Characterisation and fluidisation of synthetic pit latrine sludge

J. T. Radford and R. A. Fenner

ABSTRACT

Half of the world's urban population will live in informal settlements or 'slums' by 2030. Affordable urban sanitation presents a unique set of challenges as the lack of space and resources to construct new latrines makes the de-sludging of existing pits necessary, and this is something that is currently done manually, with significant associated health risks. Various mechanised technologies have therefore been developed to facilitate pit emptying, with the majority using a vacuum system to remove material from the top of the pit. However, this results in the gradual accumulation of unpumpable sludge at the bottom of the pit, which eventually fills the latrine and forces it to be abandoned. This study has developed a method for fluidising unpumpable pit latrine sludge, based on laboratory experiments using a harmless synthetic sludge. The implications for sludge treatment and disposal are discussed, and the classification of sludges according to the equipment required to remove them from the latrine is proposed. Finally, further work is suggested, including the ongoing development of a device to physically characterise latrine sludge *in-situ* within the pit.

Key words | developing countries, faecal sludge, pit latrine, sanitation, urban slums

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INTRODUCTION

Providing adequate sanitation to a rapidly growing urban population is one of the greatest challenges of our generation. An estimated 2.5 billion people lack access to improved sanitation (UNICEF & WHO 2012), contributing to an estimated 840,000 child deaths per year from diarrhoeal disease (UNICEF 2012). Although sanitation coverage is generally higher in urban than rural areas, the huge projected increase in urban populations in developing countries, which are forecast to double in size to over five billion by 2050 (UN-DESA 2011), makes the provision of affordable urban sanitation a significant challenge.

Urban informal settlements provide a very different set of challenges to those encountered in rural areas with regard to sanitation services. Many houses do not have space for individual toilets and those that do will typically be unable to dig a new pit when their latrine is full. An estimated 105 million urban dwellers have no option but to defecate in open spaces or plastic bags because public latrines are overflowing, too far away or unaffordable (UNICEF & WHO 2012). Regular de-sludging of existing pit latrines is therefore necessary if they are to provide a sustainable service in high density urban settlements.

Currently the most widespread method of emptying pits is to do so manually, with workers 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 they receive abuse and stigmatisation from local communities, 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 therefore been done to develop affordable mechanised pit emptying technologies for high density urban areas that cannot be accessed by conventional vacuum tankers. However, many of these systems use a vacuum to remove waste from the pit and are limited to only extracting the watery liquid fractions near the surface (Kwach 2008). This results in the progressive accumulation

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of high strength sludge at the bottom of the pit, which can only be removed manually, resulting in the eventual abandonment of the latrine or a return to manual pit emptying.

Objective scientific comparisons of the performance of different pit emptying technologies have not been conducted due to the variability of pit latrine sludge and a lack of data on its physical properties. Prototype development tests are currently either done on faecal sludge, with associated health and safety concerns, or on artificial sludges mixed with little control over their physical properties. This paper describes the development of a synthetic sludge with well defined physical characteristics that are representative of pit latrine sludge. In this investigation pit latrine sludge is treated analogously to submerged marine sediments, which are typically characterised according to their undrained shear strength (DeJong *et al.* 2011). This differs from previous work (Bösch & Schertenleib 1985) which characterised samples according to viscosity. The different approaches stem from whether pit latrine sludge is treated as a strong fluid or a weak soil, and it is suggested that the latter is more appropriate, particularly for consolidated sludges that are difficult to remove from latrines. A fluidisation process is also described that would increase the solids content and volume of sludge that can be removed from pits using a vacuum based system, as currently only the water-like supernatant is pumped out.

CHARACTERISATION OF A SYNTHETIC SLUDGE

Physical properties of pit latrine sludge

For safety and consistency in testing, a synthetic sludge was developed to replicate the range of physical properties reported for pit latrine sludge, using low cost materials available in the developing world. This was based on the only available data in the literature, an International Reference Centre for Waste Disposal (IRCWD) study that tested 58 pit latrines in Botswana during the mid-1980s (Bösch & Schertenleib 1985). A 1 litre sample was taken from the material remaining at the surface of each pit following attempted emptying by vacuum tanker, and its density, water content (WC), percentage volatile solids and viscosity were tested in a laboratory.

Sewage sludge (analogous to pit latrine sludge) is both thixotropic (viscosity decreases with time at constant shear strain rate) and pseudoplastic (viscosity decreases with increasing shear strain rate), making absolute viscosity difficult to quantify. In the IRCWD study viscosity was reported after the complete destruction of any thixotropic structure in the sludge, as a single scale reading at 'rotor speed 4' which is specific to the particular viscometer and spindle used in that study.

The procedure to convert the IRCWD data into shear strengths consisted of multiplying the viscometer scale readings by a factor of 3.88 Pa/scale graduation to convert them into shear stresses, as suggested by the viscometer manufacturer Haake (Bösch & Schertenleib 1985). The shear strain rate of the IRCWD data has been calculated as $9.4\ s^{-1}$ according to the iterative procedure proposed by Mitschka (1982). Finally, the WC of each sample has been recalculated on the basis of dry mass, i.e. mass of water divided by mass of dry solids. The shear strength and density of each sample is plotted as a function of WC in Figure 1 below. It is evident that pit latrine sludge is highly variable and, while there is no clear correlation between viscosity and WC, density is strongly negatively correlated to WC.

The IRCWD data, however, cannot be considered truly representative of pit contents as it only records the limit of what could be removed using different vacuum tankers rather than the actual maximum strength of sludge found in the pits. A maximum shear strength of 1 kPa was therefore selected for the synthetic sludge, which is more than twice the highest strength reported from Botswana.

Sludge measurements

A mini ball penetrometer developed for testing very weak marine muds (Kuo 2011) was used to measure the shear strength of the synthetic sludge (described below). The penetration rate was set using a computer controlled actuator and the shear strain rate calculated as twice the penetration rate divided by ball diameter (Randolph & Andersen 2006). The shear strength was calculated by dividing the recorded penetration resistance by a correction factor N_b, set at 14.4 through calibration against tests on low strength samples that were within the measurement range of a Brookfield DV-E viscometer with HV spindles. Penetration tests were

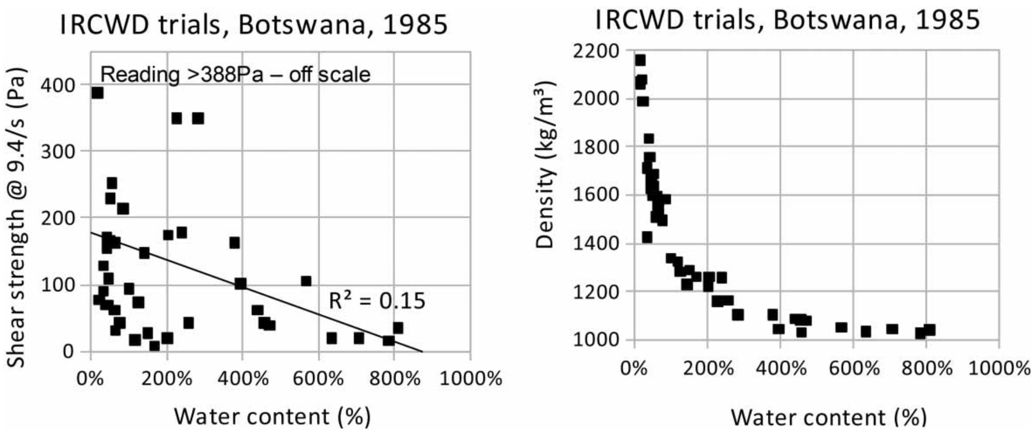

Figure 1 | Effect of water content on sludge properties.

carried out to measure shear strength at six shear strain rates ranging from 0.8 to 15.7 s^{-1}, spanning the 9.4 s^{-1} rate used in the IRCWD study, with each speed repeated three times. Bulk density and WC were determined by testing samples according to standard procedures (ASTM 2009, 2010).

Development of a representative synthetic sludge

A mixture of compost, clay and water was selected for the synthetic sludge and various compositions were tested to investigate the effect on sludge density and shear strength. Compost made from garden and kitchen waste was collected from a local recycling centre, with a mean WC of 100% and mean bulk density of 1,200 kg m^{-3}. The clay used was Speswhite, a highly refined kaolin with ultra fine particle size commonly used in geotechnical research.

An initial sludge consisting of two parts clay and one part compost by dry mass was prepared with a nominal WC of 80%, and its shear strength, density and actual WC were measured. The WC was then increased by increments of approximately 5% up to a maximum of 125% and each resulting sludge was fully characterised according to the procedure described above. The results are shown in Figure 2 below.

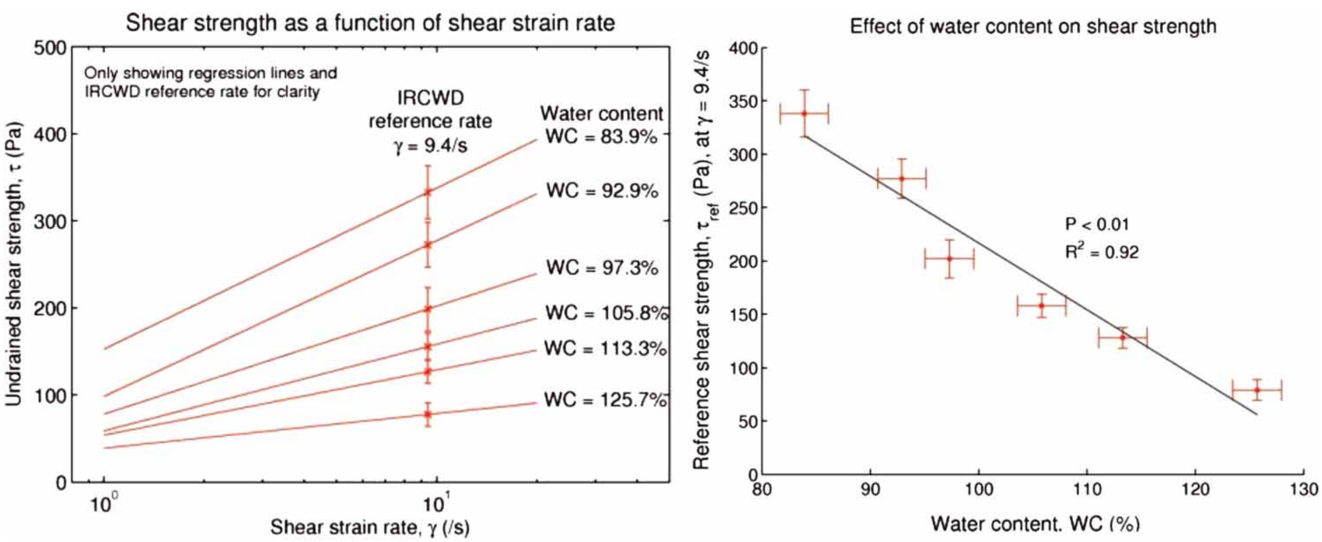

Figure 2 | Effect of water content on sludge shear strength.

The full strength range of pit latrine sludge can be covered by simply adjusting the WC of the synthetic sludge. A second series of tests was also conducted, varying the solid composition from 64 to 85% clay, while maintaining the nominal WC constant at 105%. However, the data proved inconclusive due to poor control over the actual WC of the samples, which ranged from 102 to 123%. On the basis of these tests a synthetic sludge composition of 70% clay and 30% compost was selected for the fluidisation investigation, with shear strength controlled by WC.

Comparison with IRCWD data

The undrained shear strength and density of the synthetic sludges developed here are compared with the ICWRD pit latrine samples in Figure 3 below.

It is evident that the synthetic sludge replicates and exceeds the full range of shear strengths recorded for pit latrine sludge up to a maximum strength of almost 1 kPa. However, there is a significant difference in mean densities of 313 kg m^{-3} ($p = 0.01$) due to the relatively high proportion of compost in the synthetic simulant, which has a low bulk density of approximately 1,200 kg m^{-3}. However, a recent study by AIT (2012) reported densities in the range 1,092–1,159 kg m^{-3} for faecal sludge, suggesting that the high densities reported in the IRCWD study may be due to significant amounts of sand in the sludge samples. This is indeed supported by the report, which notes that adding sand to the pit to cover faeces was commonplace and that a number of pits collapsed upon emptying – one sample is even described as 'dry sand'. Although the synthetic simulant does not replicate the range of densities reported by the IRCWD, it is considered to be representative of faecal sludge from lined pits where adding sand to cover fresh faeces is not common practice.

FLUIDISATION OF SYNTHETIC SLUDGES

A fluidisation process was investigated to reduce the shear strength of sludge within the pit, thereby increasing the solids content and volume of sludge that can be removed from pits mechanically. There are two principal effects to consider: dilution and remoulding. Dilution decreases shear strength by increasing the WC, whereas remoulding consists of mechanical agitation to break down the physical structure that develops over time as the sludge consolidates at the bottom of a pit. The simulant developed in this

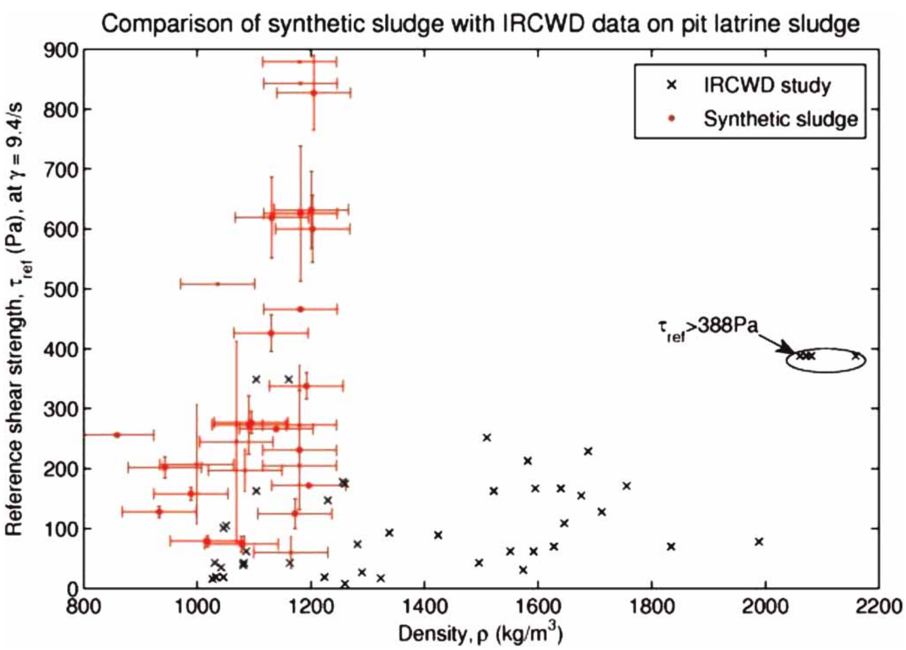

Figure 3 | Comparison of physical properties of synthetic and pit latrine sludges.

investigation is produced in a remoulded state, and consolidates when left undisturbed for prolonged periods. In order to isolate the two fluidising effects, water was added to remoulded sludge to investigate the effect of dilution alone. A series of sludges was also left to consolidate and then remoulded at constant WC by injecting compressed air to investigate the decrease in strength achievable from remoulding alone.

Experimental procedure

An 80 litre vacuum tank fitted with a 75 mm diameter suction hose and powered by a 2 kW vacuum cleaner was used for fluidisation testing. It was capable of producing a suction of 0.45 bar (45 kPa), and pressure of 0.3 bar (30 kPa) against a closed valve, significantly lower than the 0.8 bar (80 kPa) typically achieved by a vacuum tanker. A schematic of the apparatus is shown in Figure 4 below.

It is noted that transport, price negotiation and clean-up times typically dominate the pit-emptying process (Sugden & Coffey, personal communication) with pit emptying durations relatively brief in comparison. The rate of emptying was therefore discounted as a performance metric and instead it was simply noted whether the sludge was 'pumpable' and could be sucked out of the waste tank. The volume, rather than pressure, of injected water was identified as the key control variable from research into water jetting in the offshore drilling industry (Bienen *et al*. 2009). Water volume is also an important operating criterion in urban informal settlements where water may be either unavailable or unaffordable (UN-Habitat 2003).

In the dilution tests, 500 L of 'unpumpable' remoulded sludge with a shear strength of approximately 650 Pa was produced and fully characterised, before adding water in 5 L increments to the vacuum tank and mixing this into the sludge using air. Following each dilution, an attempt was made to empty the sludge into the vacuum tank and the sludge was fully characterised following successful emptying.

In the remoulding tests, submerged sludges were left to consolidate for two weeks, producing a material more representative of the contents of a pit latrine, whose strength increased with depth. The consolidated sludge was then tested *in-situ* with the ball penetrometer at the IRCWD shear strain rate of 9.4 s^{-1}, before injecting compressed air to fluidise the sludge and then repeating the shear strength profile. An attempt was then made to suck the sludge into the vacuum tank and both the residual 'unpumpable' sludge and any remoulded sludge transferred to the vacuum tank were then fully characterised.

Fluidisation results

The results from the dilution and remoulding tests are detailed in Table 1 below.

The effect of increasing WC on the shear strength of a sludge was investigated in the first part of this study. The objective of the dilution trial was therefore to test whether injecting water and compressed air into a tank of sludge would provide a sufficient mixing effect to dilute the sludge and make it 'pumpable'. The resulting 79% decrease in shear strength demonstrates that the process is feasible

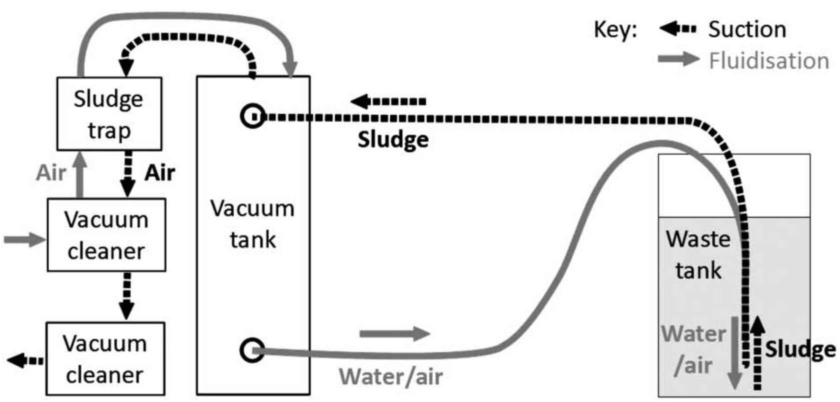

Figure 4 | Schematic of the fluidisation apparatus.

Table 1 | Fluidisation results

Test	Sludge state	Shear strength (Pa, $\gamma_{IRCWD} = 9.4/s$) Initial	Residual	Emptied	Strength decrease	Volume increase
Dilution #1	Remoulded	600	/	125	79%	76%
Remoulding #1	Consolidated	875	632	231	28–58%	0%
Remoulding #2	Consolidated	1100	827	466	25–58%	0%

and even the strongest of sludges can be rendered pumpable by adding sufficient water. However, it is also noted that dilution produces a large increase in volume which would render the process infeasible for most pit latrines which are often filled to capacity before emptying.

The true potential of *in-situ* fluidisation is indicated by the tests on consolidated sludge, which is more representative of the material found in pit latrines. Observations during testing indicate that as large slugs of air rise up from the bottom of the tank, they spread out laterally and remould a cone of sludge around the air hose. The results suggest that shear strength is reduced by almost 60% in this remoulded zone, and even in the surrounding 'residual' sludge, a 25% decrease in strength was recorded. The greatest percentage decrease in strength was recorded near to the surface where the sludge is weakest, suggesting that minimal vertical mixing occurs and the effect is indeed due to remoulding.

DISCUSSION

Field test procedures

The variability of pit latrine sludge is widely acknowledged in the literature (e.g. Strauss & Montangero 2002); however, actual data on its physical properties are currently limited to a single study from Botswana dating from 1985. There is therefore a critical need for the widespread physical characterisation of pit latrine sludge to better understand its flow behaviour and support the development of improved pit emptying technologies. An accurate tool is required for measuring the physical properties of faecal sludge within the pit to eliminate the remoulding effect of sampling and transporting sludge to a laboratory for characterisation, which reduces its strength before testing. The full-flow penetrometer used here is recommended for its high accuracy, direct measurement of shear strength and the fact it can be used to remould sludge *in-situ* to investigate the potential for fluidisation.

A low-cost, lower accuracy device for classifying sludge would also be useful for testing the performance of pit-emptying technology prototypes. Possible tests include the Marsh funnel or concrete slump test for sludge samples, or some form of manual penetrometer for *in-situ* testing. In the latter case it may prove useful for determining the type of equipment required to empty the pit, or even to estimate the volume of sludge that can be removed from a pit, to inform the customer how much it will cost and how long it will take to empty.

Sludge classification

Current standard practice for comparing pit contents and the performance of emptying technologies is to use subjective, qualitative descriptions such as 'molten chocolatey' or 'watery'. This investigation has developed a framework for the quantitative physical characterisation of faecal sludge based on undrained shear strength and density. It is proposed that different classes of faecal sludge are categorised according to the equipment required to remove them from a latrine. An initial classification based on the performance limits of the vacuum-cleaner powered system used in this investigation is presented in Figure 5 below, where the plug-drag operation consists of repeatedly 'raising and lowering the hose inlet in and out of the sludge' (Bösch & Schertenleib 1985) whereas for vacuum operation the hose inlet remains in the sludge throughout emptying.

Further work is required to expand this system to cover everything from the strong, dry sludge found in alternating

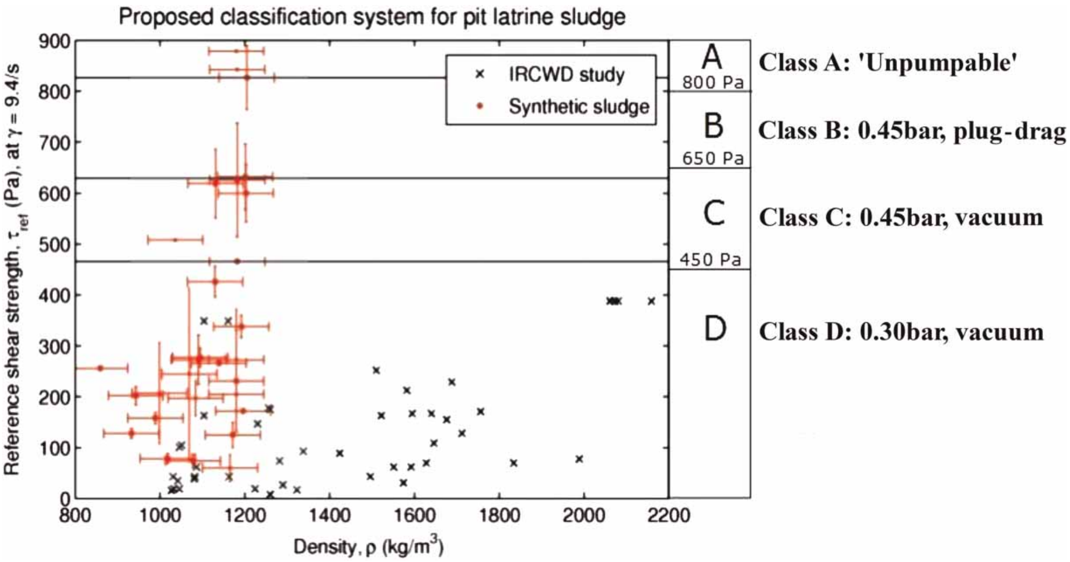

Figure 5 | Proposed sludge classification system.

pits, to the watery liquid filling those in high water table areas. Performance benchmarking of technologies ranging from hand pumps to vacuum tankers would provide the necessary classes to meaningfully distinguish between the sludge found in different pits. Each class of sludge would be clearly defined on the basis of its physical properties, but its flow behaviour would be intuitively understood through reference to its emptying requirements, for example Class D may be removed by low-pressure vacuum whereas Class A requires manual emptying with a shovel.

Increasing 'pumpability' through *in-situ* fluidisation

The investigation into fluidisation demonstrated that sludge strength can be dramatically decreased through dilution; however, this produces a correspondingly large increase in volume. One possible solution would be to first extract watery supernatant from near the top of the pit and then reinject it at the bottom to mix the contents and dilute the strongest sludge without increasing the total volume. This has the added benefit of not using any water for fluidisation, which is a valuable resource, particularly in low-income urban settlements; however, the supernatant contains the most recently deposited faecal matter and is therefore heavily contaminated with pathogens.

The fluidisation process suggested here increases the solids content and volume of sludge that can be removed from pits by mechanical means and could help prevent the gradual accumulation of 'unpumpable' sludge in pit latrines, resulting in their eventual abandonment. However, it could also result in increased environmental dumping if suitable haulage and resource recovery or sludge treatment systems are not implemented, as the slowest and most expensive part of pit emptying is transporting the sludge to its disposal point (Strauss & Montangero 2002).

Future work

This investigation is part of an ongoing research project to develop improved pit emptying services for urban areas. A portable device has been designed to physically characterise pit latrine sludge by measuring its undrained shear strength, *in-situ* within the pit, and a study to characterise one thousand latrines across ten different cities is currently being planned. Efforts are also ongoing to develop improved synthetic sludge simulants, and full-scale validation of the fluidisation tests reported here is also planned.

CONCLUSION

A simple two-component synthetic sludge has been developed to replicate the full range of shear strengths reported for pit latrine sludge. Its density is comparable to that reported for faecal sludge; however, it is significantly lower than that of sludges containing a high proportion of sand. Tests at reduced scale indicate that sludge can be diluted by injecting water into the bottom of the pit, followed by air to mix the contents. This dilution process produces a large decrease in shear strength, but requires a correspondingly large increase in WC, and therefore sludge volume. Air-blown remoulding, however, shows significant potential to fluidise pit sludge at constant WC. Tests suggest that a decrease in strength of 25–60% is achievable through air-blown remoulding, which would increase the volume and solids content of the sludge removable from pit latrines by mechanical means.

A key recommendation of this study is to physically characterise pit latrine sludge within the pit according to its undrained shear strength and density. Different classes of sludge should be defined according to the emptying technologies required to empty the pit. This would provide a standard framework for comparing the performance of technologies developed by different people in different regions of the world, where pit contents are likely to differ significantly.

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