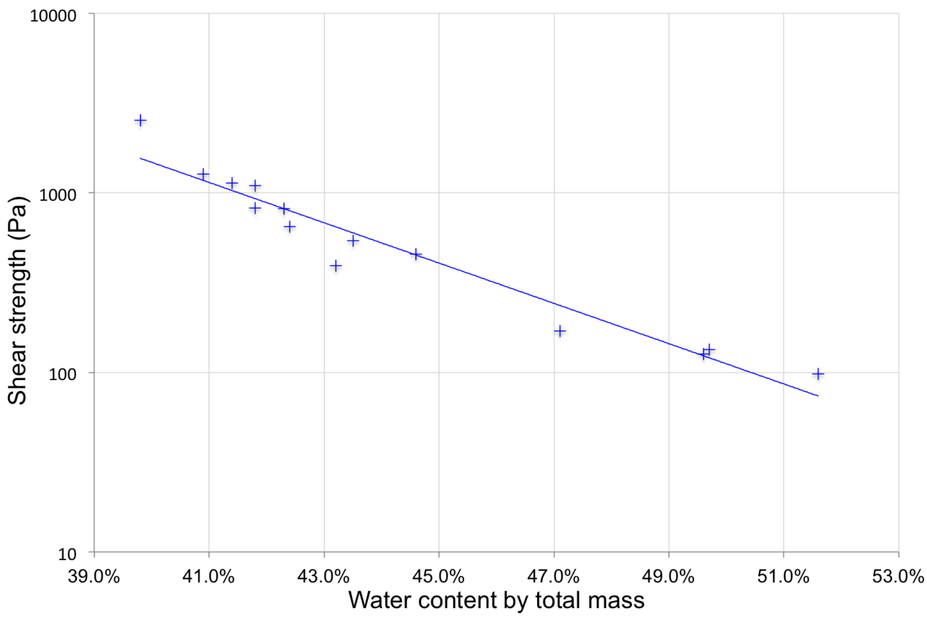

Figure 7: Correlation between water content and shear strength for the topsoil used - *The equation of the line is*: shear strength $= 5 * 10^7 e^{-25.85(Watercontent)}$ *and regression gives* $r^2 = 0.94$.

During PET testing, the data on water content and shear strength was collected again and when plotted, showed a shift in the correlation from the initial dilution data. In the later stages of testing the PETs, this equation for the new correlation (shown in Figure 8) was used to determine the water content required for a new target shear strength. Using that shifted correlation to predict the required water content for the next target shear strength worked effectively. The correlation determined during testing is compared with the initial dilution correlation in Figure 8.

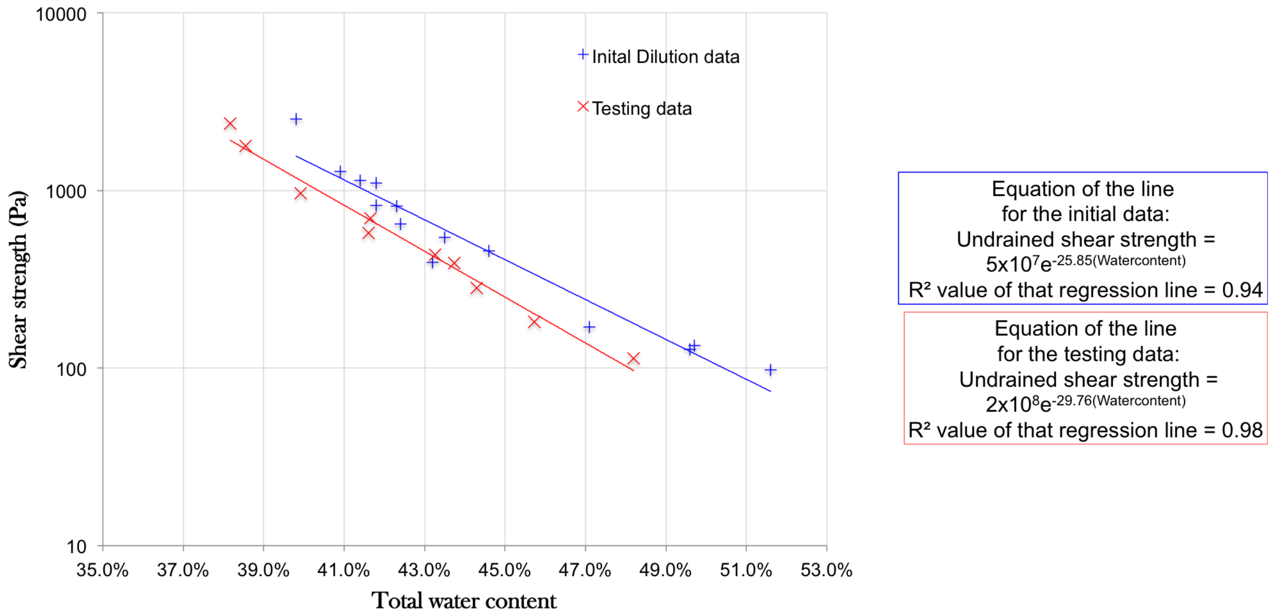

Figure 8: Comparison between the initial simulant correlation and that determined while testing the PET's.

The change in the correlation between water content and undrained shear strength is likely to be due to the topsoil drying out when it was sieved before testing. The downwards shift in the data (lower shear strengths for the same water content) is consistent with a reduction in the water content of the soil.[29]

3.3.2 PET performance

The flow rate achieved by each pump at each of the test undrained shear strengths is shown in Figure 9. The Gulper 2 was found to have the highest pumpable shear strength but the Gulper 1 achieved a higher flow rate than the Gulper 2 at and below 280Pa. Of the simulants tested, the Oxfam Diaphragm pump was only able to pump water. The results achieved for the Gulper 1 and the Gulper 2 are compared to those achieved by SaniHub[39] in Figures 10 and 11. The time to prime each device at each strength is shown in Figure 12, including a comparison to the SaniHub data.[39] Note that all SaniHub data presented is the average value of the figures achieved by each of the individual operators but neglects the data

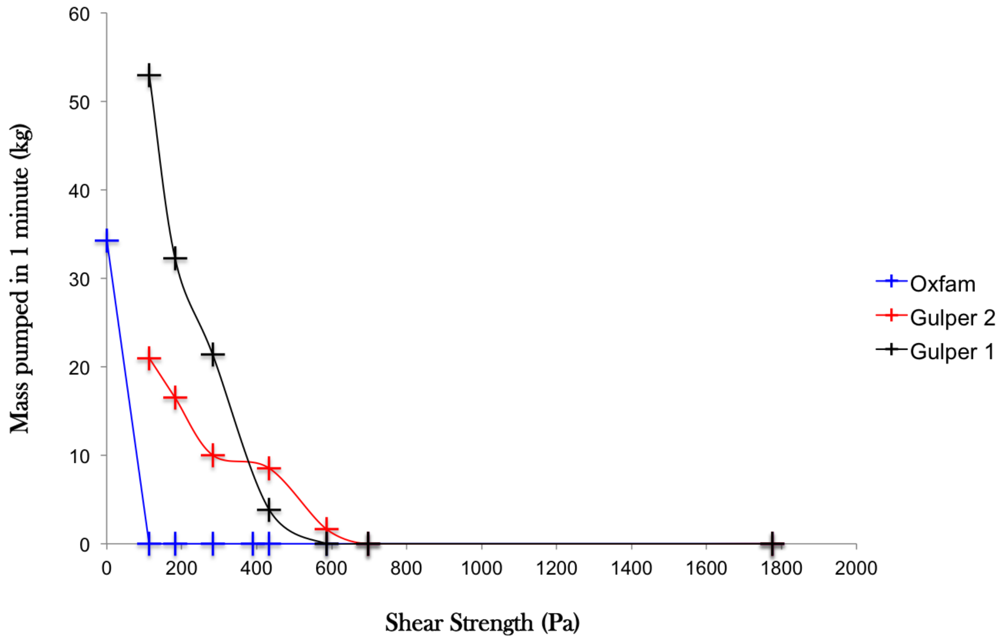

Figure 9: Performance of the Gulper 1, Gulper 2 and Oxfam diaphram pump

where two people worked together to operate the pumps.

The data obtained in this study on the performance of the Gulper 1 agrees well with that recorded in the SaniHub study, as shown in Figures 10 and 12. In fact the two data sets are remarkably similar considering that the operators in the SaniHub study are likely to have been significantly stronger than the operator in this study. In contrast, the data collected here on the performance of the Gulper 2 differs significantly from the SaniHub data both in terms of the flow rates achieved and the time taken to prime the device, as shown in Figures 11 and 12. There are three possible explanations for these differences. Firstly the differences in the data might be due to differences between the Gulper 2 tested here and that tested by SaniHub. The Gulper 2 tested here was the first prototype which was locally manufactured in Kampala and the quality of the manufacturing, especially of the valves, is now expected to be greatly improved. More significantly the Gulper 2 tested by SaniHub included a 'donkey tail' cantilever system[42] while the one tested here did not. The cantilever system increases the force an operator can apply by approximately 2.5 times (see Equation 15 in Appendix B). When operating the

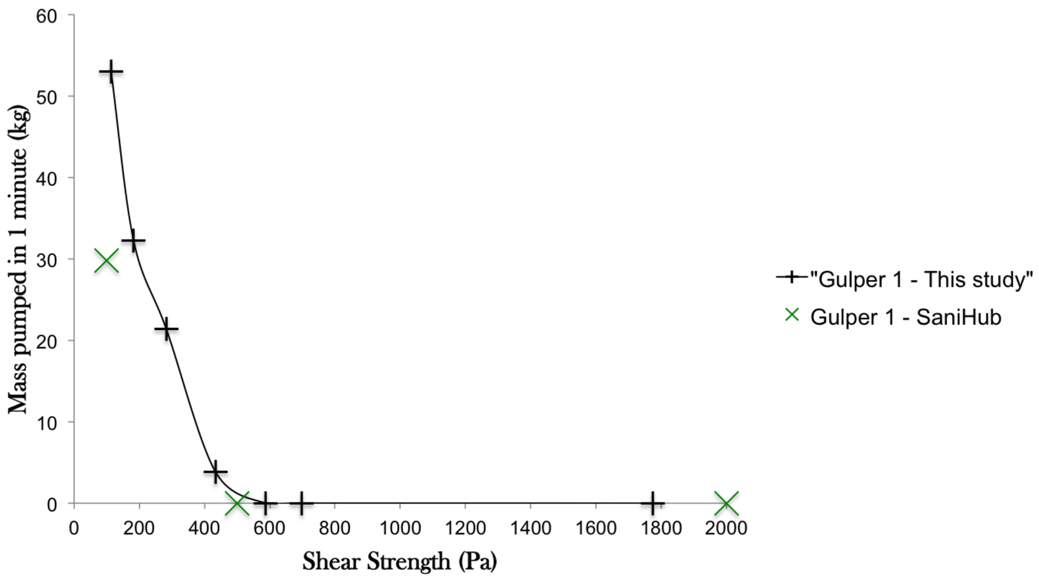

Figure 10: Comparison of data with that obtained by SaniHub for the Gulper 1 [39]

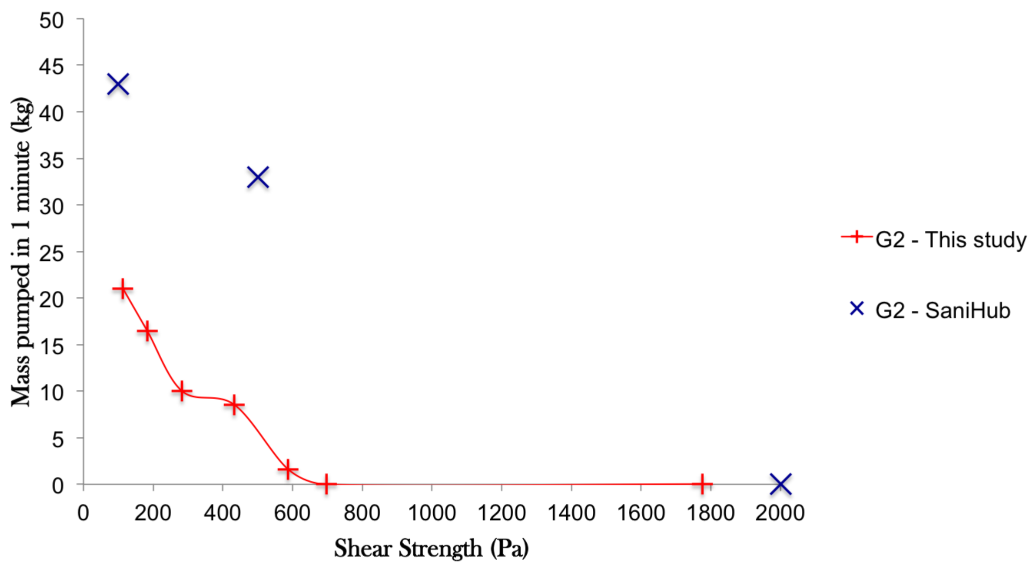

Figure 11: Comparison of data with that obtained by SaniHub for the Gulper 2 [39]

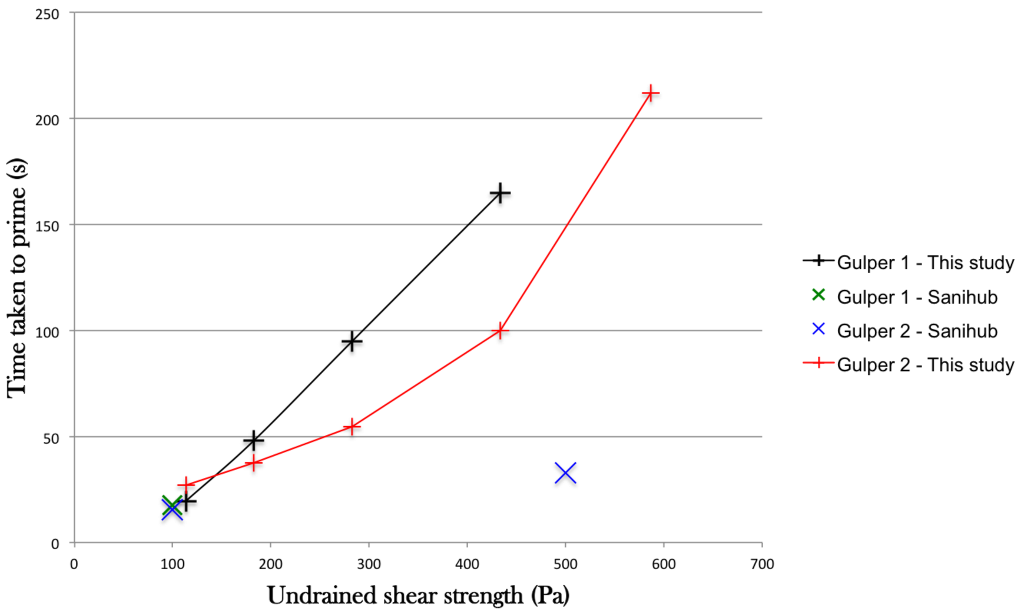

Figure 12: Time to prime each device - Comparison of this study's data with that obtained by SaniHub for the Gulper 1 and Gulper 2 [39]

Gulper 2 it seemed that the process was limited by the force which the operator could exert and so it seems likely that, by increasing that force through a lever arm, a higher flow rate may be achieved. The second possibility is that the results shown here were altered by end effects between the inlet of the Gulper 2 and the bottom of the tank. The rig was designed when only the Gulper 1 had been acquired for testing. The greater length of the Gulper 2 means that it had a very small clearance distance between its inlet and the ground at the point in the stroke when it was fully extended. This may have made it harder to pump with the Gulper 2 and hence reduced the achievable flow rate. The third possibility is that the strength of the operator has a bigger effect on the flow rate achieved by the Gulper 2 than by the Gulper 1. While operator strength appeared to have little effect on the results of the Gulper 1, it is possible that use of the Gulper 2 is much more strength dependent. The fact that the moving parts in the Gulper 2 are heavier than those in the Gulper 1 would be consistent with this. This hypothesis is also consistent with the SaniHub data shown in Table 3, where the heavier operator achieved a faster flow rate with the Gulper 2 (45.4 kg in 30s as opposed to 37.3 kg in 30 s) but a similar and actually slightly lower flow rate with the Gulper 1 (17.5kg in 30s as opposed to 18.6kg in 30 s).

Observations on using each pump

Gulper 1 Failure of the Gulper 1 at 1775, 700 and 590 Pa was due to the sludge not passing through the second valve. The plunger could be moved but a column of sludge was not lifted. The sludge moved into the pump past the first valve so this problem had to be either because the valves were not able to close in such thick sludge or because the suction produced when the top valve did close was insufficient to make the sludge move. This suggests that failure at these simulant strengths was not dependent on the physical strength of the operator. When the Gulper 1 started working at 430 Pa it was at the limit of the strength of the operator. At low undrained shear strengths the Gulper 1 was easy to use although the section of the stroke in which the plunger was above shoulder height was awkward throughout. This high part of the stroke is necessary if the pump is to outlet straight into a barrel without a hose. For the same reason a lever arm system on the Gulper 1 would not work because the lever would be above the operator's head when the plunger was fully up.

Gulper 2 At 1775Pa the outer cylinder of the Gulper 2 could not physically be pushed down into the sludge by the operator. At 700Pa the cylinder could be moved up and down a full stroke but no column of sludge was raised. Again this is likely to have either been caused by the valves being unable to close or because the closed valves produced insufficient suction to move the sludge. When the pump started to function at 590 Pa it was at the limit of the strength of the operator. Even at low sludge strengths pumping with the Gulper 2 was physically hard work. As mentioned earlier, it is likely that the addition of a lever arm would make it substantially easier to operate the Gulper 2.

Oxfam diaphragm pump The Oxfam diaphragm pump failed to pump at any simulant strength and functioned only when pumping water. When tested at 1775

Pa sludge did not even enter the inlet grating despite it being submerged at least 300mm below the surface of the simulant. When tested at 700Pa sludge entered the inlet grating but did not progress into the inlet pipe. At 590Pa and 430Pa the sludge moved into the pipe to some extent but no head was achieved. It was noted at this point that suction was being lost because air was being entrained where the hose was attached to the pipe inlet with a jubilee clip. A better jubilee clip was added, the thread of which could cope with being tightened to a greater extent. This made it harder work to pump suggesting the adaptation had improved the suction but the PET still failed. At 180Pa, sludge was lifted up the pipe to close to the pump inlet but the sludge did not move from there. At 113 Pa the sludge level was again close to the pump inlet but did not enter the pump. The head achieved at this strength was approximately 800mm. As such the pump was tested using water. This test was approximately done but showed that the pump was capable of high flow rates when pumping water. The fact that the simulant did flow into the pump suggests pump was head limited rather than shear strength limited as the simulant did flow. As such the results acquired here may be conservative as the density of the simulant is greater than that of pure faecal sludge.[27]

3.3.3 Limitations of the work

Real pit latrine sludge is neither uniform nor debris free. Debris in pits contains domestic refuse such as nappies, rags, bottles and newsprint[13] and this affects PET performance. Further work is needed to investigate the effect that debris has on pump performance relative to the baseline data presented here. In this study each PET was tested for 1 minute at a time. Note that in the field the devices will be used for much longer and so fatigue may well play a part in the achievable flow rate. To counter that it is likely that pit emptiers will be physically stronger than this experimenter and so the achieved flow rates may be faster. As mentioned earlier, based on the rather limited data available, it seems that this effect is more pronounced with the Gulper 2 than with the Gulper 1.

3.4 Suggested improvements to the method

Significant time savings could be made if the method and rig were changed slightly. This would allow more to be achieved in the same time.

1. Access to a penetrometer to measure undrained shear strength would negate the need to slump test the simulant. The slump testing process is lengthy, especially with stronger mixtures and is prone to fail with the high stickiness simulant which best replicates faecal sludge.

2. Thoroughly mixing the simulant was difficult and took a long time. This problem might be overcome by finding a more effective mixing technology than the small cement mixer and plaster stirrer combination.

3. Significant time could be saved if a smaller batch of simulant could be used. A tank with a smaller plan area would achieve this but a minimum diameter of 600mm should be specified to ensure that the walls do not affect the flow of simulant into the PETs.

4. A top tank is not necessary. It is adequate to collect sludge in buckets although a larger barrel might be better when testing the more effective PETs on low undrained shear strength sludge.

5. It would save time and technician work if the tank could be accessed easily for dilution and mixing rather than needing a forklift truck to take the top off. This should be easy to achieve if a top tank is not used. The platform above the tank would simply need to be hinged or easily removable.

6. In order to test both the Gulper 1 and the Gulper 2 a variable height platform is required. With the set up as it is, the inlet of the Gulper 1 was only just covered with simulant at the end of a run on low strength simulant suggesting that it could not be used from a higher platform. On the other hand the Gulper 2 was being operated with a clearance gap of around 5 cm when fully extended which may have affected its performance. The other option would be to greatly increase the depth of sludge in the pit but this would add volume and, as noted in the previous point, that is not desirable.

7. Finding a hose which fitted the Gulper 2 outlet properly and was robust would prevent the need to frequently replace that hose.
8. If available, the use of transparent hose with the Oxfam Diaphragm pump rather than the black one supplied would allow the experimenter to understand the performance of the pump better.

4 Practical implications of pit composition and PET performance

Pit emptying practice varies from city to city. In some areas, such as the eThekwini municipality of Durban, [43] the municipality has taken it upon itself to provide pit emptying services. However, on the whole there has been a move away from centralised provision. [6] In many places there is a large demand, little provision and a large opportunity for local entrepreneurs. [19, 44, 45] The size of the market for pit emptying in Kampala is estimated to be US$ 6.1 million per year. [45] Despite the scale of the opportunity, attempts at sanitation enterprises have faced many challenges. [19] One difficulty with sanitation enterprises as a whole is the diffuse nature of the benefit of improved sanitation. While the economic benefit of improving sanitation is substantial, it is also distributed and not necessarily felt by the owner of the toilet [6] which affects resident's willingness to pay (WTP) for pit emptying services. This is especially true where houses are owned by a landlord who does not live in the house. [15] Pit emptying also tends to be seasonal work (at least in locations with a rainy season) as the rain fills up the pits, making them more liable to flood. [12] The rain also makes the pits easier to empty. As such emptiers are forced to seek other jobs in the dry season. [12] The challenges facing pit emptying enterprises mean that it is important to maximise the performance and profitability of the service to ensure that it survives. The previous section focused on the performance of the PETs. While good PET performance is essential, it is not sufficient. It is also necessary for pit emptying entrepreneurs to be able to make a profit out of running pit emptying businesses. In this section, the effect that using different PETs might have on the profitability of a pit emptying business is explored. Firstly a cost model for the price to an entrepreneur of emptying one pit is presented. The payment model used in Kampala is then presented and the profitability of using each of the tested PETs to empty pits in Kampala is investigated. The effect of the shear strength of the pit to be emptied on profitability is explored further. Two other potential payment models are presented and the importance of understanding local pit emptying practice discussed.

In what follows the Oxfam Diaphragm pump is assumed to have a limiting strength of 50Pa, based on the observation that the pump was close to working when tested at 100Pa. The flow rate used in this range is half of that achieved with water, namely $2.9 * 10^{-4} m^3 s^{-1}$. This is a very approximate assumption given the none linear behaviour of the other flow rate data but is the best that can be done before further work is carried out

4.1 Cost model for pit emptying

An ideal emptying transaction will start with an interaction with the customer to explain the process, determine the accessibility of the facility and establish a fee before the equipment is set up, the pit emptied, the equipment taken down, the facility secured and cleaned up and the faecal sludge disposed of safely.[33] The cost of each of these stages depends to varying degrees on the PET which is being used. The simplified cost model used here has been developed to reflect the practice of the Sanitation Solutions Group (SSG) pit emptying entrepreneurs in Kampala.[42]

The cost model presented in equations 4 to 8 quantifies the cost to the entrepreneur of emptying a single pit. The model makes the following assumptions:

- The vehicle used for conveyance and to transport the PET and operators is hired rather than bought due to the high capital cost of buying a pick up. While this tends to be the case in Kampala, some operators do own their own vehicle (*G.Drummond, 2015 pers. comm.*)
- The disposal site charges on a per unit volume basis rather than on a fixed charge basis.

- There are 21 working days in a month.
- The loan used to purchase the PET is paid back over the whole lifetime of the PET.
- The pit emptiers are driving the vehicle and so the model does not include wages for a driver.
- Each team of pit emptiers has its own vehicle for both transport and conveyance. Note that this does not necessarily need to be the case in practice but it is assumed here because this is what happens in Kampala (*G.Drummond, 2015 pers. comm.*) Conveyance could be decoupled from emptying and the pick up could service multiple teams per day or just collect the barrels at the end of the day.
- Only one pit is emptied per day. This is typical in Kampala (*pers. comm., G.Drummond, 2015*).
- All pits are deeper than the PETs can reach into them and so emptying depth is limited by the PETs in each case. This assumption is rather approximate as pit depths vary widely (*G.Drummond, pers. comm.*) but the assumption is made because no data on the actual depth distribution of the pits is available. The assumption is likely to be good for the Gulper 1 and the Oxfam Diaphragm pump but less good for the Gulper 2 due to its long reach into the pit.

The following input parameters are used for the cost model:

Pump specific parameters
S, Set up and take down time (hours)
Q, Flow rate (m^3/s) achieved by the PET at the strength of the sludge in the pit (experimentally acquired)
E_{reach}, The reach of the PET into the pit. In the case of the Gulper 1 and Gulper 2 this is limited by geometry. In the case of the Oxfam Diaphragm pump this is limited by the static head which the pump can achieve.
$E_{strength}$, Proportion of the sludge in the pit which each PET can empty due to

the strength of the sludge
n, number of workers in operating team
C_c, Capital Cost of PET ($)
Lt, Typical Lifetime of a PET
M_p, Maintenance cost per year of PET ($/year)

Location specific parameters
T, Average transport time per pit (hours)
T_D, time it takes to dispose of the sludge at the treatment plant (hours)
N, Negotiating time (hours)
P_A, Typical plan area (m^2) - *note that pit dimensions vary greatly.*
W, Wage for manual worker ($/hour)
I, Interest rate on micro credit loan (%)
F, Conveyance vehicle fuel/km (litres/km)
C_f, Cost of fuel per litre ($/litre)
V, Vehicle rental per day ($)
D, Charge for dumping of a specified volume ($\$/m^3$)
H, Hours in a working day
d, Average distance that the conveyance vehicle must travel per pit (km/pit).
n_p, Number of pits emptied per day

E_{reach} for the Gulper 1 and Gulper 2 is determined by the geometry of the pumps and is equal to 1.5m and 3m [20] respectively. The static head which the Oxfam pump can achieve is approximated as follows. During experimental work a head of approximately 0.8m of simulant was achieved. The simulant had a density of 1450 kg/m^3. The average density of faecal sludge in Kampala is reported to be 1001 kg/m^3 [25] and so, if pumping faecal sludge, the pump might achieve 1.15m of head. This value is used throughout the analysis for E_{reach} for the Oxfam Diaphragm pump. This assumption highlights the need for further work to more accurately measure the static head which the Oxfam Diaphragm pump can achieve. The values for the complete set of parameters used in the model are presented in Appendix A, apart from where the variables were found experimentally and presented in section 3. The experimentally derived flow rate data was converted from mass flow rates to volumetric flow rates using the densities measured during experimental work. In Equations 4 to 8, the variables which are dependent on the PET used are shown in blue. Where variables are not self explanatory they are labelled. The numbers in the equations are simply conversions between time units.

$$\text{Cost/pit} = \text{Emptying cost/pit} + \text{Conveyance cost/pit} + \text{Disposal cost/pit} + \text{'Hidden cost'/pit} \tag{4}$$

$$\text{Empting cost/pit} = \text{Length of emptying process} * \text{Cost per hour} \tag{5}$$

$$= (T + S + N + T_D) + \overbrace{\frac{P_v.E_{reach}.E_{strength} * 60^2}{Q}}^{\text{time to empty pit}}) * (W.n)$$

$$\text{Cost of conveyance/pit} = \text{Cost of vehicle hire/pit} + \text{Cost of fuel/pit} \tag{6}$$

$$= (\frac{V}{n_p}) + (F.d.C_f) \tag{7}$$

$$\text{Disposal cost/pit} = \text{Disposal cost/unit volume} * \text{Volume of sludge removed} \tag{8}$$

$$= D * P_v.E_{reach}.E_{strength}$$

$$\text{Hidden cost/pit} = \frac{1}{n_p}\Big(\overbrace{\frac{C_c}{L_t * 21 * 12}}^{\text{depreciation}} + \overbrace{\frac{C_c * I}{21 * 12}}^{\text{interest}} + \overbrace{\frac{M_p}{21 * 12}}^{\text{maintenance}}\Big) \tag{9}$$

4.2 Profitability of using different PETs in Kampala

4.2.1 Volume profile of pits in Kampala

In order to analyse what proportion of the sludge in a pit each PET can remove, it is necessary to know how much sludge of a given shear strength there is in the pit. The Kampala study which was presented in Figure 1 is the only known study which can be used to create a volumetric-weighted strength profile. The shear strength and displacement values were obtained from the author of that paper and analysed to calculate the proportion of sludge in certain ranges in each pit. The sludge shear strength data was divided into bins according to the different strengths at which the PETs were assessed. The penetrometer used in the pit profiling study was only capable of measuring up to 2000 Pa [25] and so this analysis does not account for any sludge stronger than 2000Pa. The penetrometer is also only capable of reaching up to 2.5m [25] into the pit so where the pit is deeper than that then a proportion of the pit contents are neglected. Since only the Gulper 2 is longer than 2.5m , the effect of this is a likely underestimation of the Gulper 2 efficacy. The shear strength ranges used here are shown in Figure 13.

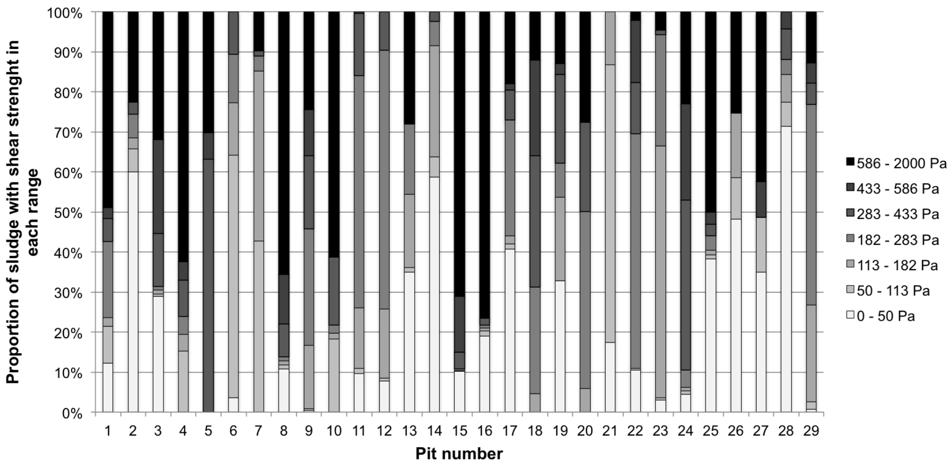

Figure 13: The volumetric strength profile of 29 pits in Kampala - *6 shear strength ranges were defined based on the shear strengths at which flow rates were measured during experimental work and the proportion of the sludge in each pit which fell into each range is shown here*

The analysis was done such that future users could easily change the shear strength ranges used. It was assumed that the plan area of the pit did not vary with depth and that the shear strength varied in the depth direction only. The data for one of the pits was not received and the author suggested that data for 5 of the pits be discarded due to to different experimental settings. As such only 29 of the 35 pits tested were analysed. The results, presented in Figure 13, show that the pits contain highly variable proportions of sludge in each range, suggesting that the PETs may perform very differently on different pits.

4.2.2 The effect of choice of PET on profitability in Kampala

In Kampala, emptiers charge on the basis of the volume of sludge removed from a pit. This charging model is shown in Equation 10 where C_{PET} is the charge per volume of sludge emptied ($\$/m^3$) and the other symbols are as defined previously. This model will henceforth be referred to as 'paid per volume'.

$$\text{Price} = P_A.E_{reach}.E_{strength}.C_{PET} \tag{10}$$

The cost model and the above payment model were used to calculate the profit earned by a pit emptying entrepreneur from emptying each of the 29 pits. The Sanitation Solutions Group entrepreneurs in Kampala charge \$10 per 200 litre barrel of sludge emptied therefore $C_{PET} = \$/m^3$. As the volumetric strength profile is known in this case, the flow rate Q in equation 4 is replaced by a weighted average of the flow rate $\overline{Q}$ which accounts for the variation in flow rate due to the variation in strength. $\overline{Q}$ is defined in Equation 11 in which the i represent the 6 shear strength ranges,the Q_i represent the average flow rate in each shear strength range and the P_i represent the proportion of each shear strength range in the pit. The pit contents tend to be mixed up to some extent before emptying as solid waste is 'hooked' out of the pits. As such the strength profile of the whole pit is used even in cases where that profile extends to depths which are out of reach of the PET.

$$\overline{Q} = \sum_{i=1}^{i=6} Q_i.P_i \tag{11}$$

The proportion of the sludge in a pit which the PET can empty based on its strength is defined in equation 12 in which $\tau_{max,pet}$ is the maximum shear strength which the PET can empty.

$$E_{strength} = \sum_{\tau=0}^{\tau_{max,pet}} P_i \tag{12}$$

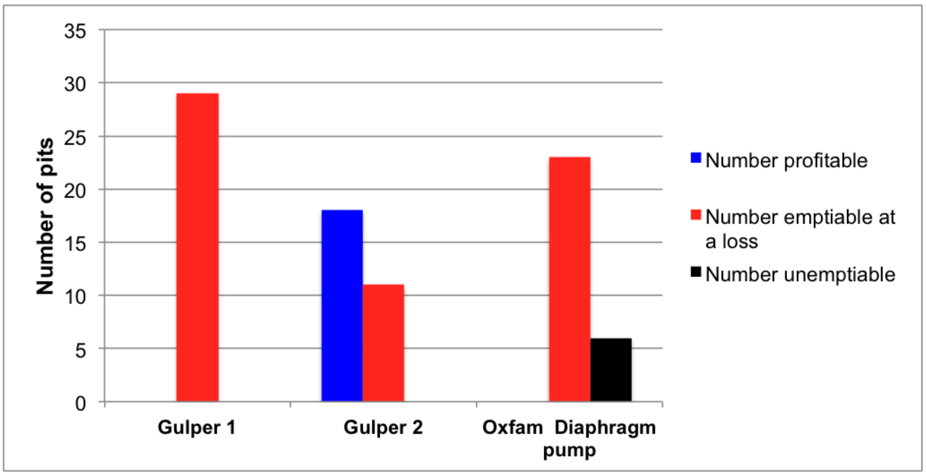

Figure 14: Comparison of profit using different PETs in Kampala

Figure 14 shows the number of pits which proved profitable for each pump using the cost model presented earlier. The average profit over the 29 pits for the Gulper 1, Gulper 2 and Oxfam Diaphragm pump was US$ -30, US$ 1.7 and US$ -86 respectively. The cost model used here therefore predicted that, if the Gulper 1 or Oxfam Diaphragm pump were to be used on any of these pits the operator would sustain large losses, and that the use of the Gulper 2 will only yield a very modest profit. This finding may be a result of inaccuracy in the model data or it may be that anecdotal reporting of pit emptying entrepreneurs making a profit using the Gulper 1 in Kampala neglects 'hidden' costs such as depreciation and interest. More work is required to review the results and input data in collaboration with SSG. If we assume an underestimation of profitability by a constant factor we can still draw some interesting conclusions about what determines the profitability of a PET.

The Gulper 2 outperforms the Gulper 1 because it can empty a larger volume of sludge ($2m^3$ as opposed to 0.9 m^3). This is due in part to the ability of the Gulper 2 to empty stronger sludge but predominantly because of the increased reach of the Gulper 2 into the pit. The Gulper 1 also outperforms the Oxfam Diaphragm pump due to its ability to empty a larger volume of sludge than the Oxfam pump ($0.9m^3$ as opposed to $0.20m^3$). In this case the difference is due to the the ability of the Gulper 1 to empty thicker sludge than the Oxfam Diaphragm pump can.

While these results suggest that designing and using PETs which can empty large volumes of sludge will maximize profit, it is worth considering the willingness to pay (WTP) of the latrine owners. In Kampala currently entrepreneurs typically remove 1.2 m^3 of sludge on average [42] and it may be that latrine owners have insufficient cash flow to pay for more than that amount to be emptied. In the case of the Oxfam Diaphragm pump the average value of $0.20m^3$ of sludge removed from each pit may be less then an owner would be prepared to pay for, given the time invested in organising the service. The results also suggest that, even if the model input parameters change significantly, it would be hard to make a profit with the Oxfam pump because its inability to empty thicker sludges means in can only remove small volumes of sludge from most pits.

A break down of the cost of emptying reveals that two of the costs are far larger than the others. The combined cost of vehicle hire and fuel amounts to US$ 36 which amounts to between a third and a half of the overall cost. The wages of workers, dependent on the time that the process takes is the other important factor. When the achieved flow rates are low the emptying of the pit takes a long time, pushing up the cost of emptying. While the Gulper 1 achieves a higher flow rate than the Gulper 2 and so empties pits faster, the cost saving is overruled by the increased price the Gulper 2 operator can charge for emptying a much bigger volume of sludge. The depreciation, maintenance and loan repayment costs are larger for the Oxfam pump than the Gulpers due to its higher capital cost and assumed (see Appendix B) greater need for maintenance.

4.3 Comparison of profitability between countries

In this section the cost model is applied to idealised, single strength pits in Kampala and Durban in order to investigate how the cost balance might vary in different countries and to further investigate the effect of the strength of the sludge in the pit on the profitability of emptying it. The data used for the Durban analysis is from the eThekwini municipality and may be above market rates as the municipality pays these costs. The model input data for Durban is presented in Appendix A. The main difference between the two data sets is that the cost of disposal in

Durban is an order of magnitude higher than that in Kampala.

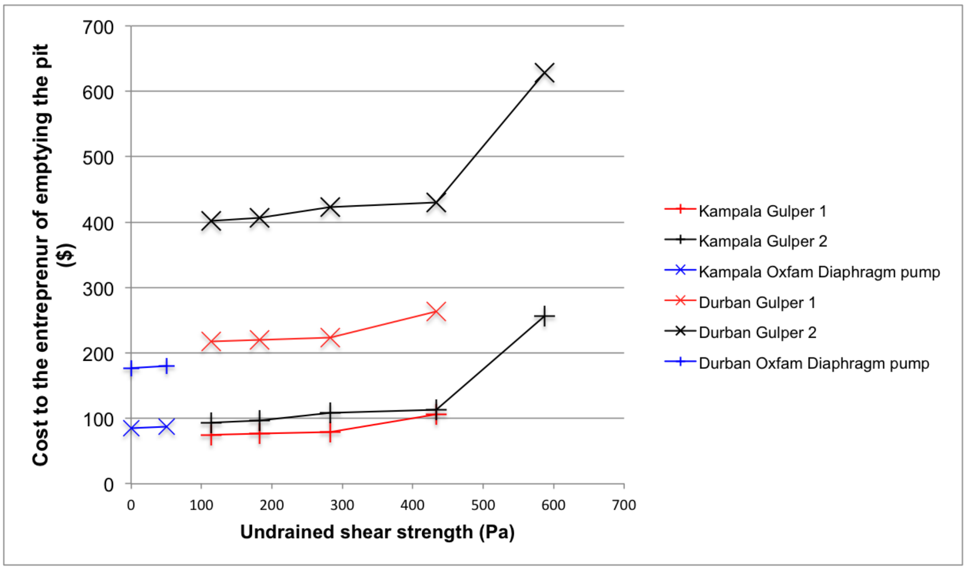

Figure 15: The cost to the entrepreneur of emptying one pit of a single, uniform strength using each PET in Kampala, Uganda and in Durban, South Africa

The profit that a pit emptying entrepreneur might make emptying a single pit of uniform strength is shown in Figure 16. The cost of emptying pit in Durban is higher due to the higher fee for sludge disposal but the larger charge per unit volume emptied means that larger profits can be made in Durban than in Kampala. The same patterns are present with the fixed cost of the vehicle dominating apart from at very high shear strength where the time taken to empty the pit becomes very long and dominates the cost. The larger income from the Gulper 2 outweighs the higher price of emptying with the Gulper 2 meaning that the Gulper 2 makes a larger profit than the Gulper 1. The profit values here are larger than those found in the previous section because the PETs can empty all of the idealised 'single strength' sludge in each pit. This is not realistic but the analysis allows us to examine the effect of sludge shear strength on the profitability of emptying. As shown in Figure 15, the G2 is capable of emptying sludge that would defeat the G1, but the very low flow rate achieved at this shear strength means that it would cost the entrepreneur 2 1/2 times as much to empty it and so unless there is a way in which they can charge more for emptying these 'difficult' pits, the

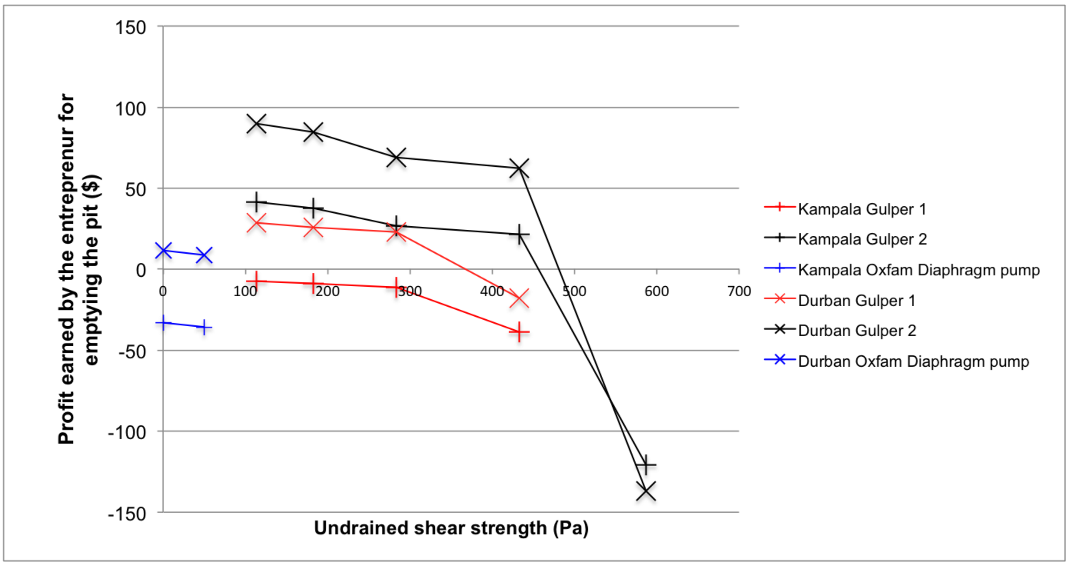

Figure 16: Profit from pit emptying using different PETs in Kampala and Durban

entrepreneur is likely to just use the Gulper 2 to make bigger profits emptying pits with weaker sludges. In the long term this strategy will result in pits filling up with unpumpable sludge and so this effect of the paid to empty cost model is undesirable.

4.4 Other payment models

In this section two additional payment models are proposed: paid to completely empty the pit and paid according to the value of the sludge itself under a resource recovery scheme. This section is intended to explore which business models might complement each PET. In these models the following symbols are used in addition to those presented earlier:

C_{man}, Charge per volume of sludge emptied manually ($\$/m^3$)
R, Price paid by resource recovery operator per unit mass of dry solids ($/kg)
F, Fee paid by the client to empty pit completely ($)
WC, Water content of sludge by wet mass (%)
ρ, Density of the sludge (kg/m^3)

4.4.1 Paid to empty

In some cases pit owners prefer to have all of the sludge removed from the pit.[19] To reflect this demand the business model assumes that the service the owner buys is to have the pit fully emptied. If the device used cannot fully empty the pit then they must pay a manual emptier to finish the job for them. As such there is a real cost to the pit emptier if their device cannot empty the pit fully. This model is anecdotally reported in West Bengal and in Bihar (*J.Radford, 2015, pers. comm.*).

$$\text{Price} = F - (P_A(1 - E_{reach}E_{strength}).C_{man}) \tag{13}$$

4.4.2 Resource recovery

Faecal sludge has a intrinsic potential worth. It can be used to make fertilizer,[?] using processes such as co-composting with other organic waste,[46] or dried and burned to generate power.[46] Fertilizer is expensive in the developing world[?] and both power shortage[?] and significant demand for sustainable biofuels[46] motivate interest in using FS for power generation. We now assume that the emptier gets paid for the sludge by a resource recovery operator making fertilizer. We assume that there is a set price per unit dried mass for faecal sludge because resource recovery processes such as co-composting requires low water content sludge[46] and so thicker sludge is more valuable. The cost of disposal ceases to be important in this case and indeed becomes negative due to the value realised from marked demand for the by-products of faecal sludge. Resource recovery from latrine sludge is currently practised in Nairobi, Kenya[?] although in that case the same provider manages the pit emptying and the resource recovery process.

$$\text{Additional income due to resource recovery} = R.(1 - WC).\frac{E_{reach}E_{strength}.P_A}{\rho} \tag{14}$$

4.4.3 Comparison of business models

When analysed with dummy input data for R, C_{man}, F and W_c it is clear that the alternative models are more favourable for the Gulper 2 than for the other two PETs. This is because the profit in both of the alternative models relies heavily on how much sludge can be removed from the pit. This analysis is important because it shows how reliant performance metrics are on the local specifics of the cost model used. The most profitable pump in one area may not be the most profitable pump in another. As such there is a need to assemble data on pit emptying business models in more cities as only local data is applicable to a local entrepreneur choosing a technology to invest in.

5 Conclusions

Objective: To characterise the performance of 3 PETs in terms of the range of shear strengths they can pump and the flow rates they achieve within that envelope of shear strengths.

The maximum pumpable shear strength for the Gulper 2, Gulper 1 and Oxfam Diaphragm pump was found to be 590 Pa, 430Pa and approximately 50 Pa respectively. While the Gulper 2 had the highest pumpable shear strength the Gulper 1 was found to achieve higher flow rates than the Gulper 2 at and below shear strengths of 280Pa. The data obtained for the Gulper 1 agreed very well with a previous study while the data obtained for the Gulper 2 showed significantly lower flow rates than achieved in a previous study. This may have been due to differences in the physical strength of the operators or due to a design difference between the two pumps tested. The Oxfam Diaphragm pump achieved a high flow rate when tested on water but failed to pump 110Pa simulant, the thinnest tested. The Oxfam Diaphragm pump did successfully move simulant at 180Pa and below but the head achieved was less than that required to lift the simulant out of the tank.

Objective: To use those results and existing data on pit composition to analyse the *effect of differences in PET performance on the success of various pit emptying business models.*

A cost model was developed to estimate the cost to an entrepreneur of emptying a pit and 3 different payment models by which an entrepreneur might charge a client for pit emptying have been proposed. The cost model was used to estimate the profitability of emptying 29 pits in Kampala using each PET. It was found that on average, when emptying only one pit per day, entrepreneurs using the Gulper 2 would make a very small profit emptying these pits. Entrepreneurs using the Gulper 1 could empty at least some sludge from each pit but would make a loss in all cases. Entrepreneurs using the Oxfam Diaphragm pump would be unable to empty sludge from 6 of the pits and would make a loss emptying sludge from all of the pits which it could empty sludge from. These profits are smaller than those reported in Kampala suggesting that either the model is inaccurate or that hidden costs are not being accounted for in Kampala. This uncertainty reveals the need to understand the economics of pit emptying better before large investment into PETs is made such that development can focus on those aspects of performacen that most affect profitability. The superior profitability of the Gulper 2 is due to its ability to empty a larger volume of sludge and so charge a higher price, thus allowing it to cover the high fixed cost of vehicle hire and fuel. The Gulper 2 performs well independent of the cost model and its good performance highlights the importance of designing PETs which can empty to greater depths. Examination of a cost breakdown suggested that use of the Gulper 1 could be profitable if the controlling parameters changed whereas the Oxfam Diaphragm pump was found to empty such a small volume of sludge from most pits that it seems unlikely that a pit owner would contract the service. As such the Oxfam diaphragm pump was found to be unfit for the purpose of pit emptying due to its poor performance financially and physically. The high quality field data on shear strenghts in Kampala allowed these conclusions to be made. This highlights the reliance of rigorous lab testing on high quality field data. While the Gulper 2 is able to pump thicker sludge than the Gulper 1 it was found that the cost to the entrepreneur of pumping that thick sludge would be prohibitively high unless a cost incentive for emptying thick sludge existed. Two alternative payment models were proposed which incentive the use of PETs which can empty large volumes from the pit and hence the use of PETs which can pump thicker sludge.

6 Further work

The effect of stickiness on the Abrams slump test needs to be investigated further. Previous work [29] on simulants with 20-40 % kaolin content suggested that stickiness did not affect the slump test. 60 % kaolin content simulant was used in this study and stickiness caused significant difficulty suggesting that further work at higher kaolin contents is required. The failure of the slump cone to release meant that the slump cone had to be oiled. The effect of oiling the cone on the accuracy of the slump test as a measure of shear strength needs to be investigated.

These tests were carried out at almost full scale and it is possible that, at this scale, the simulant may have begun to settle out due to self weight creating a strength gradient in the pit. If this is the case then PETs are pumping thicker sludge than has been reported as their inlets are low down in the pit. Use of an in-situ tool such as the manual cone penetrometer would avoid the need to use the approximate and slow slump test and would also allow the user to see if strength gradients are present in the tank.

PETs were tested on pure simulant here in order to assess their baseline performance. Real pits contain debris and so the performance of the PETs when there is debris in the simulant needs to be investigated. This work will improve understanding of the extent to which debris affects PET performance as well as showing differences between the ability of individual PET's to cope with debris.

Only semi-mechanized PETs were tested here. Futher testing of other semi-mechanised PETs and also of mechanised PETs is neccesary to give a more complete picture of the performance of currently available technologies.

Further testing of the Oxfam Diaphragm pump is required at lower shear strengths and densities. The static head which the Oxfam Diaphragm pump can achieve needs to be investigated to allow more accurate calculation of how deep into a pit the Oxfam Diaphragm pump can be expected to empty sludge from.

Further investigation of the properties of pit latrine sludge around the world is still required. This information is important both to assess the limitations of current PETs when it comes to emptying real pits and in order to assess possible business models for pit empting in different areas. There are currently two promising tools to help with collecting undrained shear strength data. The first is the portable penetrometer which is already successfully profiling pits.[25] The second is a manual cone penetrometer which uses a known impact from dropping a weight from a height and measures the distance that a cone moves in the sludge.[15] This device needs calibrating in order to convert these measurements to undrained shear strengths so that data collected using this device can be compared with existing data. Tests being done by the University of Botswana are showing mixed results for this device currently[47] but the simplicity of the device means it merits further investigation.

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A Input data for Section 4

The values of the parameters presented in 4.1 are given in Tables 4 and 5.

	Gulper 1	**Gulper 2**	**Oxfam Diaphragm pump**
Set up and take down time, S (hours)	1.5 (G.Drummond, *pers. comm.*)	2 (G.Drummond, *pers. comm.*)	1.5*
The reach of the PET into the pit, E_{reach} *(m)*	1.5 [20]	3 [20]	1.15**
Number of workers, n	4 [42]	4 [42]	3***
Capital Cost of PET, C_c *(US$)*	150 [42]	215 (G.Drummond, *pers. comm.*)	415 [21]
Typical lifetime of PET, L_t *(years)*	3 (G.Drummond, *pers. comm.*)	3 (G.Drummond, *pers. comm.*)	3****
Maintenance cost per year of PET, M_p*, ($/year)*	10 (G.Drummond, *pers. comm.*)	10 (G.Drummond, *pers. comm.*)	20*****

Table 4: Input data for the pump specific parameters in the cost model. *The assumptions made to select those data values marked with asterix are explained below*

* The Oxfam pump is quick to assemble and simple to set up and so the same set up time is used as for the Gulper 1, which is also simple to set up.
** The assumptions and process used to derive this figure for the static head of the Oxfam Diaphragm pump are presented in section 4.2.2.

	Kampala	**Durban**
Average transport time per pit, T (hours)	4 (G.Drummond, *pers. comm.*)	0.64 [43]
Time it takes to dispose of the sludge at the treatment plant, T_D (hours)	2.5(G.Drummond,*pers.comm.*)	2.5*
N, Negotiating time (hours)	0.5 (G.Drummond, *pers. comm.*)	0 [43]
Typical plan area, P_A (m^2)	0.9 (G.Drummond, *pers. comm.*)	
Wage for manual worker, W (\$/hour)	0.72 [42]	1.32 [43]
Interest rate on micro credit loan I,(%)	20 (G.Drummond, *pers. comm.*)	9 [43]
Conveyance vehicle fuel/km, F (litres/km)		0.095 [43]
Cost of fuel per litre (\$/litre), C_f		0.095 [43]
Average distance that the conveyance vehicle must travel per pit, d (km/pit)		27 [43]
Overall fuel cost per day, $F.C_f.d$ (\$/day)	16 (G.Drummond, *pers. comm.*)	
Vehicle rental per day, V (\$)	30 (G.Drummond, *pers. comm.*)	42 [43]
Charge for dumping of a specified volume, D (\$/m^3)	1.6 [42]	122 [43]
Hours in a working day,H	11 (G.Drummond, *pers. comm.*)	9 [43]
Number of pits typically emptied per da,n_p	1 (G.Drummond, pers. comm.)	2 [43]

Table 5: Input data for the country specific parameters in the cost model

*** The Oxfam pump is not as physically fatiguing to use and so it is likely that a team could operate with one less member.
**** While the diaphragm may need replacing during the lifetime of the pump it seems likely that the metal casing and lever of the pump will last as well as the Gulper 1 and Gulper 2 do.
***** The Oxfam pump contains a rubber diaphragm and these are reported to have high failure rates [33]

B The mechanical advantage of a lever arm for the Gulper 2

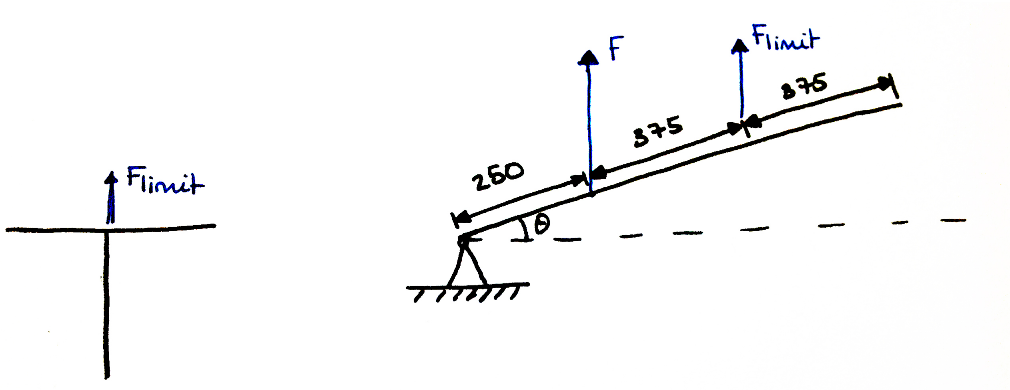

Figure 17: Schematic of the direct action plunger (left) and the lever arm (right) - F_{limit} *is the maximum upwards force that an operator can exert*

$$\text{Taking moments about A: } F_{limit}(250+375)cos\theta = F(250cos\theta)$$
$$F = 2.5F_{limit} \tag{15}$$

C Risk Assessment Retrospective

The main hazards identified in the initial risk assessment were manual handling of heavy batches of test material, the risk of trips and falls around the work area and the inhalation of clay powder. No accidents occurred during the investigation. To avoid musculo-skeletal injury from carrying, a trolley was used for moving heavy batches. Scaffolding was erected around the tank to protect the operator from falls. A personal respirator was used to prevent inhalation of clay powder when working with dry kaolin.

During the course of the investigation two other hazards were identified. The first was the risk of musculo-skeletal injury from the physical effort of operating the PETs themselves. This risk was minimised by only pumping with each device for a minute at a time. The second was the use of a cement mixer. Use of safe lab procedures for using the cement mixer minimised the risk of accidents in this case.