# PHYSICAL CHARACTERISATION OF PIT-LATRINE SLUDGE

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## ABSTRACT

*It is estimated that half of the world's urban population will live in informal settlements or "slums" by 2030, totalling some 3 billion people. The provision of affordable urban sanitation presents a unique set of challenges as the lack of space and resources to construct new latrines makes it necessary to empty existing pits, which is typically done manually with significant health risks for the emptiers. Various mechanised technologies have therefore been developed to facilitate pit emptying, and these are currently either tested on faecal sludge, with associated health and safety risks, or on an 'ad-hoc' simulant that approximately replicates the behaviour of faecal sludge, in the opinion of the tester. In both cases there is very limited information available on the physical properties of the sludge, which can range from a watery consistency in some pour flush latrines to the strong soil found in many alternating ventilated improved pit latrines. This makes it difficult to evaluate the effect of changes to a design, or to compare the performance of different technologies produced by different firms in different countries.*

*This study developed the portable penetrometer, a man-portable device to physically characterise pit-latrine sludge, which measures the in-situ shear strength of the sludge in the pit. The current machine produces continuous profiles of shear strength with depth and is capable of testing to approximately 2.5m below the slab. The portable penetrometer was manufactured and tested in the UK, before being used to profile approximately 30 pits in Kampala, Uganda. That data is compared to the literature on the physical properties of faecal sludge, and is found to significantly extend the measured strength range with a maximum value approximately four times higher than previously reported. The effect of physical remoulding is identified through comparison of data from undisturbed and remoulded strength tests and highlights the potential to increase the 'pumpability' of faecal sludge through in-pit fluidisation.*

*The implications for the development of pit emptying technologies and synthetic sludge simulants are discussed, and potential further work is identified. These include studies on factors affecting pit function and fill-up rates as well as scientific tests on the effect of modifications to latrines. In both cases any change in the physical properties of the faecal sludge can be identified through repeated profiling using the portable penetrometer. It is hoped that the portable penetrometer can contribute to an improved understanding of the physical properties of faecal sludge and the factors affecting pit function, supporting the development of improved faecal sludge management services.*

Keywords: DENSITY, FLUIDISATION, LATRINE SLUDGE, SHEAR STRENGTH

## ABBREVIATIONS

BCG – Boston Consulting Group
JMP – Joint Monitoring Programme
UNDESA – United Nations Department of Economic and Social Affairs
UN-HABITAT – United Nations Human Settlements Programme
UNICEF – United Nations Children's Fund
VIP – Ventilated improved pit latrine
WHO – World Health Organisation

## INTRODUCTION

Providing adequate sanitation to a rapidly growing urban population is one of the greatest challenges facing our generation. An estimated 2.5 billion people lack access to improved sanitation (WHO/UNICEF JMP 2012), which contributes to more than 1.5 million child deaths per year from diarrhoeal disease (WHO 2009). Urban informal settlements provide a very different set of challenges to those encountered in rural areas as many houses do not have space for individual toilets and those that do are typically unable to dig a new pit when their latrine is full. An estimated 1.2 billion urban dwellers have limited access to faecal sludge management services (BCG 2012). This problem is set to get worse with urban populations in developing countries forecast to almost double to over five billion by 2050 (UNDESA 2012). Much of this growth will be in informal settlements or slums which already house over 860 million people (UN-HABITAT 2012).

Regular pit emptying is a necessary service if latrines are to provide a sustainable service in high density urban settlements. The *vyura* (frogmen) of Dar Es Salaam earn a living from manually emptying pits – spending up to six hours at a time waist deep in faecal sludge without protective clothing. In addition to the wide range of diseases they may contract, pit emptiers are also at risk from the collapse of unlined pits and are often stigmatised by the communities they serve, forcing them to work after dark and to dump the extracted sludge illicitly in the nearest available sewer or stream (Eales 2005).

Significant work has been done to develop affordable mechanised pit emptying technologies as alternatives to large vacuum tankers for high-density urban settlements. However, there is very limited information available on the physical properties of pit-latrine sludge on which to base design decisions. Furthermore, latrine sludge is observed to vary widely from the 'watery' contents of some pour-flush vaults to the strong soil found in alternating VIPs. The absence of a method to physically characterise latrine sludge has prevented the objective and quantitative comparison of the performance of different technologies and comparisons are instead made on the basis of anecdotal evidence and personal preference.

This paper presents a methodology for the physical characterisation of pit-latrine sludge according to its density and shear strength. A device has been developed for testing latrine sludge which produces a continuous shear strength profile with depth, and the results of an initial study testing 30 pits in Kampala, Uganda are presented.

## METHODS

<u>Shear strength</u>

Undrained shear strength was selected as the most appropriate measure of resistance to flow, in contrast to the only known study in the literature which reported the viscosity of pit-latrine sludge (Bösch & Schertenleib 1985). This is because consolidated pit-latrine sludge behaves more like a soil than a fluid and does not readily flow, making shear strength a more intuitive measure than viscosity. The two parameters can however be readily compared as shear strength ($\tau$) is equal to the product of viscosity ($\mu$) and shear strain rate ($\gamma$):

$$\tau = \mu . \gamma \qquad [1]$$

The portable penetrometer consists of a plastic ball and extensible shaft suspended from a load cell, which records the resistance to penetration. The major advantage of this design over strain-gauging the shaft (Stewart & Randolph 1994) or using in-ball measurement (Kuo 2011) is that none of the delicate and expensive electronics pass into the latrine. This also simplifies the design of the extensible shaft as no data or power cables need to pass down the shaft to the measurement device. A small direct current motor coupled to a leadscrew drives the ball through the sludge and velocity is recorded using a draw wire potentiometer connected to a data logger. The whole system is man-portable, powered by a 12 volt lead acid battery and connected to a laptop via USB cable for data logging purposes.

Figure 1: The portable penetrometer packed for transport and in use testing a septic tank

The device is a form of full-flow penetrometer, which produces a continuous profile of undrained shear strength without the need for empirical correlations or pore pressure adjustments (Stewart & Randolph 1994). The resistance to penetration (q) is calculated as the force exerted on a ball as it is driven through the sludge, divided by the projected area of the ball (A). The shear strength of the sludge is then obtained by dividing by a correction factor, $N_b$:

$$\tau = \frac{q}{N_b} = \frac{F}{A.N_b} \qquad [2]$$

A correction factor of 10.5 has been selected, as used extensively in geotechnical studies (e.g. Chung 2005). Further work is planned to calibrate the portable penetrometer against a laboratory fall-cone to validate this selection of $N_b$. The shear strain rate at the surface of the ball can be estimated as twice the penetration rate (v) divided by the ball diameter (D) (Randolph & Anderson 2006):

$$\gamma = \frac{2.v}{D} \qquad [3]$$

The ball diameter was set at 40mm to enable two tests to be conducted through a 100mm squat hole without overlap of their zones of influence, which measure 2.5 ball diameters (Yafrate, DeJong & DeGroot 2007). The minimum acceptable ratio of ball to shaft area is 5:1 (*Ibid.*) which therefore set a maximum shaft diameter of 18mm. The system was designed to measure strengths up to a maximum of 2kPa on the basis that the strongest recorded sludge in the literature, reported by Bösch & Schertenleib (1985), had a shear strength of approximately 500Pa (Radford 2011).

The first penetration stroke through undisturbed sludge records a shear strength profile with depth for the consolidated sludge in the pit. As the ball is driven down through the sludge the shaft is extended in sections until it reaches the bottom of the pit or the maximum shaft length of 2.5m. The ball is then cycled up and down ten times to fully remould the sludge, breaking down any physical structure in the material (Chung 2005). The remoulded sludge is then thoroughly characterised by testing at five different shear rates, with three repeats at each speed, to determine the material's shear strength-strain rate relationship. Penetration tests were carried out at shear strain rates ranging from 0.3 to 13.2/s which cover both the standard geotechnical reference rate of 1/s (Chung 2005) and the 9.4/s rate used by Bösch & Schertenleib (Radford 2011).

Density

A 60ml syringe was modified for taking samples of thick sludge by drilling an 8mm diameter hole in its end. It was then attached to two 2.5m lengths of plastic pipe that fitted snugly over the syringe and plunger so that samples could be taken at depth within the pit. After shear strength profiling was complete the portable penetrometer was removed and a density sample was extracted from as deep as possible in each pit. The volume was measured using the graduations on the syringe before the sample was transferred into a container and weighed using the portable penetrometer's load cell.

Following review of the density data it was found that a number of the samples were apparently less dense than water, which was attributed to systematic errors in the density measurement methodology. The majority of the pits were therefore re-sampled during subsequent fieldwork using the same apparatus. The new samples were stored in labelled airtight containers and their bulk densities determined the following day in a laboratory environment according to standard procedures (ASTM D7263).

## RESULTS AND DISCUSSION

Shear strength

A total of 30 latrines were tested in Kampala, Uganda, in the community of Nsambya Gogognya. The study area spans a valley and as a result the latrines varied in construction from very deep unlined pits sited well above the water table, to shallow lined vaults down in the valley.

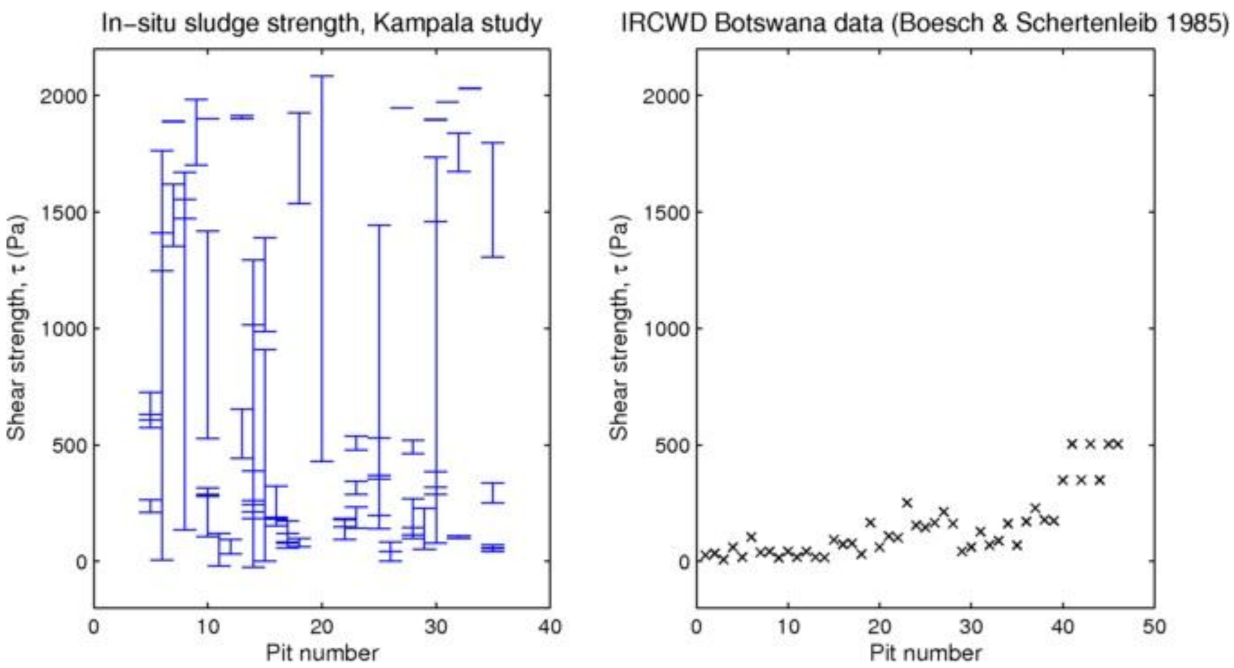


Figure 2: Comparison of shear strength data with the literature

Figure 2 compares the shear strength data from the first profile through undisturbed sludge in each pit with the data reported by Bösch & Schertenleib (1985) whose viscosities have been converted into shear strengths by Radford (2011). The large ranges in shear strength reported in the present study reflect changes in strength over the depth of the pit, whereas Bösch & Schertenleib recorded the maximum strength of sludge that could be removed using different vacuum tankers, yielding a single reading for each latrine. It is evident that the present research has increased the maximum reported strength of pit-latrine sludge by a factor of approximately four, from 500Pa to 2kPa. The actual strength of the sludge found in seven of these pits exceeds 2kPa, as indicated by the very small strength ranges recorded at the upper end of the scale where the portable penetrometer reached its maximum reading. It is noted that almost every pit (87%) in this study contained some weak sludge of comparable strength to that previously reported, however the majority of pits (60%) also contained sludge stronger than the previously reported maximum.

This variability in pit contents is further demonstrated by Figure 3 below, which shows two shear strength profiles.

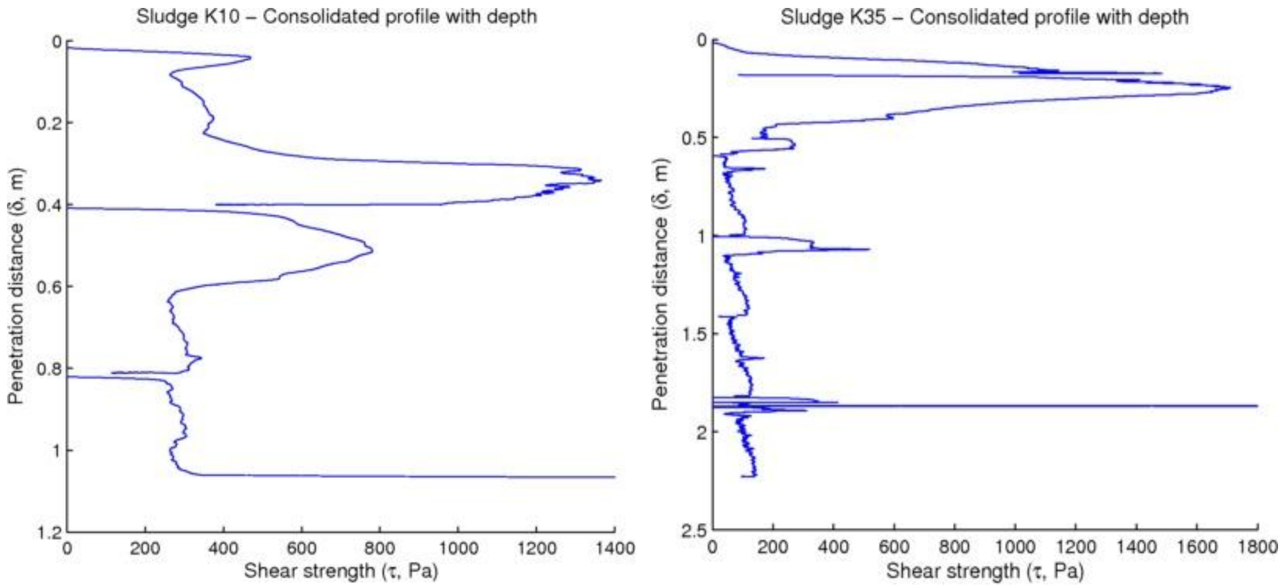


Figure 3: Shear strength profiles demonstrating sludge variability within pits

It is evident that both pits are highly variable with depth and that the sludge observed at the top of the pit is not necessarily representative of the pit contents. The presence of a high-strength crustal layer at the surface hiding weak sludge below, as shown on the right in Figure 3, was repeatedly observed, with crustal layers 5-15 times stronger than the underlying sludge. On observing the surface of the pit one may conclude that the sludge is too strong to be emptied with mechanised pit emptying technologies, whereas actually the majority of the pit volume is filled with a weak, watery sludge. The pit would also appear to be functioning well with natural degradation processes producing a thick, strong sludge, whereas in reality the opposite is true.

The effect of remoulding the sludge to break down its physical structure was also investigated and the ratio of the undisturbed and remoulded shear strengths, termed sensitivity, calculated for all pits. Sensitivities ranged from 1 to more than 10, with 3.3 considered representative of the latrines sampled during this study. This indicates that there is significant scope to improve pit emptying performance by first fluidising the pit contents, thereby reducing their strength to the lower, remoulded state and increasing the volume of material that can be emptied from the pit. Initial laboratory tests at reduced scale have successfully fluidised sludge with shear strengths of approximately 1kPa through the injection of air into the bottom of the pit (Radford, 2011).

It is noted that the remoulded strength data recorded in Kampala is comparable to the strengths reported by Bösch & Schertenleib (1985) who removed samples from the pit for laboratory testing. It is possible that the process of sampling and transporting the faecal sludge caused sufficient remoulding to produce a significant decrease in strength. In-situ testing of shear strength is therefore recommended as the most accurate method of characterising the undisturbed contents of pit latrines.

<u>Density</u>

Density data for samples collected from 18 of the pits are presented in Figure 4 below. The samples from Kampala have a mean density of 1001kg/m$^3$ which is significantly lower (p=0.01, Cohen's d = 1.77) than the 1423kg/m$^3$ reported by Bösch & Schertenleib (1985), however it is comparable to data recently reported for septic tank “wet bottom sludge” with a density of 1092-1159kg/m$^3$ (AIT 2012).

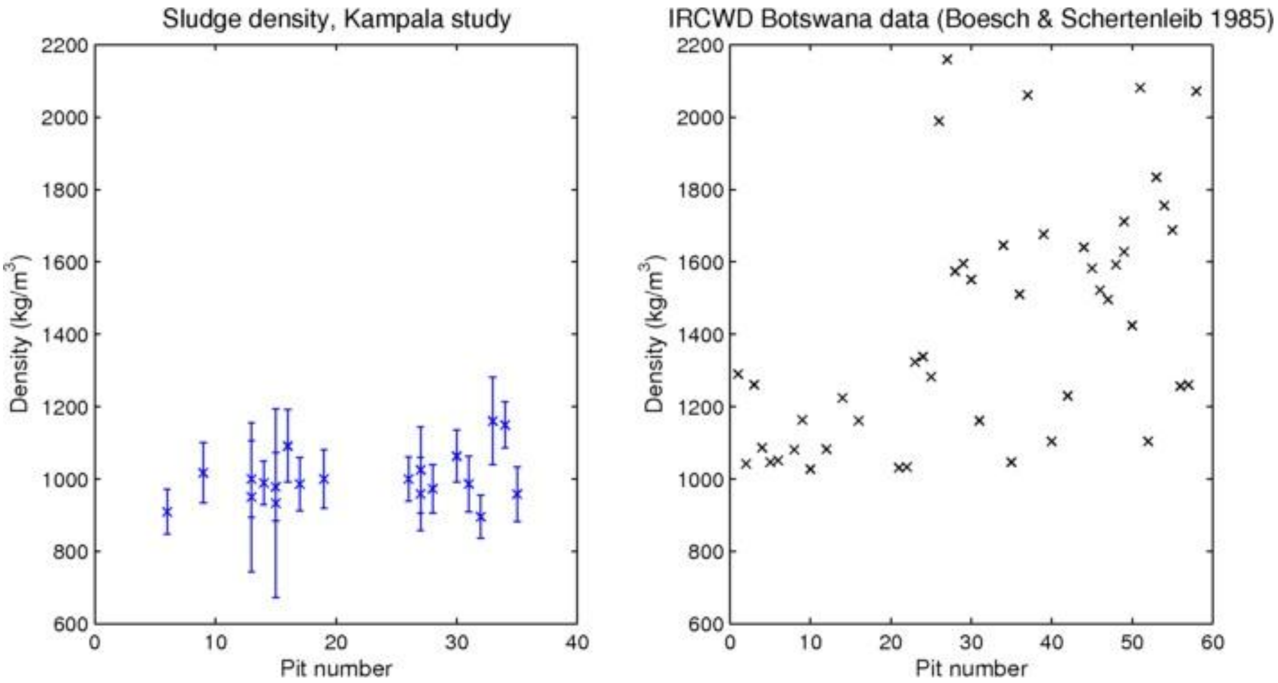


Figure 4: Comparison of density data with the literature

It is suggested that the sludges sampled in Botswana contained significant amounts of sand and earth which increased the sludge bulk density due to their high specific gravity. This is further supported by the fact that many of the pits were unlined and samples were taken after attempted emptying – in some cases it is even reported that the pits collapsed upon emptying and the sample consisted of "dry sand."

Further work

The data presented here indicates that pit-latrine sludge is both significantly stronger and less dense than previously reported in the literature. However, this study only characterised the contents of 30 latrines in a single community in Kampala, and a larger study testing hundreds of pits across multiple cities is now required to develop a better understanding of the range of physical characteristics of faecal sludge. This will provide the data necessary to inform the design of improved pit emptying technologies and produce the best information to date on the range and distribution of strengths of faecal sludge, helping to define the potential market size for different technologies according to their emptying performance.

The portable penetrometer enables studies to test the effect of different factors on pit function and fill-up rate, as the sludge volume and strength can be directly measured without emptying the pit or removing samples. The characterisation process can be repeated on a regular basis to identify how the sludge changes with time and to measure the difference in sludge properties between 'experimental' and 'control' pits. Possible tests could investigate the effect of a change in pit management practice (e.g. adding additional water) or a technical innovation (e.g. installing a drain-pipe and soakaway).

Work is ongoing at the University of Cambridge to develop improved synthetic sludge simulants that replicate the full range of shear strengths and densities reported for faecal sludge. These will provide a material on which to test prototype pit emptying technologies which is safe to handle and truly representative of the physical characteristics of faecal sludge.

## CONCLUSIONS

A sample of 30 pit latrines in Kampala, Uganda have been physically characterised using the portable penetrometer, a bespoke device developed during this study. The maximum undisturbed sludge shear strengths were approximately 2kPa, four times stronger than previously reported in the limited literature on the subject. The faecal sludge tested here was found to have a sensitivity of 3.3, indicating significant potential to increase emptying capabilities through in-pit fluidisation. Density samples from these pits were significantly lower than reported by Bösch & Schertenleib (1985) and had a mean value of 1001kg/m$^3$, which is broadly in agreement with a recent study by AIT (2012).

The portable penetrometer developed here has demonstrated an ability to measure both the undisturbed and remoulded shear strengths of faecal sludge in-situ, and its use is therefore recommended for future studies. Continuous shear strength profiles through the pits have demonstrated an unexpected variability within individual latrines, with the strength of layers found at different depths varying by a factor of up to 15.

Finally, further studies have been suggested including the widespread physical characterisation of faecal sludge, controlled scientific studies into the factors affecting pit function and fill-up rates, and the development of improved synthetic sludges to support the testing of new pit emptying technologies.

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