Fluidisation of synthetic pit latrine sludge
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

The World Health Organisation estimates that 2.6 billion people lack access to improved sanitation, many of whom live in urban informal settlements or 'slums', which are projected to house half of the world's urban population by 2030. Affordable urban sanitation presents a unique set of challenges as the lack of space and resources to construct new latrines makes desludging existing pits necessary and is something that is currently often done manually with significant associated health risks.

There has therefore been a concerted effort to develop mechanised technologies to facilitate pit emptying in high density urban settlements. The majority of these devices use a vacuum to remove material from the top of the pit, however they are typically only able to remove the water-like supernatant fluid. This results in the gradual accumulation of 'unpumpable' sludge in the pit, which eventually fills the latrine, forcing it to be abandoned. The main aim of this project was therefore to develop a method for fluidising 'unpumpable' pit latrine sludge, through a series of laboratory experiments on harmless synthetic sludge.

The first phase of the investigation involved the development of the synthetic sludge and a process for its physical characterisation. Reference data on the physical characteristics of pit latrine sludge were obtained from a study done by the International Reference Centre for Waste Disposal in Botswana during the 1980s. A synthetic sludge consisting of clay and compost was developed to replicate these characteristics. Undrained shear strength and density were identified as the critical parameters controlling 'pumpability'.

It was found that for a given solid composition of sludge, water content correlates strongly with undrained shear strength, and by varying its water content the full range of reported sludge shear strengths could be achieved. The density of the synthetic sludge was found to be significantly lower than that reported by the IRCWD, with a difference in means of around 300kg/m^3. This is due to the low density of the organic matter in compost, and clay-stabilised soil has been proposed as a possible alternative synthetic sludge with higher density.

It was not possible to determine the effect of solid composition on sludge flow behaviour due to difficulty in controlling water content when different solid compositions were used. The variability in water content of the compost used in the sludge also prevented the development of an absolute 'recipe' for different strengths of sludge and certain amount of experimentation will therefore always be required when developing synthetic sludge from

locally available materials. Nevertheless, the synthetic sludge mixture was deemed suitable to investigate the effect of fluidisation.

The reduction in sludge shear strength from fluidisation was found to be caused by two effects – dilution, which increases water content, and remoulding, which involves mechanical agitation to break down the structure of the material. A one-fifth scale pit emptying device, powered by two modified vacuum cleaners, was used to carry out the fluidisation tests.

The first series of tests was done on a uniform sludge and demonstrated that fluidisation by dilution alone was feasible, however a 23% increase in water content was required to make a strong sludge 'pumpable'. Samples were then left to consolidate before being characterised, producing a material more representative of that found in a pit latrine. Injecting air into these samples produced a three-fold decrease in strength as a result of remoulding at constant water content.

The large increase in water content during fluidisation by dilution causes a large increase in volume which would probably be impractical as there would be insufficient space in the pit. One solution could be to suck weak supernatant off the top of the pit for fluidisation, thereby eliminating the volume increase, however this has associated health risks as the supernatant is heavily contaminated with pathogens. Fortunately this may not be necessary in many cases as air-blown remoulding alone would be sufficient to fluidise all but the strongest of sludges.

The implications for sludge treatment and disposal have been discussed, with the increase in volume and solids content of the sludge removable from the pit potentially encouraging illegal dumping if not managed carefully. It has also been proposed that sludges should be classified according to the equipment required to remove them from the latrine, and possible field tests have been suggested to estimate sludge density and shear strength.

The performance of the equipment used in the laboratory greatly exceeded expectations. This serves as a proof of concept that cheap and easily replaceable vacuum cleaners could be used to replace the expensive vane pumps currently used in most suction-based pit emptying technologies.

Finally, various suggestions have been made for further work, including the development of a synthetic sludge that is more representative of pit latrine sludge and full-scale fluidisation trials using both synthetic and actual pit latrine sludge to validate the findings of this investigation.

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1 Introduction

1.1 Justification for study & context

Providing adequate sanitation to a rapidly growing urban population is one of the greatest challenges facing our generation. An estimated 2.6 billion people lack access to improved sanitation, contributing to some 1.8 million deaths per year from diarrhoeal disease [WHO & UNICEF, 2010]. At the World Summit on Sustainable Development in 2002 an additional Millennium Development Goal target was agreed "to halve, by 2015, the proportion of people who do not have access to basic sanitation"[UN-Habitat, 2003] and yet to achieve this, 370,000 people will need to be provided with 'improved sanitation' every day from now to 2015. The situation is in fact worse than these already daunting figures would suggest as "'improved' sanitation is often no more than a latrine, to which access is difficult, shared among [sic] many households" [UN-Habitat, 2003]. Although 84% of the urban population of Africa, Asia and Latin America has 'improved' sanitation, less than half of those same populations have 'safe' or 'adequate' sanitation [UN-Habitat, 2003].

Urban informal settlements also provide a very different set of challenges to those encountered in rural areas with regards 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 100 million urban dwellers have no option but to defecate in open spaces or plastic bags as public latrines are overflowing, are too far away or are unaffordable [UN-Habitat, 2003]. This is a problem which is only set to get worse – urban populations in developing countries are experiencing exponential growth, averaging more than 60 million new inhabitants each year over the last decade [UN-Habitat, 2001], and much of the future urban growth will be in informal settlements or 'slums' which already house an estimated 828 million people globally [Reliefweb, 2010].

Regular desludging of existing pit latrines is therefore necessary if they are to provide a sustainable sanitation service [Jere et al., 1995] 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 [Still, 2002] without any protective clothing. In addition to the wide range of diseases they may contract[Sugden, S., p*ers. comm.*, Nov. 2010], pit emptiers are also at risk from the collapse of unlined pits and receive abuse and stigmatization from local communities, forcing them to work after dark [Eales, 2005] and to dump the extracted sludge illicitly in the nearest available sewer or stream.

There has therefore been significant work done to develop affordable mechanised pit-emptying technologies (PETs) for use in high-density urban settlements where limited access prevents the use of large vacuum tankers. The most common device uses a vacuum to draw waste out of the pit, either by hand-pumping (eg. MAPET, developed by the Dutch NGO WASTE or 'Gulper' developed by Steve Sugden of LSHTM) or using a diesel motor to drive a vacuum pump (eg. UN-Habitat Vacutug or the 'Dung Beetle' used in Ghana) [O'Riordan, 2009]. The principal advantages of a vacuum-based system are that it minimises human contact with pit contents and therefore reduces social nuisance from odour and flies, and the sludge does not pass through the pump, reducing the likelihood of blockages.

However most vacuum-based PETs can only generate a few metres of static head and are therefore limited to extracting the liquid fractions of waste at the top of a pit [Kwach, 2008]. Combined with the limited capacity of households to pay for complete pit emptying [Sharpe, 2010], this leads to the progressive build up of highly viscous and dense sludge at the bottom of pits, which becomes 'unpumpable' after around two years of consolidation.

1.2 UN-Habitat project

UN-Habitat has supported the development of improved pit-emptying technologies for more than 20 years, with the current project focussing on improved pit design for mechanical emptying. The proposal is to build a pre-fabricated, low cost concrete pit and pour-flush slab which would prevent domestic solid waste and extraneous matter entering the pit (one of the most common causes of Vacutug blockages [Coffey, M., p*ers. comm.*, Nov. 2010].) The design also includes a permanent suction pipe providing access to the bottom of the pit for a vacuum-based emptying system. This ensures that the densest waste will be removed first, preventing the gradual accumulation of unpumpable solid sludge at the bottom of pits, while also reducing the lengthy clean-up times for hoses and avoiding contamination of the toilet area with faecal sludge [Coffey, 1990].

1.3 Project aims

The focus of this project is to develop a synthetic sludge that is physically representative of pit latrine sludge. This will enable like-for-like comparisons of the performance of different PET prototypes, something that is currently limited due to the variability of pit latrine sludge. It will also facilitate prototype development as tests are currently done either on faecal sludge, with associated health and safety concerns, or an artificial sludge is mixed with little control or repeatability of its physical properties [O'Riordan, M., p*ers. comm.*, Nov. 2010].

The experience gained from characterising the synthetic sludge will also help form recommendations for a testing procedure that can be used in the field on actual pit latrines to gather more data on the physical properties of faecal sludge. This will be important for the future development of PETs, increasing knowledge of the variability of pit latrine sludge due to diet, anal cleansing methods and ground conditions.

The second phase of the project will be to develop a fluidisation process that extends the capability of a vacuum-based system by increasing sludge 'pumpability'. This will be done by injecting pressurised water and air into an 'unpumpable' sludge.

1.4 Research objectives

- To create a recipe for synthetic sludge that replicates the range of properties of pit latrine sludge, using inert materials that are readily available in the developing world.
- To specify a process for the physical characterisation of pit latrine sludge that can be used in the field with minimal specialist equipment or training.
- To develop a fluidisation process that significantly increases the range of sludges that can be pumped.

1.5 Methodology

The investigation will consist of two phases of laboratory experiments – firstly developing a synthetic sludge, and then investigating the effects of fluidisation. The research will be carried out at the Schofield Centre of the University's Geotechnical Research Group.

2 Previous studies

2.1 IRCWD Botswana investigation

The only comprehensive investigation of the flow behaviour of pit latrine sludge in the literature was undertaken by the International Reference Centre for Waste Disposal (IRCWD) [1] in Gaborone, Botswana during the mid-1980s. That report [Bösch & Schertenleib, 1985] presents the density, water content and viscometer scale reading of 47 samples of pit latrine sludge, as shown below in Figure 1. Sludges were classified according to BHRA strength classes [IRCWD, 1985], which range from 'low-' to 'high+'.

Figure 1: Effect of water content on sludge properties

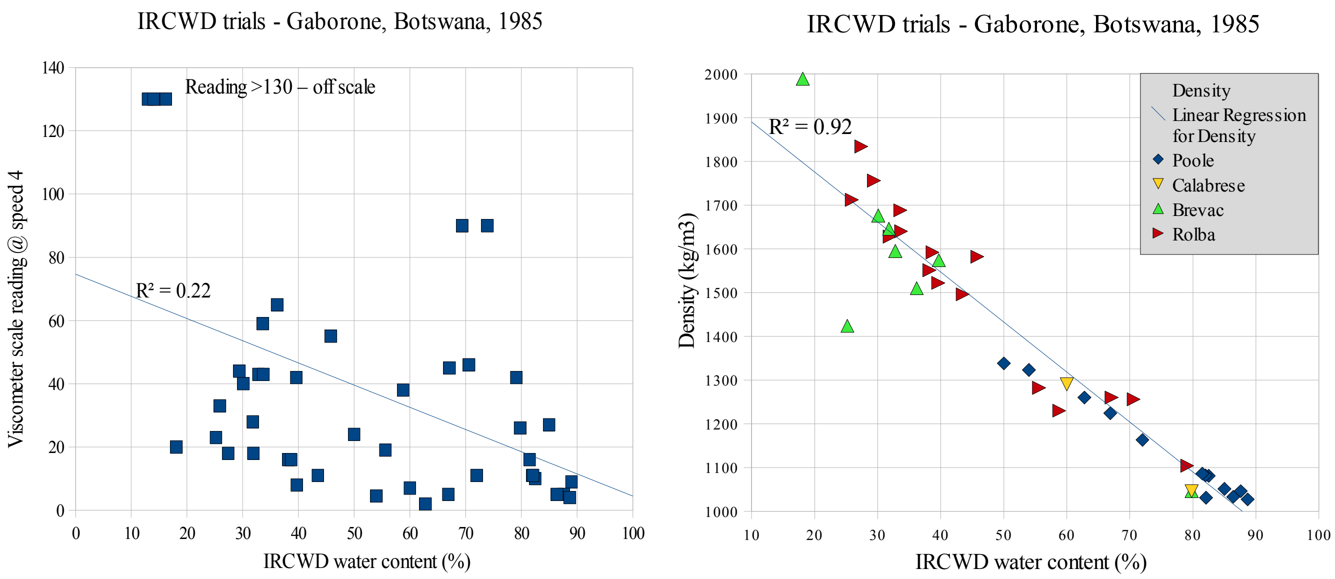

Figure 1 (a): Viscosity – water content

Figure 1 (b): Density – water content

This figure highlights two key points: pit latrine sludge is highly variable (viscosity ranges from 2-65 scale units, density from 1027-1989kg/m^3) and there is no clear correlation between viscosity and water content, whereas density is strongly negatively correlated to water content. The recorded strengths are at the limit of what could be removed from the pit, and Figure 1 (b) suggests that any clustering in the data is a result of the different capabilities of the suction tankers (Poole, Calabrese etc.) used.

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[1] Now the Department of Water and Sanitation in Developing Countries at the Swiss Federal Institute of Aquatic Science and Technology (Eawag)

2.2 UN-Habitat trial

A UN-Habitat Vacutug trial found that the injection of a relatively small volume of water, followed by a burst of compressed air, has a marked fluidising effect on consolidated sludges [Coffey, M., p*ers. comm.*, Nov. 2010]. This is supported by evidence in the literature that a relatively small increase in water content, of order 2%, can have a “dramatic effect on sludge fluidity...[reducing] resistance to flow 30-300 fold”[Hawkins, 1982]. However, the water must be injected into the bottom of the latrine – if water is added from the top it simply floats on the surface and has no fluidising effect.

3 Theoretical considerations

3.1 Water content

The IRCWD study defines water content as $WC = \frac{mass\ of\ water}{total\ mass}$, whereas in this study the geotechnical convention $WC = \frac{mass\ of\ water}{mass\ of\ dry\ solids}$ is used instead. [BS 14688, 2004].

3.2 Density

The height that a sludge can be lifted is determined by both the available suction and the density of the sludge in question. A worn Vacutug only achieves 20kPa suction [Coffey, M., p*ers. comm.*, Nov. 2010], equivalent to 1.8m static head for a sludge of density 1100kg/m^3. As the connection to the sludge tank is ~1.5m above the ground, it would therefore only be able to empty the top 30cm of material.

3.3 Viscosity

The IRCWD study used viscosity as the characteristic parameter for flow behaviour. Sewage sludge is both thixotropic (viscosity decreases with time at constant shear rate and pseudoplastic (viscosity decreases with increasing shear rate) [Brookfield, no date] making an absolute viscosity difficult to quantify. However, the IRCWD report specifies the methodology used in that study to construct a replicable DTS (totally destroyed thixotropic structure) curve for a sludge sample. The process used to convert this data into undrained shear strengths is described in §11.1.

3.4 Shear strength

Consolidated pit latrine sludge behaves more like a soil than a fluid as it does not readily flow, therefore undrained shear strength has been selected as a more intuitive measure of 'pumpability' than viscosity. Shear strength is also usually found to correlate well with density, thereby linking the two properties which control sludge flow. Shear strength is a function of both shear strain (c.f. thixotropy) and shear rate (c.f. pseudoplasticity), with these non-linearities widely reported in soil mechanics.

It should be possible to predict the suction required to pump a sludge of known shear strength using bearing capacity theory from soil mechanics. However, extrapolation of shear strength to the high shear rate within the suction pipe can only provide an order-of-magnitude estimate, as demonstrated in §11.2 of Appendix A.

3.5 Consolidation

Any submerged soil left undisturbed for a prolonged period will undergo consolidation as water drains to the surface, producing a linear increase in both density and shear strength with depth. A consolidated soil can also display sensitivity, whereby its strength decreases after many cycles of applied strain, termed 'remoulding'. Sensitivity is defined as the ratio of the strength of an 'undisturbed' or consolidated state and the strength after remoulding. It is likely that remoulding accounts for much of the reported decrease in strength from fluidisation [Hawkins, 1982].

3.6 Effects of scale

The effect of scale will be negated during sludge characterisation by ensuring the container used is larger than the zone of influence of the device being used.

Fluidisation tests will be conducted at reduced scale due to the impracticality of using a full-sized pit and Vacutug in the laboratory. Dimensional analysis has been used to estimate the effect of scaling on the results – full details are given in §11.4 of Appendix A, and the potential consequences for a full sized system are discussed in §6.1.3.

4 Phase I – Synthetic sludge characterisation

4.1 Introduction

The purpose of this phase of testing was to develop a synthetic sludge that is broadly representative of the range of physical characteristics of pit latrine sludge. Various sludge compositions were tested to investigate how different changes affect its physical behaviour.

4.2 Materials and methods

The materials used for the synthetic sludge must be low-cost and readily available in the developing world, where most work on pit-latrine emptying is conducted. Materials considered include compost, clay, sand, animal feed, maize meal and shredded newspaper. A mixture of compost, clay, sand and water was selected to investigate how varying the relative proportions would change sludge density and shear strength. The sand and clay were supplied in dry form and the compost collected from Waterbeach Waste Management Park.

Uniform sludge samples were mixed manually in a 20L bucket and tested immediately. The use of unconsolidated sludges that are uniform with depth greatly reduced the amount of waste generated in the early stages of the investigation as samples could be modified, remixed and immediately reused. It also eliminated the risk of producing a synthetic sludge that is more sensitive than pit latrine sludge, which would overestimate the effect of fluidisation.

Figure 2: Mini-ball penetromter

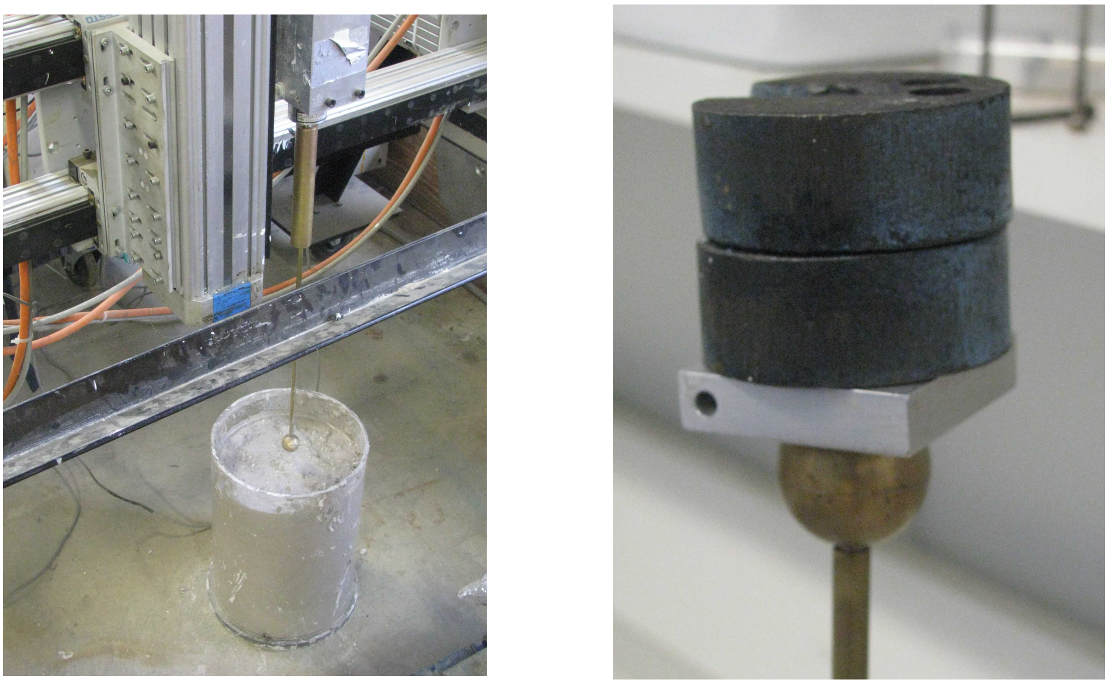


Figure 2 (a): Mini-ball penetrometer in testing rig

Figure 2 (b): Penetrometer calibration

A mini ball penetrometer developed for testing very low strength marine muds was used to measure shear strength (see Figure 2 above) The penetrometer uses a local measurement device within the ball [Kuo, 2011] and a linear calibration curve was plotted by placing small masses on top of the ball and taking readings, as shown in Figure 2(b) above. The penetrometer is driven by a computer-controlled actuator and the penetration rate was calibrated using a linear voltage distance transducer (LVDT).

Viscosity measurements were made on those sludge samples with sufficiently low strength using a Brookfield DV-E viscometer and HB spindles. The procedure described in the IRCWD study was used to plot DTS curves at a range of shear rates. This model of viscometer cannot be connected to a datalogger, therefore readings were recorded manually.

4.3 Theoretical considerations

4.3.1 Viscometer

The disc-shaped HB spindles used in this investigation do not have a standard calibration factor to convert viscosity data into shear strengths. Instead an iterative procedure was used [Mitschka, 1982], where the slope of a log-log plot of shear strength against rotational speed is used to determine a factor $k_{N\gamma}$, which converts rotational speed into shear rate. Shear strength can then be calculated from viscosity and shear rate, $\tau = \dot{\gamma}\eta$ and the process iterated. Viscosity data was used as a first approximation for shear strength and the process converged after two repeats in all cases.

4.3.2 Ball penetrometer

The shear rate at the surface of a ball penetrometer can be estimated as twice the penetration rate divided by the ball diameter (25.4mm) [Randolph & Andersen, 2006]. The required penetration rate to match the shear rate of 9.4/s from the IRCWD report, is therefore 120.7mm/s.

The shear strength of a sludge is calculated by dividing the recorded penetration resistance by a correction factor, N_{ball}, which is typically taken as 10.5 [Kuo, 2011], however for remoulded samples a higher value of 15~20 is considered appropriate [Yafrate et al.,2007].

The zone of influence of the penetrometer extends ~1.25 ball diameters, in this case 32mm, either side of its shaft [Yafrate et al.,2007].

4.4 Pilot studies

A pilot study was carried out on eight samples of synthetic sludge to determine the approximate moisture content required and to gain experience of the experimental technique. Further details were included in the Technical Milestone Report.

4.5 Experimental design

An initial sludge with 15% water content and equal proportions by dry mass of compost, clay and sand was selected as the starting point for the investigation. The moisture content was then increased by increments of ~5% until a cohesive sludge was produced that could be tested using the ball penetrometer. The test procedure described below in §4.6 was carried out to characterise the sludge before increasing the moisture content by ~5% and repeating until a 'low' strength sludge was recorded.

A second series of tests was done, varying solid composition while keeping the nominal water content constant at 105%. An initial solid composition of 64% clay, 36% compost was selected. After characterisation was complete, additional clay was added to produce a 5% increase in clay content, up to a final composition of 85% clay, 15% compost.

4.6 Laboratory procedure

Moisture contents and bulk densities were determined according to standard procedures [ASTM D2216-10, ASTM D7263-09] and viscosity testing was done in a 600ml beaker as specified in the viscometer manual.[Brookfield, no date] Penetrometer tests were done in a 200mm diameter, 300mm high one-ended plastic cylinder which was large enough for four tests to be done around its perimeter and one in the centre without the zones of influence overlapping.

Viscosity testing was done at rotational speeds of 100, 60, 30, 12, 6 and 3rpm using an appropriate spindle to ensure that the reading was always between 10 and 100% of the full-scale range. The experimental procedure described in the IRCWD report was carefully followed to produce comparable results. The readings were observed to 'drift' to lower values over time at all speeds due to thixotropy, therefore a compromise was required between gathering additional data at a given speed and completing the whole test procedure as quickly as possible.

Penetration rates of 5, 10, 20, 50, 100 and 200mm/s were used for initial shear strength tests, with three repetitions of each speed. The lowest three speeds produced constant shear strengths after displacements of less than 3 diameters, whereas the higher speeds required longer strokes to attain a constant reading. Analysis of the results showed a minimum shear strength at 10mm/s, suggesting that the 5mm/s test produced partially drained conditions and therefore these data were discarded.

The data recorded at 200mm/s was found to be more variable than that at slower speeds. At this speed the test duration was only ~1s, making the 200ms duration of acceleration and then decceleration significant. Subsequent tests were therefore done at rates of 10, 20, 50 and 125 mm/s, with four repeats of each. The slightly higher speed of 125mm/s was selected to be equivalent to the shear rate of the viscometer data from the IRCWD report.

4.7 Data analysis

The raw data outputed from the ball penetrometer was found to be very noisy, with interference from the environment distorting the signal. A five-point least squares regression filter was used to clean the data in MATLAB, as demonstrated by Figure 3 below.

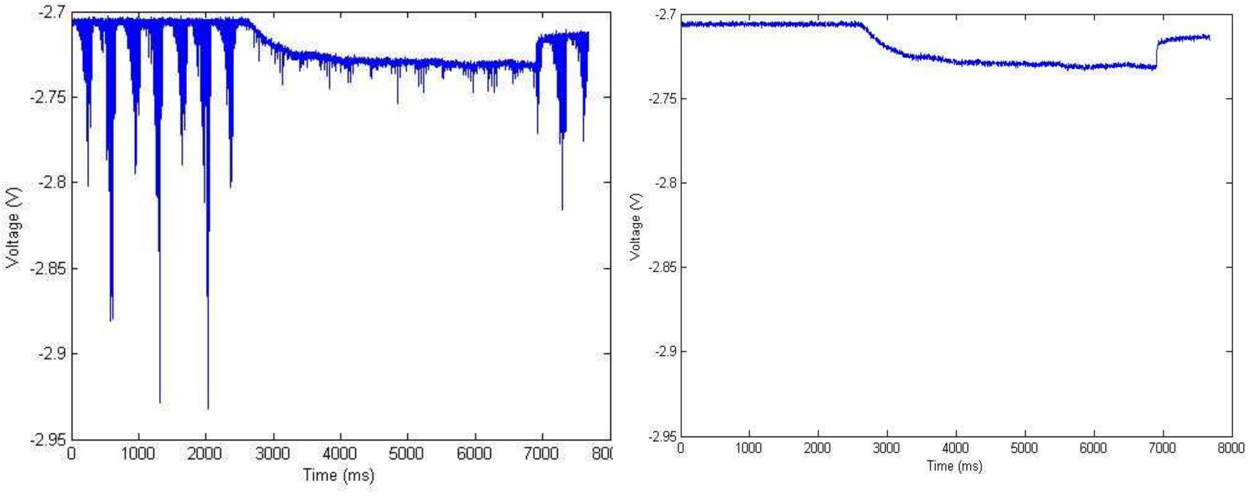


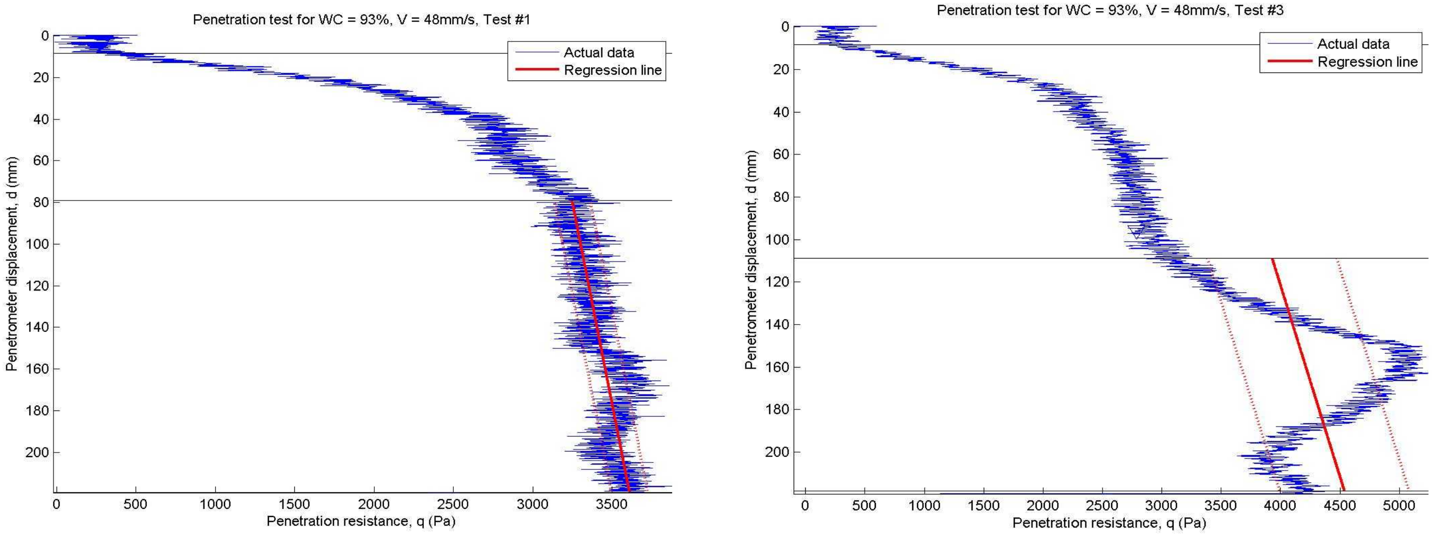
Figure 3: Effect of filtering ball penetrometer data

Figure 3 (a): Unfiltered data

Figure 3 (b): Filtered data

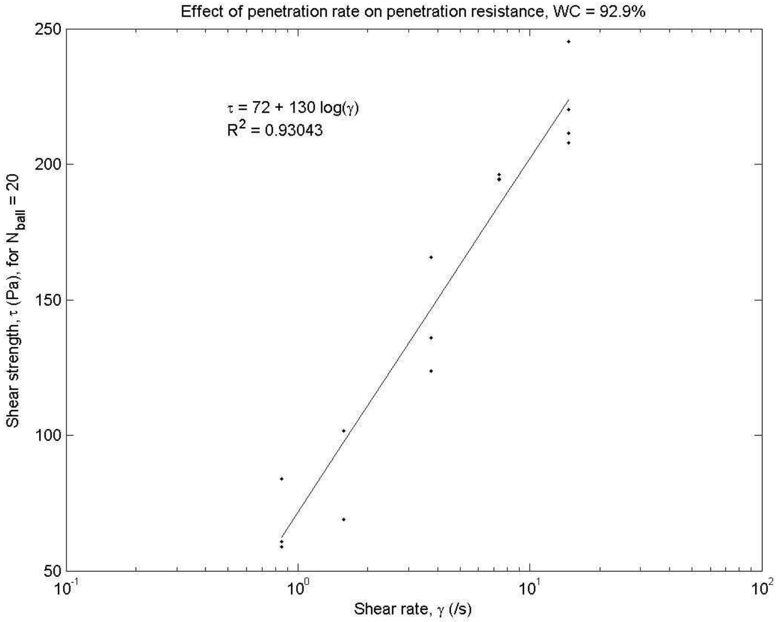
The inhomogeneous nature of the sludge made it difficult at times to identify a representative undrained shear strength, as demonstrated in Figure 4 below.

Figure 4: Variability of ball penetrometer data



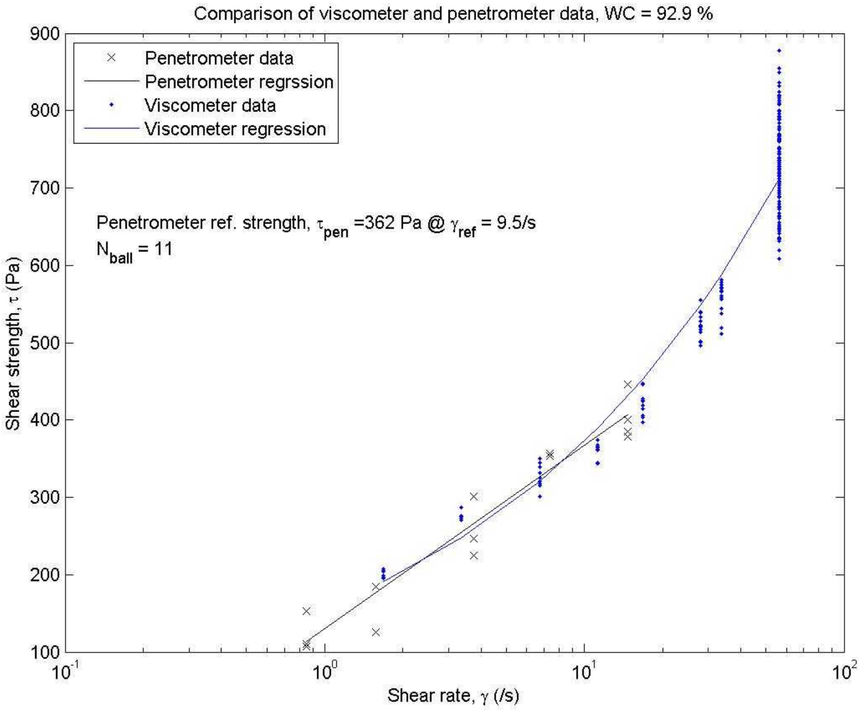
An iterative procedure was therefore adopted, whereby a semilog plot of the initial shear strength estimates was used to identify and potential anomalous points that were then reanalysed. An example semilog plot is shown below in Figure 5 and the clear linear regression suggests that the shear strength depends logarithmically on shear rate.

Figure 5: Semilog plot of ball penetrometer data



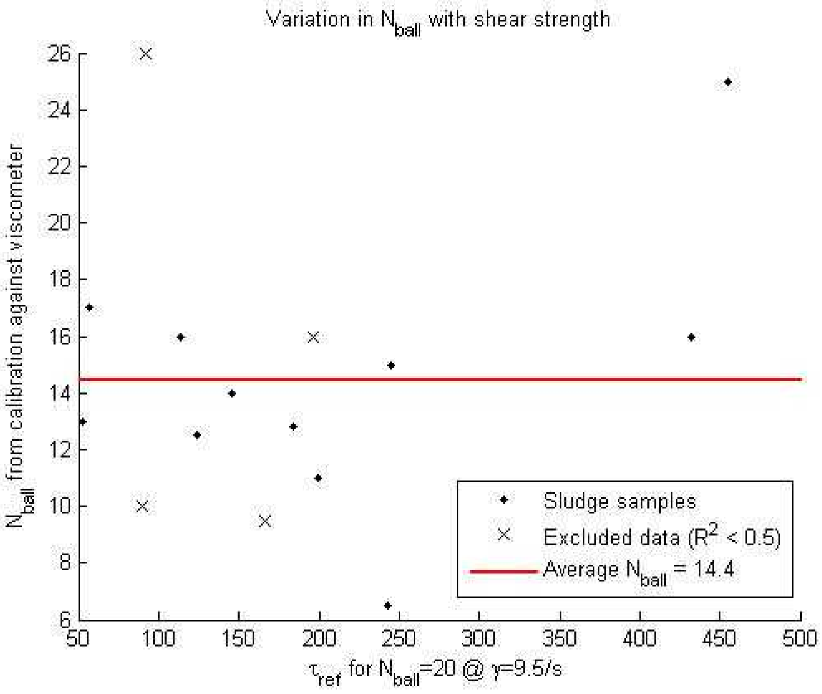
Viscosity data were then plotted on log-log axes as part of the process to convert them to shear strengths,. The ball penetrometer data was then plotted with converted viscometer data (see §4.3.1 for details) as shown below in Figure 6. The conversion factor, N_{ball}, was calculated as the value required for the two data sets to overlap and hence the ball penetrometer could be calibrated against the viscometer.

Figure 6: Ball penetrometer and viscometer data



N_{ball} is then plotted against reference shear strength for each sludge tested, in Figure 7 below.

Figure 7: Average correction factor, N_{ball}



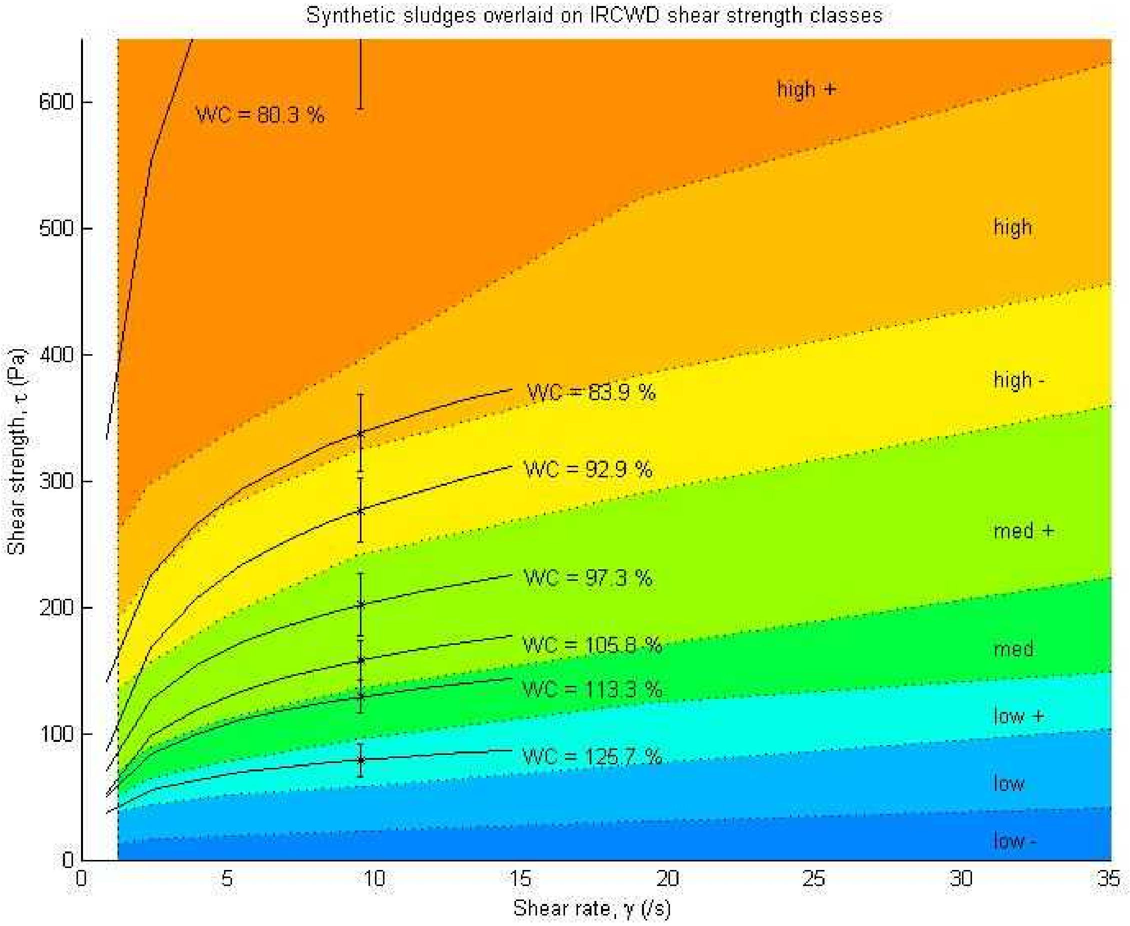
The average value of N_{ball} was found to be 14.4, which was used to calculate the final reference shear strength for all sludges.

4.8 Results & Discussion

4.8.1 Effect of water content

The effect of water content on sludge shear strength is demonstrated by Figure 8, which overlays the strength of different sludges on the IRCWD strength classes.

Figure 8: Effect of water content on sludge shear strength

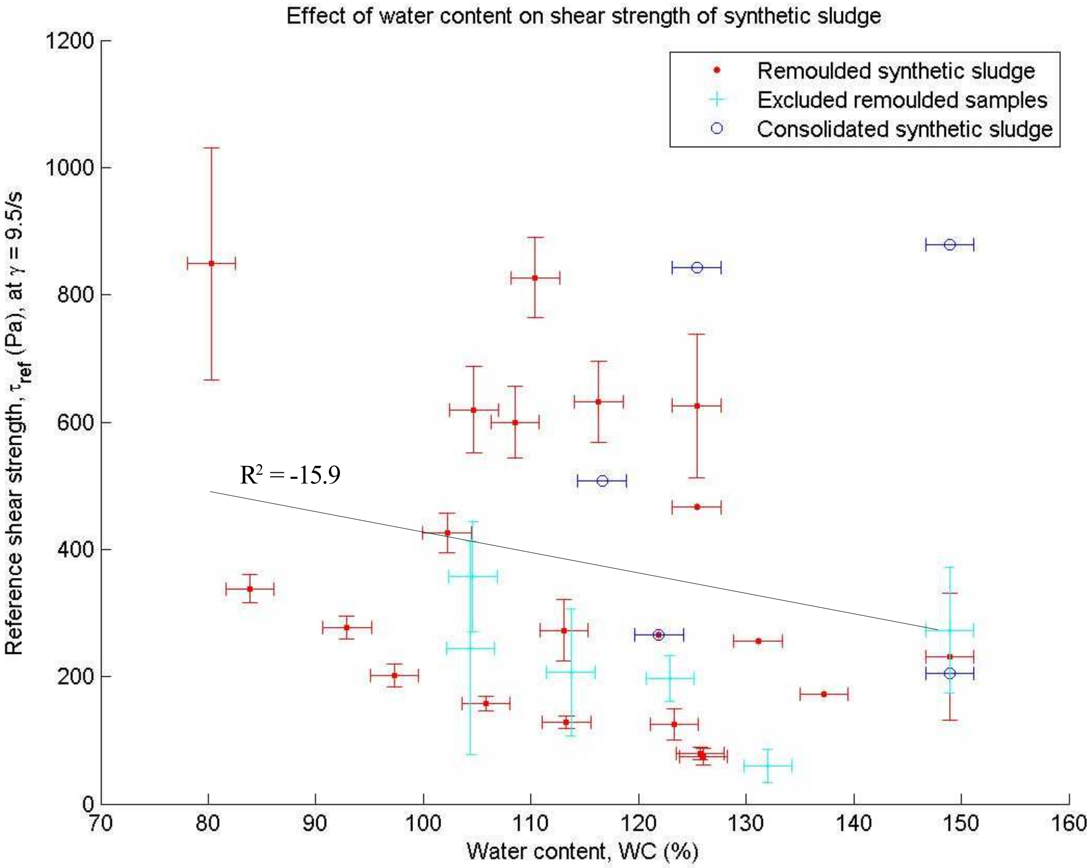


The error bars indicate 95% confidence intervals, calculated using a regression ANOVA table as described in §11.3 of Appendix A. All seven shear strength profiles were found to be significant at the 5% level.

It is clear from Figure 8 that the synthetic sludge developed here can cover the reported range of strengths of pit latrine sludge by simply adjusting the water content. It can also be seen that the effect of shear rate on the strength of the synthetic sludge is similar to that found for actual pit latrine sludge as the superimposed lines closely match the shape of the sludge class boundaries.

It was evident from an early stage of the investigation that the shear strength of a sludge is strongly negatively correlated to its water content, however no such trend was observed in the Botswana data, as demonstrated by Figure 1 (a) of §2.1. In an attempt to explain this difference, a regression analysis was carried out on all of the synthetic sludge samples that have been tested, as shown below in Figure 9.

Figure 9: Regression analysis of shear strength and water content – all data

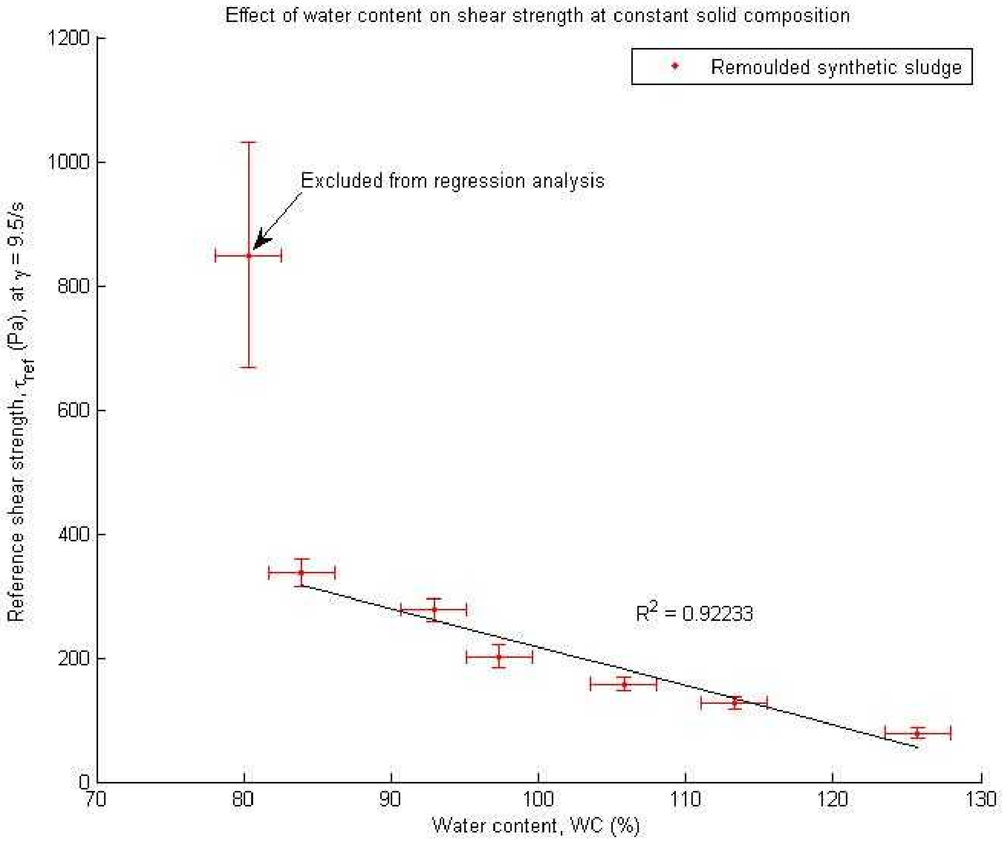


The large negative adjusted R-squared value indicates a weak correlation, and an ANOVA test shows it to be not significant at the 10% level. The probability of finding these results with no correlation between shear strength and water content therefore exceeds 10%.

The regression analysis was then repeated on a subset of data consisting of a group of sludges with the same solid composition but different water contents, as shown in Figure 10 below. An ANOVA test showed no significant correlation between shear strength and water content at the 10% level if all of the data points are included, however if the highlighted outlier is excluded, the regression is significant at the 1% level.

The high shear strength of the excluded data point at 80.3% water content may be explained by the lab observation that a void was formed behind the penetrometer during testing. Further investigation would be required to determine whether there is a step-change in readings at this point. If that were the case, it could be used to identify the critical water content above which a material behaves like a sludge rather than a soil, which would be useful when planning how to empty a latrine.

Figure 10: Regression analysis of shear strength and water content – single solid composition



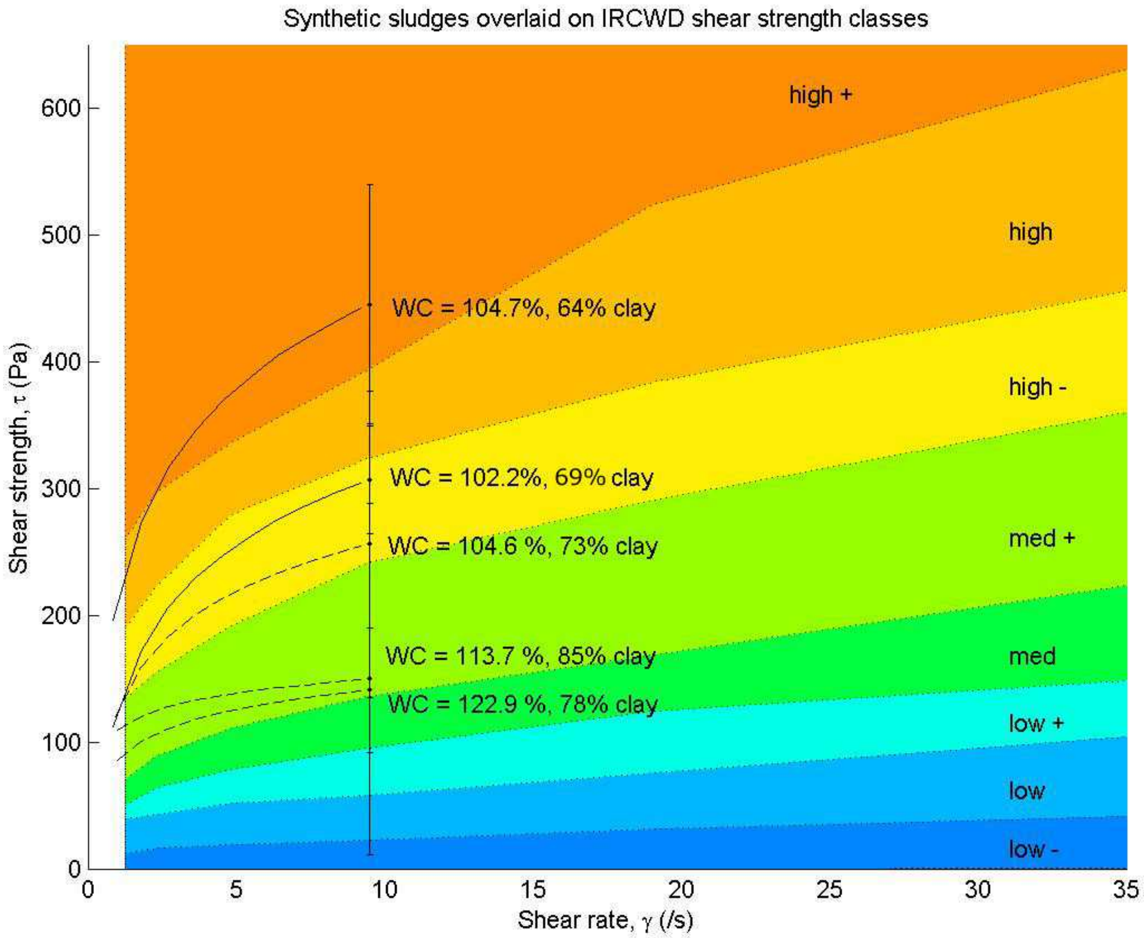
The difference in results of the two ANOVA tests suggests that any relationship between shear strength and water content in the Botswana data may be masked by the variability of pit latrine sludge. In addition to water content, multiple factors such as diet, anal cleansing methods, type of pit latrine and groundwater conditions on site [Strauss & Montangero, 2002] can all affect the physical characteristics of a sludge.

4.8.2 Effect of solid composition

After completing the first series of tests the sand was replaced with additional clay due to concern that the heavy sand particles would settle to the bottom, producing unwanted strength and density gradients in 'uniform' sludges.

The results from varying the solid composition of a two-component (compost-clay) sludge are presented below in Figure 11. An ANOVA table was used to generate the 95% confidence intervals shown in the plot and the regression lines of the two highest strength sludges were found to be significant at the 5% level. The remaining three compositions did not have significant rate-dependence and have been included in Figure 11 as dashed lines.

Figure 11: Effect of relative proportions of clay and compost on sludge strength



It can be seen from the strongest three strength profiles in Figure 11 that increasing the proportion of clay in a sludge, at approximately constant water content, reduces its strength. This can be explained by the fact that compost has a moisture content of ~90%, whereas clay is supplied in dry form. Therefore, at a given water content, less liquid water is added to a high-compost sludge due to the moisture in the compost. This results in compost-rich sludges having higher strength and appearing drier than clay-rich sludges of equal water content.

To separate the effects of water content and solid composition it may be more appropriate to express the sludge mix on the basis of the actual mass of constituents – ie the dry mass of clay and the hydrated mass of compost. Alternatively a water content based on 'free water' – ie the mass of water added to the mix, might produce more intuitive results.

The water content of the compost used in this investigation was found to vary considerably both within and between bags. This prevented accurate control of water content, as demonstrated by the 20% variation between samples of the same nominal water content in Figure 11. Unfortunately the standard water content test requires oven drying for 24 hours, so the sludge properties could not be verified and adjusted before testing. An attempt was made to use density as an indicator of water content, however the results of density testing were found to have a relatively high coefficient of variation (3.2%), making predicting water content impractical.

As a result of the difficulty had in determining the effect of solid composition, it was decided that a 70% clay, 30% compost sludge would be suitable for fluidisation testing, with shear strength controlled by adjusting water content.

4.8.3 Ball penetrometer calibration factor

Calibration of the ball penetrometer conversion factor, N_{ball}, against viscometer readings produced an average value of 14.4, as shown in Figure 7 of §4.7. This is significantly higher than the accepted value in the literature of 10.5 [eg. Ganesan & Bolton, 2010] for undisturbed soils, however it does lie within the range of 8-17 reported by Yafrate et al (2007) [Yafrate et al., 2007] for moderately sensitive soils.

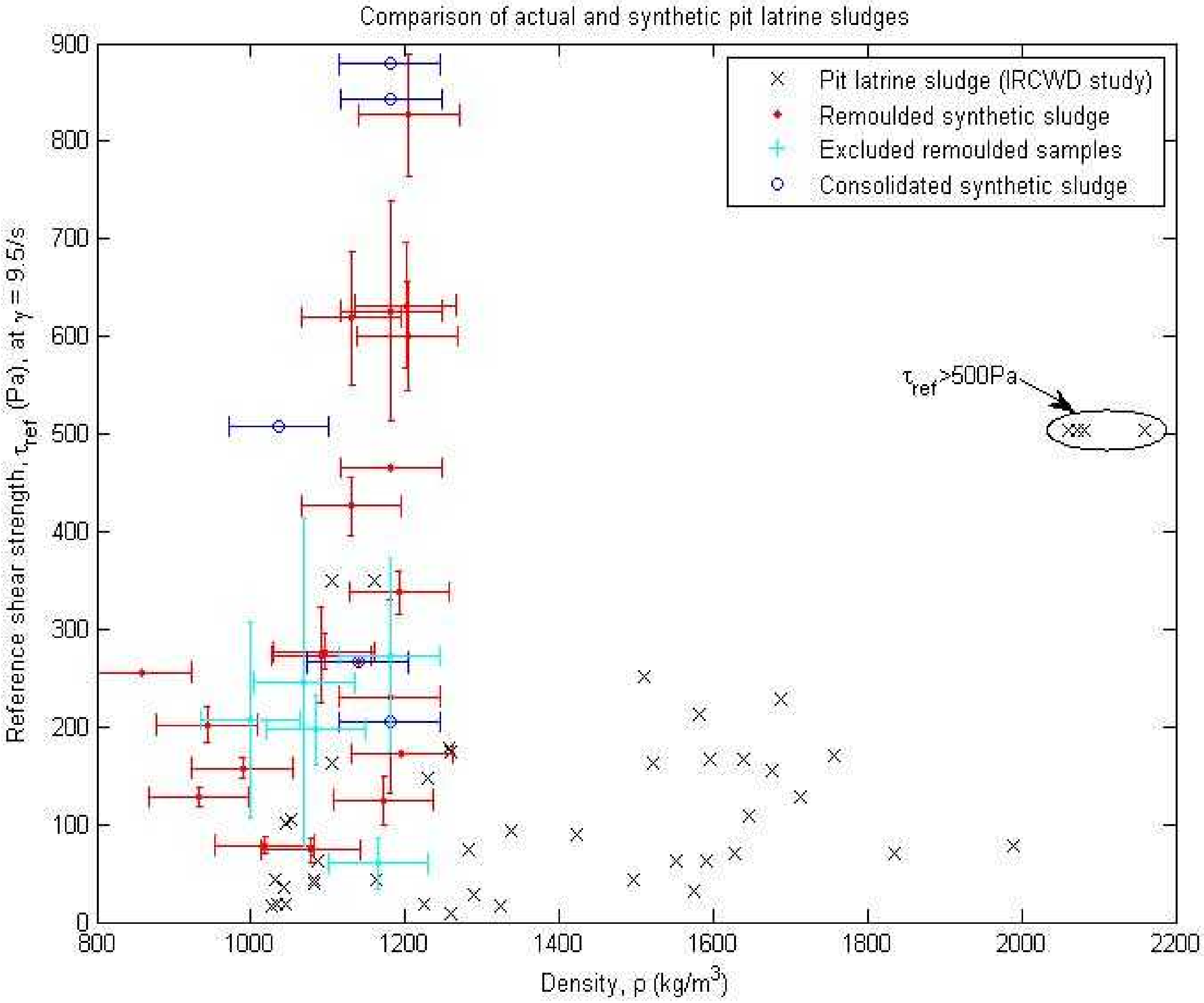
4.8.4 Comparison with IRCWD data

The undrained shear strength and density of the range of synthetic sludges produced in this investigation are compared with those recorded by the IRCWD in Figure 12 below. Two trends are evident - firstly that the synthetic sludge has a lower density than many reported from Botswana and secondly that the entire range of shear strengths from the IRCWD report has been covered.

A two-sample t-test was used to compare the mean density of the synthetic and pit latrine sludges. The difference of means was found to be 313±126kg/m^3, equivalent to 1.3 standard deviations, which is significant at the 1% level. Full details are included in §11.3 of Appendix A. It is also noted that the highest synthetic sludge density was only 1200kg/m^3, compared to a maximum of almost 2200kg/m^3 observed in Botswana.

The difference in densities is caused by the synthetic sludge's relatively high proportion of compost (30%), which has a low bulk density of ~1200kg/m^3 due to its organic nature. This was noted at an early stage in the investigation, however it was decided that replicating the range of shear strengths was more important than matching the densities. This is because shear strength controls whether a sludge can be fluidised at any scale, whereas the effect of density is also a function of the height of the vacuum tank above the sludge and is therefore affected by the reduced scale of this investigation. The implications of this investigation's findings for emptying a full-scale latrine are discussed in §6.1.3.

Figure 12: Comparison of physical properties of synthetic and pit latrine sludges



A similar t-test could not be carried out on the shear strengths recorded, as these are not random samples from a population, but instead were controlled during the investigation. Although the vast majority of sludges tested in Botswana had strengths less than 400Pa, it should be noted that the IRCWD report records the highest strength sludge that was removable by a given vacuum tanker – in some cases using up to 30m of suction hose, with significant additional head loss. The Botswana data cannot therefore be treated as representative of the strengths of pit latrine sludges, but rather the limits of the technologies tested in those trials. This highlights one of the main problems associated with top-down pit emptying – that significant amounts of consolidated sludge are left at the bottom of pits which progressively fill up and become unusable.

A number of unlined or poorly-lined pits were reported to have partially collapsed resulting in a very sandy, high strength sludge. Although not identified in the report, this could explain the anomalous group of stong sludges highlighted in Figure 12.

4.8.5 Synthetic sludge 'recipe'

This investigation has demonstrated that a simple two-component synthetic sludge can cover the full range of shear strengths observed in actual pit latrine sludge by adjustment of water content. The development of a 'recipe' for different types of sludge has been limited by the variability of the compost used – simply replicating the nominal composition of a sludge in this investigation will not necessarily produce the same strength of material. The lack of an instantaneous test for water content ensures that a certain amount of experimentation will always be required to determine suitable sludge mixes.

4.8.6 Control parameters

4.8.6.1 Strength

Throughout this investigation undrained shear strength has been used as the control parameter for slugdge strength to determine whether it will flow under suction. This would appear to be in contrast to the IRCWD report which used a viscometer to characterise samples and quoted 'scale readings', rather than absolute strengths. This was due to uncertainty over calibration factors and the complicated non-Newtonian behaviour of sludge, as discussed in §3.3 and §3.4. However, these viscometer 'scale readings' are in fact proportional to undrained shear strengths, despite being referred to as viscosities thoughout.

Although apparently arbitrary, the different viewpoints perhaps stem from the fact that water and sanitation are often dealt with jointly by the same people, making it seem natural to approach the problem of pit latrine sludge as one of hydraulics and fluid mechanics. In contrast, as this investigation was based in the Schofield Centre of the Geotechnical Research Group, it was equally natural to treat the sludge as a weak soil, rather than a strong fluid.

However, this different approach to the problem has yielded unforeseen benefits, not least by enabling the researcher to draw on the advice and of geotechnical experts. Where pit latrine sludge was previously seen as an unusual, non-Newtonian fluid, whose viscosity was difficult to quantify in absolute terms, here it is instead treated analagously to a very weak marine sediment. Unlike pit latrine sludge, sub-sea sediments are a popular area of research due to their relevance to the offshore oil and gas industry, and complicated rate-dependant strength behaviour is widely reported in geotechnics. Conceptually it also makes sense to treat the sludge as a solid soil rather than a fluid – if it behaved as a fluid then fluidisation would not be required and emptying latrines would be a far easier proposition.

4.8.6.2 Density

Although the strength of a sludge is an important parameter controlling whether it will flow towards a suction hose, density is equally important in determining the depth to which a pit can be emptied. Unfortunately density is often overlooked and there are numerous pit emptying devices with unnecessarily high tank mountings, increasing the lift height required to remove the sludge and therefore the suction required. The IRCWD report focused on the 'viscosity' or shear strength, while simply noting in passing that a higher density will also decrease 'pumpability'.

4.8.7 Laboratory procedure

The ball penetrometer was calibrated using a viscometer where possible, as described in §4.7. Unfortunately a typical sludge strength of a few hundred pascal lies near both the lower limit of the penetrometer's sensitivity and the upper limit of the viscometer's range, resulting in problems gathering reliable data for the weakest and strongest sludges respectively.

Additionally, the viscometer could not be connected to a datalogger, which meant that readings had to be recorded manually. This made it more difficult to distinguish time-dependent trends from noise in the data, and also made post-processing to remove noise infeasible due to the small number of readings. The lab procedure would be significantly quicker and produce less variable data if a viscometer designed for measuring pastes or gels, coupled with an electronic datalogger, were used to calibrate the ball penetrometer. These devices tend to use a vane-type spindle, which would therefore reflect the geotechnical convention of calibrating full-flow penetrometer tests against vane shear tests.

An alternative method for calibrating the ball penetrometer (ie calculating Nball) would be to carry out a series of fall cone tests, from which the undrained shear strength can be deduced. These tests are typically conducted on clays but may produce meaningful data for the synthetic sludge despite its inhomogeneous nature.

5 Phase II – Sludge fluidisation

5.1 Introduction

The second phase of testing investigated the fluidising effect of injecting water and compressed air into the bottom of a pit of sludge. This could greatly expand the range of sludges that are removable by vacuum-based systems such as the Vacutug. Remoulded sludge was used to demonstrate the efficacy of dilution and then a series of consolidated sludges were fluidised using just air to investigate the decrease in strength from remoulding alone.

5.2 Materials and methods

Fluidisation tests were done in a 100L bucket, with a concrete mixer used to batch the sludge. A one-fifth scale Vacutug, fitted with a 75mm diameter suction hose and powered by a 2kW vacuum cleaner was made by Manus Coffey Associates. The system produced a suction of 0.3bar, and pressure of 0.27bar. An additional vacuum cleaner could be connected in series to generate 0.45bar suction, but was not modified to blow. The vacuum cleaners had inbuilt thermistor-controlled overheat protection. The apparatus is shown below in Figure 13.

Figure 13: Laboratory apparatus for fluidisation testing

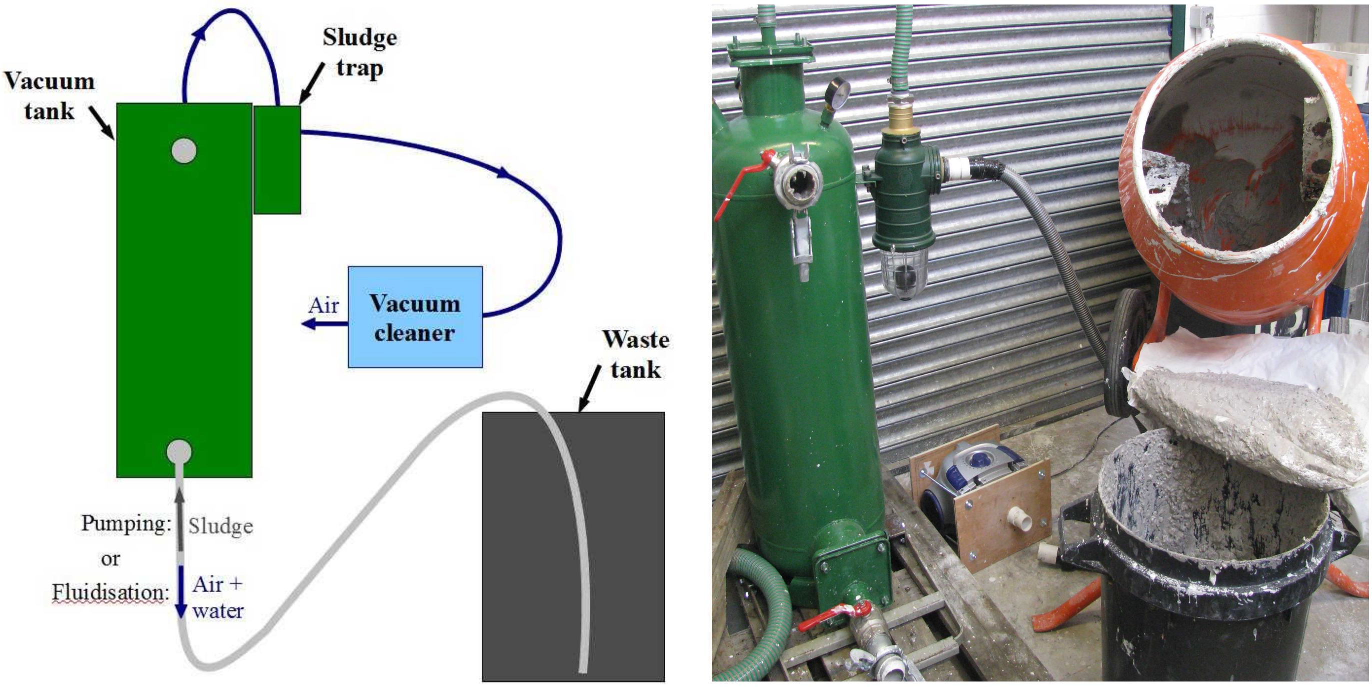


Figure 13(a): Schematic diagram

Figure 13 (b) Photograph

5.3 Theoretical considerations

There are two principal effects to consider in the fluidisation process – dilution and remoulding. Dilution decreases shear strength by increasing the water content, whereas remoulding decreases shear strength at constant water content as a result of mechanical agitation that breaks down the structure of the material.

5.4 Experimental design

The time taken to pump out the contents of a pit latrine is negligible in comparison to that required for washing down equipment and transporting the sludge for disposal [Coffey, M., p*ers. comm.*, Nov. 2010]. It was therefore decided that percentage removal of sludge should be optimised, rather than the time taken for emptying. The key control variables are water injection volume and pressure, and the number of fluidisation cycles. Parallels with offshore engineering [Bienen et al., 2009] suggest that the volume of water injected, rather than the injection pressure, would prove critical, therefore water volume was identified as the key parameter to optimise. This is also an important criterion for operation in urban informal settlements where water may be either unavailable or unaffordable[UN-Habitat, 2010] and therefore any use for waste disposal should be minimised.

An 'unpumpable' high+ strength sludge was selected for the dilution trial and characterised according to §4.6. Water was then added in small increments to determine the point at which the sludge became 'pumpable' and that sludge was then characterised. In the final series of tests, submerged sludges were left to consolidate for two weeks, producing a material more representative of the contents of a pit latrine, to investigate the effect of air-blown remoulding. The two-week period was chosen as it was expected that significant consolidation would occur and there would be sufficient time to do multiple tests.

5.5 Laboratory procedure

I. The strength of the consolidated sludge is tested 'in-situ' with the ball penetrometer.
II. The depth of sludge prior to fluidisation is measured using a dipstick and tape.
III. The pump is set to blow and turned on, developing pressure within the vacuum tank.
IV. The valve is opened and a burst of compressed air is forced into the waste tank.
V. The valve is closed, the pump switched off, the suction hose removed and the sludge strength tested again 'in-situ'.
VI. The pumps are connected in series, set to suck and turned on.
VII. The valve is opened and sludge may flow into the hose. If 'pumpability' has been achieved, the vacuum tank will fill with sludge and the waste tank will empty.

VIII. The depth of any residual sludge in the waste tank is recorded and a sample taken for characterisation.

IX. The waste tank is covered and the vacuum tank emptied under pressure.

X. A sample of the fluidised, remoulded sludge is characterised.

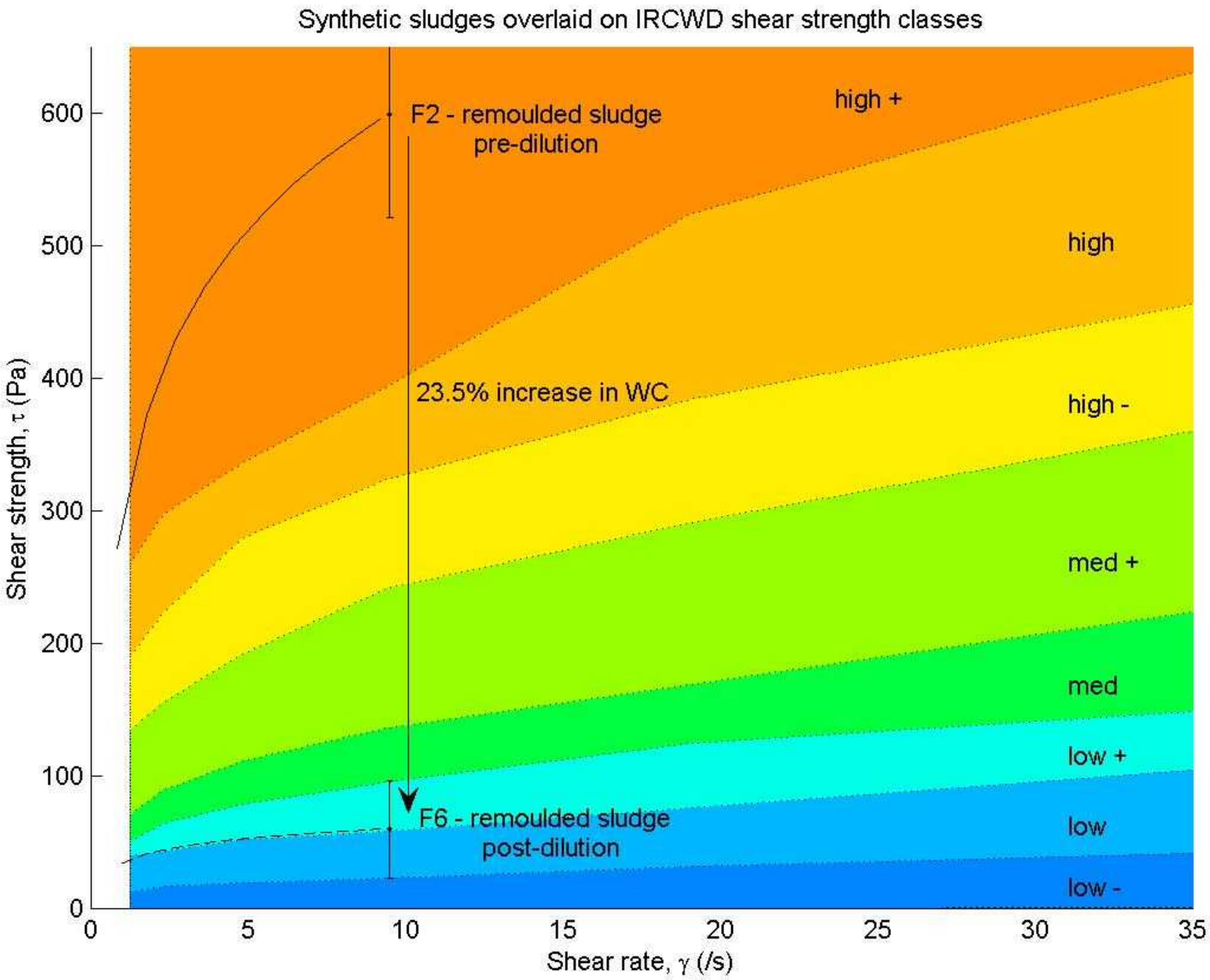
XI. Once all testing is complete, the inside of the vacuum tank and hoses are rinsed twice by sucking up a bucket of water and then discharging it.

5.6 Results & Discussion

5.6.1 Dilution

Results from the dilution tests on remoulded sludge are presented below in Figure 14.

Figure 14: Effect of dilution on remoulded sludge



It is evident that a dramatic decrease in strength has been produced by dilution, and a previously 'unpumpable' high strength sludge was successfully emptied using a single vacuum cleaner, with a static head difference of 1.5m. However, it should be noted that this required an increase in water content of 23.5%, which would equate to a volume of around 350L for a

1m^3 pit latrine.

The results from this phase of testing should be treated more as a 'proof of concept' that the process of injecting water followed by compressed air does effectively mix the sludge. The fluidisation effect seen here is an extremely conservative worst case scenario, negating the effect of remoulding, however it does demonstrate that even the strongest of sludges can be rendered pumpable after sufficient dilution.

5.6.2 Air-blown remoulding

The system's potential is better indicated by tests on consolidated sludge, which is more representative of the material in pit latrines, as shown below in Figure 15. The consolidated samples have strength gradients with depth and were therefore tested 'in-situ' making calibration against viscometer data and the calculation of confidence intervals impractical.

Figure 15 – Effect of air-blown remoulding on consolidated sludge, at depth 160mm

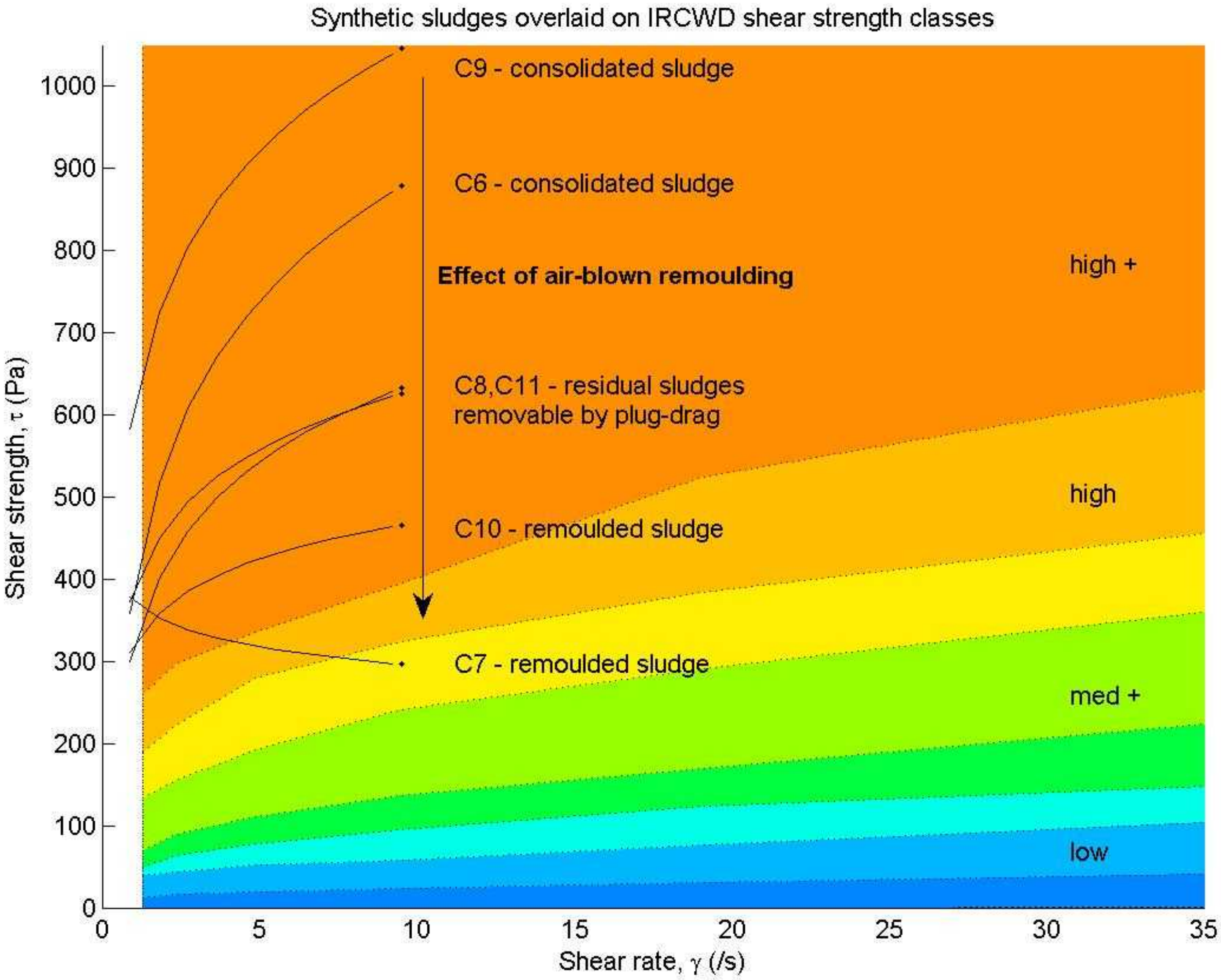
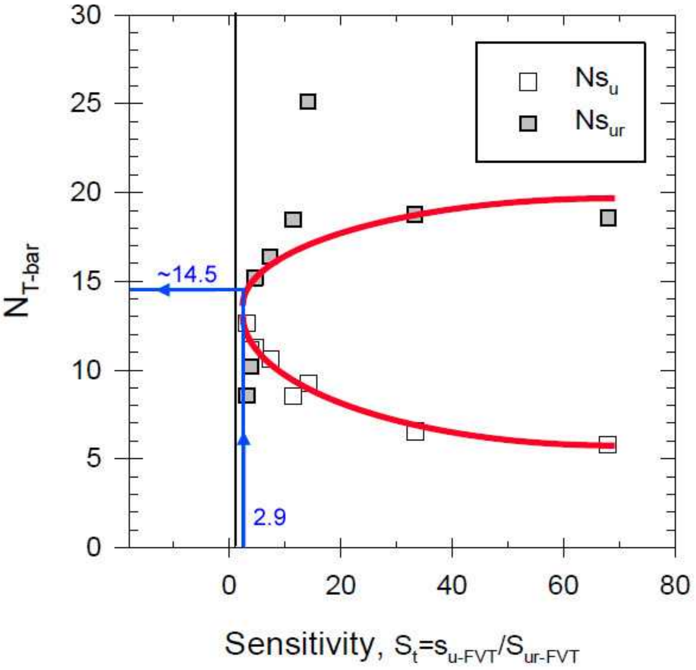


Figure 15 demonstrates that air blown remoulding alone can reduce shear strength by a factor of 2.9. This is compared with data from Yafrate et al. (2007) in Figure 16 below, which would suggest N_{ball} ~14.5 which agrees well with the mean value of 14.4 found here.

Figure 16 – Estimate of N_{ball} from sensitivity, using figure fromYafrate et al. (2007)



A sensitivity of 3 is relatively low[BS14688] and it is therefore unlikely that the synthetic sludge would overestimate the fluidising effect of remoulding.

The presence of a strength gradient in the consolidated samples means there is also potential for mixing of weak sludge near the surface with stronger sludge at depth. This would produce a more homogeneous material with strength increasing near the surface and decreasing at depth. The opposite effect was observed (see Figure 18 (c) below), suggesting minimal vertical mixing of the sludge and a decrease in strength caused by remoulding.

After pumping the fluidised sludge out of the tank, residual material of intermediate strength remained around the edges, as shown in Figure 17 below.

Figure 17: Residual sludge in tank after fluidisation and emptying

This may be partly explained by the fact that the suction hose was inserted from the top of the tank and therefore disturbed the sludge in the centre of the sample. However it is also likely that slugs of air bubbles from the suction hose spread over a wider area as they rise through the sludge, therefore fluidising a greater proportion of the sludge near the surface.

This residual sludge was found to be removable by operating the system in 'plug drag' mode, repeatedly "raising and lowering the hose inlet in and out of the sludge" [IRCWD, 1985, Table 2.1, p10]

The effect of air-blown remoulding at different depths is demonstrated in Figure 18 below, which compares strength profiles before and after remoulding. Figures 18 (a) & (b) show strength profiles before and after fluidisation, and Figure 18 (c) plots the percentage change in shear strength due to air-blown remoulding.

<u>Figure 18: Strength profiles with depth showing effect of fluidisation</u>

<u>Figure 18(a) – Pre-Fluidisation</u> <u>Figure 18(b) - Post-Fluidisation</u>

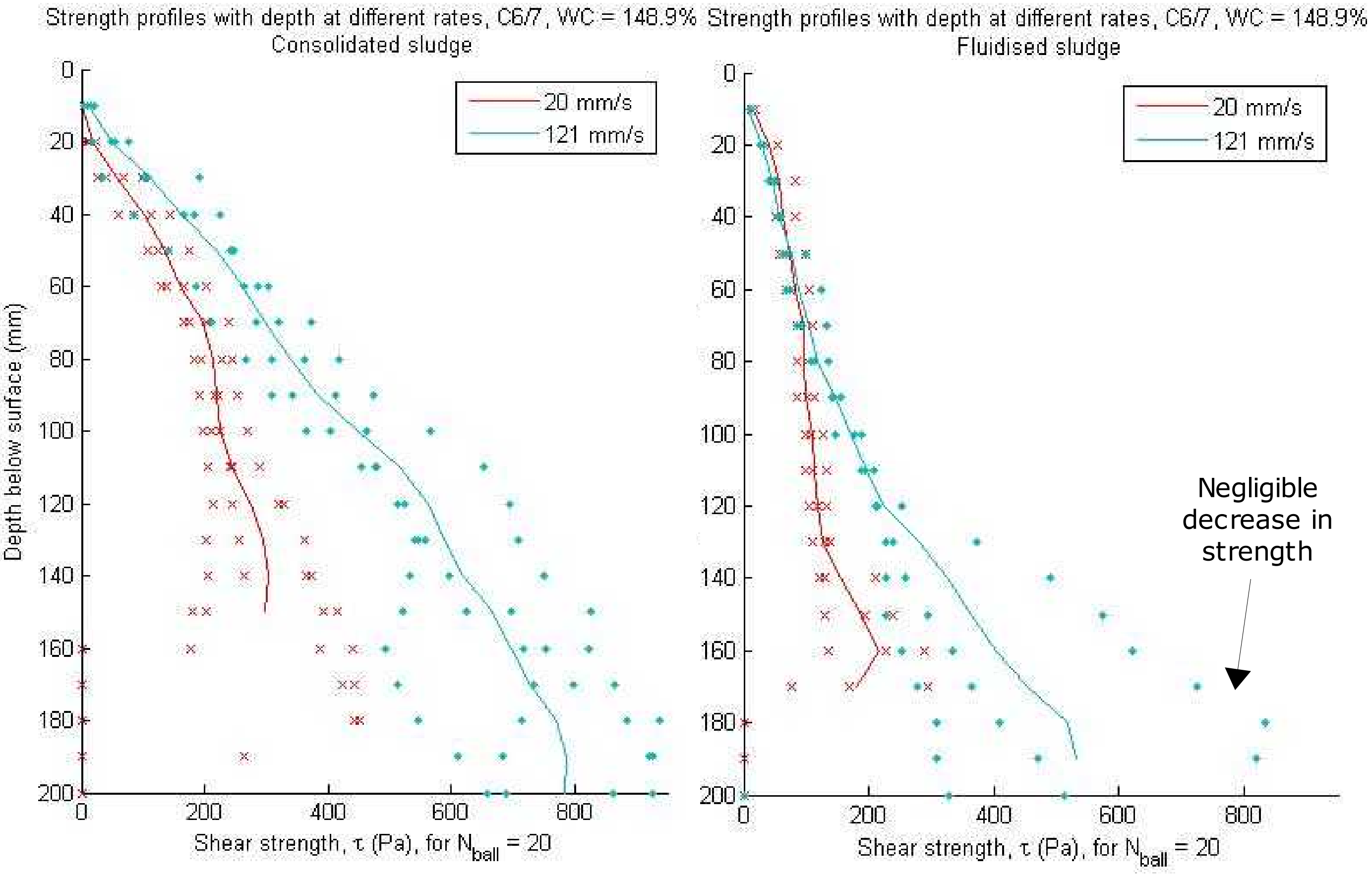
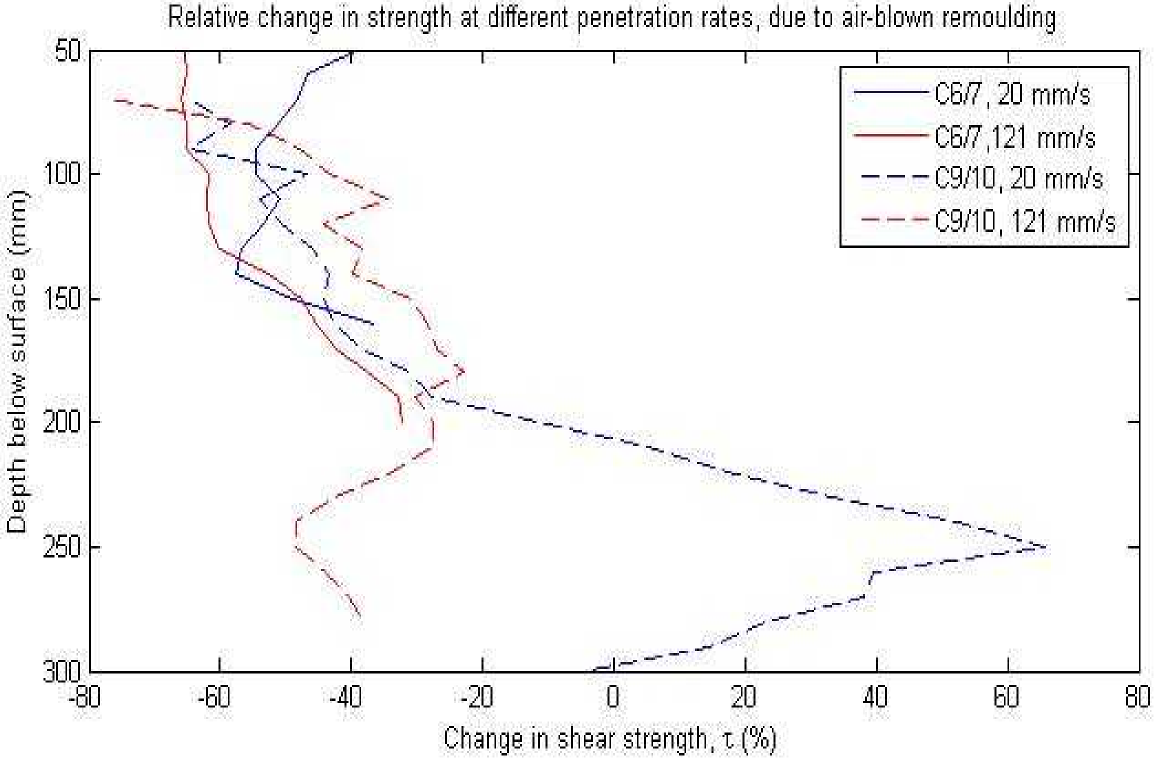


Figure 18(c) – Percentage change in strength from fluidisation



Data is presented for two shear rates – 20mm/s which is often used as a reference shear rate in the literature and 121mm/s which is equivalent to the shear rate quoted in the Botswana report, as shown in §4.3.2. Although the data is variable, it is clear from Figure 18 (c) that the shear strength of the top 150~200mm of the sample is reduced by 30~70%, whereas below this depth the effect of fluidisation is less pronounced. This is reinforced by Figure 18 (b) which includes a single test for which there was negligible decrease in strength below 150mm.

Different attempts made to pump sludge with the equipment available in the lab are summarised in Table 1 below and the derived limits are plotted on Figure 25 in §6.4.

Table 1: Summary of sludge pumping

ID	τ_{ref} (Pa)	# Pumps	Emptying mode	Laboratory observations
F3	273	1	Continuous	1.5m head – suction hose part filled (~5% sludge volume), visible suction cone
F4	125	1	Continuous	1.5m head – partial emptying, 0.3m static head – complete emptying
C1	508	1	Continuous	1.5m head – suction hose part filled (~5% sludge volume), visible suction cone
C2	256	1	Continuous	1.5m head – partial emptying (~30% sludge volume)
C2	256	2	Continuous	1.5m head – complete emptying (just)
C4	341	2	Continuous	1.5m head – suction hose part filled (~20% sludge volume)
C5	172	2	Continuous	1.5m head – partial emptying, overheat cutout
C7	231	2	Continuous	0.3m head – complete emptying of top half of tank leaving residual sludge
C8	632	2	Plug drag	0.3m head – complete emptying
C10	466	1	Continuous	0.3m head – failure to empty – suction hose did not fill
C10	466	2	Continuous	0.3m head – complete emptying of top half of tank leaving residual sludge
C11	626	2	Plug drag	0.3m head – complete emptying
C12	827	2	Plug drag	0.3m head – failure to empty – suction hose did not fill

It was observed that if sludge were pumpable it would start to flow within the first few minutes of suction and the amount of time required to empty the waste tank was small in comparison to that required for the whole process. There is therefore little scope for optimising the fluidisation process to speed up pit emptying.

The highlighted sludge, C1, has a strength that was recorded as 'unpumpable' for a single pump on other samples. This can be explained by a combination of factors – firstly that a surface crust formed by dessication of the sample made measurement of the strength of the weak sludge just below the surface difficult. The quoted strength is therefore that of the consolidated sludge around the perimeter at the bottom of the tank. The sludge in the centre would have been disturbed by the suction hose and therefore have lower strength.

Additionally, when the hose is inserted it is filled with a plug of strong sludge from the bottom of the tank, which is removed in 'plug-drag' mode when suction starts. This may have then allowed weaker sludge from the surface to be drawn down into the observed 'suction cone'. This would suggest that the recorded strength is not representative of the sludge removed.

Testing of the actual material removed, rather than the 'unpumpable' sludge that remains, could identify performance limits more precisely, but would take longer as the device would need to be emptied for every test.

6 Discussion: Implications for practice

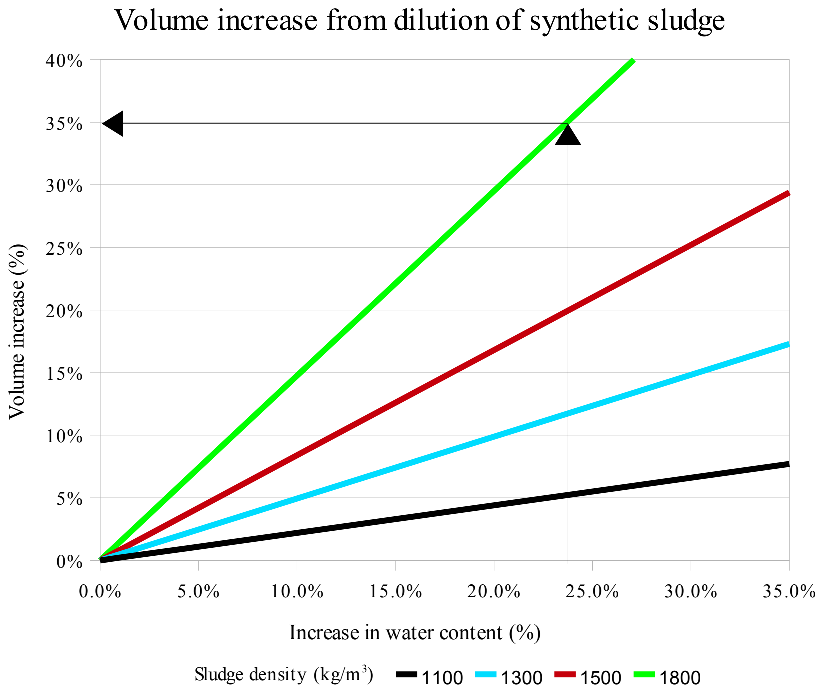
The preceding sections have demonstrated that the full range of strengths observed in pit latrine sludge can be replicated using synthetic sludge and that both dilution and air-blown remoulding have significant fluidising effects under laboratory conditions. In this section the implications for emptying actual pit latrines are discussed.

6.1 Sludge fluidisation

6.1.1 Dilution

The investigation into fluidisation and pit emptying using remoulded sludges found that all tested strengths of sludge could be made 'pumpable' by sufficient dilution, establishing an upper bound on the amount of water required for fluidisation. The resulting 23.5% increase in water content would increase volume by 35% for a sludge of density 1800kg/m^3 as demonstrated in Figure 19 below.

Figure 19: Increase in sludge volume from dilution



This level of dilution may not be feasible, as the expense of emptying a pit latrine means that they are typically filled until they become unusable, with the sludge level 30~50cm below the covering slab [Jere et al., 1995], leaving insufficient space for a large increase in volume. Additionally, this level of dilution would require 350L water per cubic metre of sludge. Although poor quality water could be used, the only option available in many urban informal settlements would be to use potable water bought from vendors.

One potential solution would be to first empty some of the weak supernatant fluid from the top of the pit and then use it to fluidise the remaining sludge. This would avoid wasting valuable potable water for pit emptying, while at the same time eliminating the increase in volume. However, the supernatant fluid contains the most recently deposited faecal matter and is therefore heavily contaminated with pathogens [Reed, B., *pers. comm.*, March 2011], so this recirculation process could negate some of the health and safety benefits of emptying the pit after mixing its contents. It would also require an additional attachment point at the top of the pit for the vacuum tanker.

It has been widely reported in the literature [Strauss & Montangero, 2002] that the slowest and most expensive part of pit emptying is transporting the sludge to its disposal point. This can be mitigated somewhat by using local sludge transfer stations, however any increase in sludge volume is clearly undesirable as it would increase transport costs and encourage pit emptiers to dump sludge illegally into the local environment.

6.1.2 Air-blown remoulding

It can be seen in Figure 20 below that there was significant 'splatter' of sludge during fluidisation, which could pose a health hazard if sludge were to escape through the squat-hole.

Figure 20: 'Splatter' of sludge during remoulding

Figure 20 (a) – Covered for fluidisation

Figure 20 (b) – Splatter on lid

A pour-flush latrine would not suffer from this problem, but an air vent would need to be included to allow presssurised air to escape.

When predicting the required frequency of pit emptying it should be noted that an annulus of consolidated sludge is expected to form around the inbuilt suction pipe at the bottom of the tank, reducing the effective volume of the latrine for holding fresh sludge.

The laboratory trials also suggest that it may be possible to fluidise 'normal' latrine pits that do not have an inbuilt suction pipe, by lowering the hose through the squat hole and pushing it as deeply into the sludge as possible. Although unlikely to be as efficient, this is what was done in the laboratory and there is no evidence to suggest that it would not work on a real latrine.

However, it should be noted that one of the major benefits of developing a pit with external connections for the suction hose is the ease and cleanliness with which it can be emptied, saving time, inconvenience and water as well as reducing the public health risk by preventing fouling of the superstructure and squat plate during emptying.

6.1.3 Effects of scale

The laboratory investigation was necessarily conducted at reduced scale, therefore dimensional analysis has been used to predict how the results may differ at full scale in an actual pit latrine. The following dimensionless groups are proposed to be constant regardless of scale, therefore by keeping them constant comparable results should be obtained at full scale. Further details of calculations are tabulated in §11.4 of Appendix A.

(1) $\frac{Q}{D^2\sqrt{2gL}}$ - As suggested in reference to air lift pumps [Parker, 1980]

(2) $\frac{L}{D}$ - Aspect ratio of suction pipe

(3) $\frac{p}{\rho g L}$ - Suction pressure normalised by static head difference

(4) $\frac{p}{s_u}$ - Injection pressure normalised by undrained shear strength of sludge

(5) $\frac{H}{\sqrt{A}}$ - Aspect ratio of sludge in pit latrine

(6) $\frac{D}{\sqrt{A}}$ - Relative sizes of suction pipe and pit latrine

The first three parameters relate to whether sludge will flow in the pipe – (1) describes the effect of head loss on flow rate, (2) affects pipe friction and (3) determines whether there is sufficient suction to pump the sludge surface up and out of the latrine.

The time to empty the tank was found to be negligible to that required for setup and rinsing down the equipment, therefore (1) cannot been used to predict changes in pit emptying time. Parameter (2) suggests that at full scale a 3.3m long pipe could be used without increasing pipe friction. However, (3) shows the critical importance of sludge density and static lift height when emptying pits with a three-fold increase in suction from that required at lab scale. This relates to an impossible 1.35 bar for the two-pump system, so any practical system is likely to be critically affected by static head limits.

In contrast, (4) gives a measure of whether fluidisation of the sludge will be possible for a given air pressure and it can be seen that this is constant at all scales. Therefore if a sludge can be fluidised in the lab, it will also be fluidised at full scale.

The final two parameters control the fluidisation mechanism in the pit – one can envisage that the three dimensional spread of air through the sludge may be affected by both the relative size of the pipe aperture and the shape of the tank. Parameter (5) was controlled in the laboratory to match the proposed UN-Habitat pit design. The change to a full-scale system will decrease (6) by a factor of 2.3. This may reduce the cone angle of the zone of fluidised sludge, producing a more localised effect that fluidises a smaller volume of sludge.

6.2 Extraneous matter in pit latrines

The synthetic sludge produced in this study is an idealised representation of the material found in most latrines. A significant problem that affects many mechanical pit emptying technologies is the presence of extraneous matter such as bottles, plastic bags or batteries in the sludge, causing blockages while emptying. An example of this can be seen below in Figure 21 showing sludge that has been manually dug out of pit latrines in South Africa.

Figure 21: Extraneous matter in pit latrine sludge.

Photo courtesy of Dave Still, Partners in Development

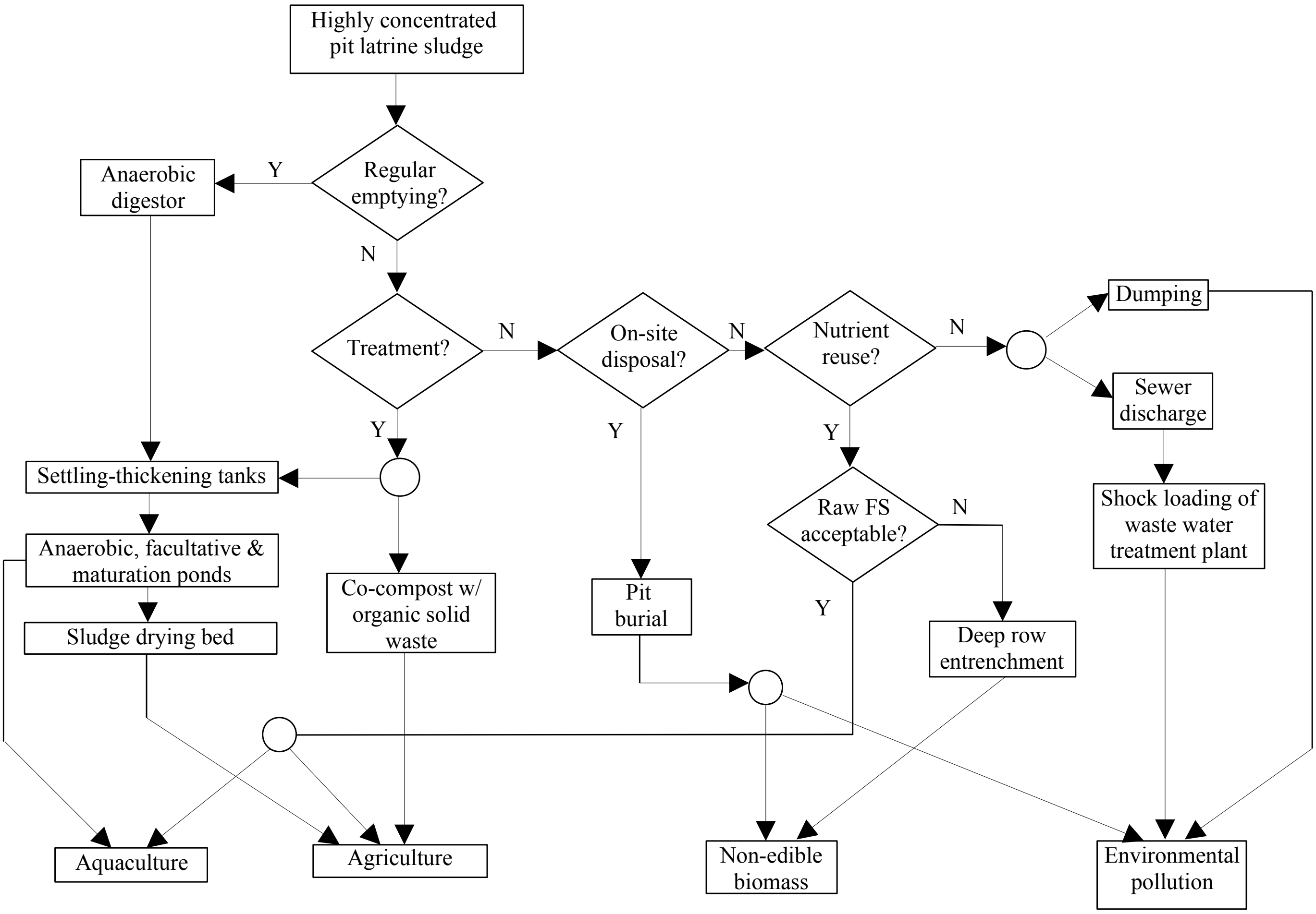
The sludge may also contain significant quantities of newspaper, which is sometimes used for anal cleansing, and its effect could be investigated by including newspaper or plastic in the synthetic sludge.

The IRCWD report reported blockages in the suction hose occuring "occasionally more than six times per pit."[IRCWD, 1985, p28] Blockages from solid objects such as bottles can be avoided by covering the end of the hose with a loose mesh, however this may then become blocked with paper or plastic. This highlights another advantage of the proposed UN-Habitat pour flush latrine, in which it would not be possible for extraneous matter to enter the pit.

6.3 Sludge treatment and disposal

The need to empty pit latrines in order to provide sustainable improved sanitation in urban areas is undisputed, however it is important to consider the various effects that such a system might have in an unplanned settlement. Various sludge treatment and disposal options have been considered, as summarised below in Figure 22, which mostly focus on solid-liquid separation [Strauss & Montangero, 2002].

Figure 22: Disposal options for concentrated faecal sludge from pit latrines



Unfortunately there is currently no standard common practice, or recognised best practice, for the disposal of pit latrine sludge. In Kibera, Nairobi, it is often discharged into the sewerage system (around one third of the pit-emptiers are licensed to do this [Scott, no date]), whereas in Dar es Salaam pressurised discharge into a settlement lagoon or landfill site is common [Coffey, M., p*ers. comm.*, Nov. 2010] and in Accra it is dumped into the sea [Boot & Scott, 2008].

Disposal of pit latrine sludge to an existing wastewater treatment plant is unacceptable and uneconomical because even a large plant can't treat more than a few loads per day, at significant expense [Bhagwan et al., 2008], as it has not been designed to handle such highly concentrated waste. The Durban wastewater treatment works had to be shut for a number of days after receiving a large shock load of latrine sludge, resulting in untreated sewer discharge into the environment [O'Riordan, M., p*ers. comm.*, Nov. 2010].

There is great potential for the reuse of nutrients from faecal sludge in agriculture, as the resource value of human excreta compares very favourably with both cow manure and compost [Strauss, 1985], however its use is subject to social acceptability. In China it is traditional to use treated nightsoil as fertiliser[Chao, 1970], whereas PiD have developed a pelleting machine to make pasteurised pit latrine waste socially acceptable for use as fertiliser in South Africa [Still, D., *pers. Comm., March 2011*]. Deep-row entrenchment of untreated sludge is also being trialled as a slow-release fertiliser for non-edible biomass plantations [Still et al., 2010].

The fluidisation process suggested by this investigation would increase the solids content and volume of sludge that can be removed from pits mechanically, as currently only the water-like supernatant is pumped out. This could pose a problem as “Appropriate low-cost treatment options for such FS [faecal sludge] need as yet to be developed.”[Koné & Strauss , 2004] Nevertheless, it should be noted that the older, consolidated sludge from the bottom of the pit is partially decomposed and poses less of a public health hazard [Sharpe, 2010], therefore even if it is dumped directly into the environment it would be an improvement over the current practice of dumping only the most contaminated sludge that is pumped from the top of the pit.

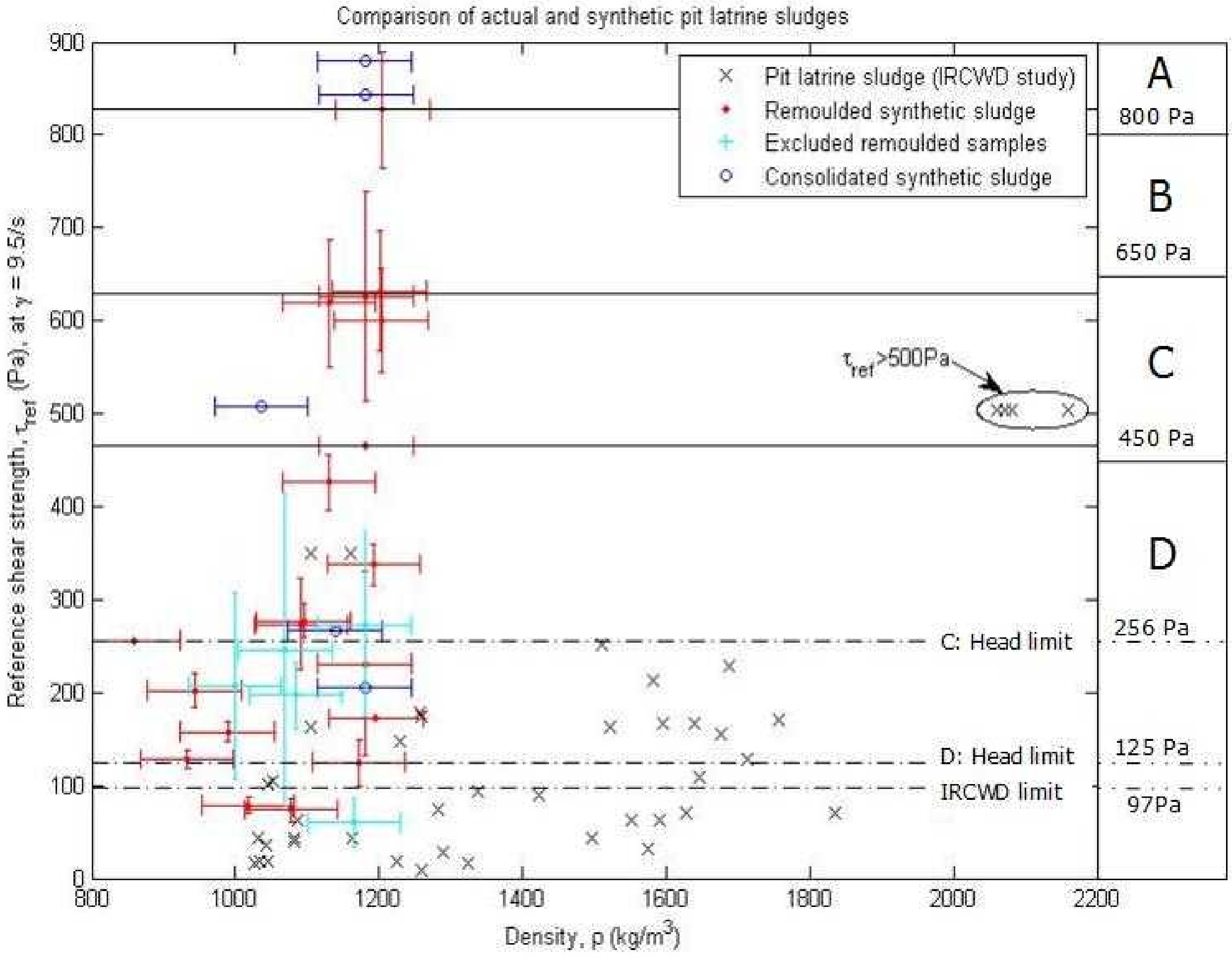
The increased volume of sludge extracted could however lead to more environmental dumping if suitable haulage and treatment processes are not implemented. There is a particular need for the development of decentralised treatment [Strauss & Montangero, 2002] or transfer stations - for example the Vacutug is limited to only 5kph, making sludge transport the most time-consuming, and therefore costly, part of the process. To prevent indiscriminate dumping it is important that innovative management systems are developed so that pit emptiers can be reimbursed rather than charged for delivering sludge to treatment works [Strauss & Montangero, 2002; Newton, 2010].

6.4 Sludge classification

An important part of this investigation is to make recommendations on how different 'classes' of pit latrine sludge could be categorised in the field. It would not be feasible to take the delicate and expensive laboratory equipment used here into the field to collect further data on actual faecal sludge. Furthermore, if a significant database of knowledge on the physical properties of pit latrine sludge is to be developed, then that data will need to be collected by the pit emptiers themselves rather than in isolated scientific studies. Sludge testing must be of benefit to pit emptiers and it is therefore proposed that sludges are classified according to the emptying methods and equipment required.

The data from Table 1 in §5.6.2 has been overlaid on all available data for synthetic and pit latrine sludges, to create the class boundaries shown in Figure 23 below.

Figure 23: Proposed sludge classification



It can be seen from Figure 23 that the static head limits for emptying are achieved at significantly lower shear strengths than the corresponding sludge class boundaries. This demonstrates that sludge density is even more important than previously considered when sucking over short distances, as relatively strong sludges can be pumped provided that no static lift is required. The height over which the sludge must be lifted should be minimised by positioning the vacuum tank downhill from the pit latrine where possible – this could be particularly relevant in informal settlements built on steeply-sloping marginal land, such as Kibera in Nairobi.

Comparison of the reported limit from the Botswana trial with the data from this investigation would suggest that the IRCWD study was operating at close to the maximum density sludge that could be lifted from the pit. This is further reinforced by the estimated required increase in suction pressure to empty a pit at full scale, as discussed in §6.1.3.

Whether the Botswana data was also representative of the maximum pumpable shear strength is debatable – the strength limit of 'pumpability' was found to be much higher in this study, but that is partly due to the reduction in head loss from using a shorter suction hose. One advantage of developing a small system is that it will have improved access in the narrow streets of informal settlements, enabling shorter suction hoses to be used, and stronger sludges to be removed.

The IRCWD report did note that crews were occasionally embarassed and wasted time looking for non-existant blockages when a lack of static head caused pit emptying to cease. However, it would appear that the shear strength of the sludge remaining in the pit was recorded, regardless of whether the sludge was not flowing towards the pipe or could not be lifted out of the pit. It would certainly be harder to determine the difference in a dark underground pit than in a bucket in the laboratory.

6.5 Implications for vacuum-based PETs

6.5.1 A low cost alternative

The successful conversion of 'Class A' strength sludges into 'Class C' material by air-remoulding alone has a number of important implications for vacuum-based pit emptying technologies. Firstly, it confirms the findings of the UN-Habitat trial discussed in §2.2, that the range of sludges removable with vacuum-based systems can be greatly extended by fluidisation, which would help prevent the gradual accumulation of 'unpumpable' sludge in pit latrines.

Perhaps more importantly though, it serves as a 'proof-of-concept' for the use of vacuum cleaners to power mechanical PETs. The maximum vacuum head of the ALH and Calabrese tankers tested in Botswana was 0.5bar – a marginal increase on the 0.45bar achieved using two vacuum cleaners in series, despite their inflation-adjusted cost of ~$60,000 today[2].

Previous attempts to develop 'low-cost' technologies, such as the UN-Habitat Vacutug, have been hampered by the use of sliding vane pumps. Despite being significantly cheaper than full-scale vacuum tankers, they remain unaffordable to entrepreneurs in informal settlements. The combination of heavy use and limited non-essential maintenance also results in significant wear and loss of suction performance after a few years, with replacement pumps costing ~$600 [Coffey, M., *pers comm.*, May 2011].

In contrast, the pair of 2kW vacuum cleaners used in this investigation cost €50 each and can be readily modified to both suck and blow. Although there may be some loss of performance with time, the availability of vacuum cleaners throughout the world would allow a poorly performing 'pump' to be easily and affordably replaced. This may enable entrepreneurs to start their own pit-emptying businesses, as crucially the cost of replacing the 'pump' could be covered by pit-emptying fees, unlike the Vacutug where the long-term performance is often dependent on municipal support for major maintenance costs [Kwach, 2008].

One problem that was encountered is that the vacuum cleaners have a tendency to overheat, particularly when straining to empty a sludge close to, or above, the limit of their capabilities. Although equipped with overheat protection, once this cutout was tripped a half a hour wait ensued before the machine was cool enough to resume operation. This is clearly not ideal for a commercial system, therefore it is recommended that either a vacuum cleaner is sourced with an integral cooling fan, or that a separate cooling fan is added to the existing system.

6.5.2 Plug-drag emptying

A vacuum-based system that is designed to operate in plug-drag mode would be able to pump significantly stronger sludges than those achievable through continuous emptying. Although not suitable for a pit with inbuilt suction hose, it would increase the emptying depth achievable for a hose lowered through the squat hole of a 'normal' latrine.

It should be noted that although feasible at demonstration scale, the Botswana study reported that plug-drag mode is significantly more tiring for the pit emptiers who have to

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[2] US inflation rate from 1985-2011, based on CPI = 108.7% [US inflation rate REF]. Quoted price in 1985 ~ $30,000 [IRCWD ref]

repeatedly lift and lower the hose and resist the sudden suction force it generates. The higher load on the vacuum pumps straining to pump a stronger sludge was also found to make overheating more likely in the lab, and careful design of a cooling system would be required.

6.6 Development of a sludge database

6.6.1 Benefits to the pit emptier

The proposed method of sludge classification could provide benefits to pit emptiers by saving them time and money through enabling them to use the necessary procedure first time around, only injecting water if required. It could also mean that heavily contaminated supernatant is only recirculated when air-blown remoulding is insufficient to achieve fluidisation, thereby reducing the risk to public health. Finally, if tests were done when emptying ceased, it may be possible to determine whether there is a blockage in their equipment or if they have reached the limit of what they can remove from the pit.

6.6.2 Faecal sludge management chain

The benefits outlined above would provide an incentive for pit emptiers to characterise the sludge before emptying, and in a well-managed system the class of the sludge may be reported upon delivery for treatment, before the emptier receives payment from the treatment works. Alternatively the volume and class of sludge discharged into a local transfer station may be recorded so that it can be emptied by the local municipality as and when required.

Unfortunately faecal sludge management chains in the developing world are usually far removed from the smooth-running system described above[Boot & Scott, 2008]. One potential problem is that there is no incentive for pit emptiers to characterise the sludge left in the pit after they have 'emptied' it (although it could perhaps be assumed to be the next class up from what was removed.) This 'unpumpable' sludge is of more interest for developing new, improved PETs, than whatever was removable using existing equipment.

6.6.3 Field test procedures

The variability of pit latrine sludge is widely acknowledged in the literature [eg. Strauss & Montangero, 2002], however there is a danger that a loosely controlled data collection effort using different methods and procedures will amplify that variability due to poor scientific methodology, generating large amounts of poor data. Tests are therefore needed that are cheap, intuitively simple and can be carried out by a poorly-educated pit latrine emptier. Additionally, contact with faecal sludge should be minimised in order to maintain the benefits to public health of mechanised pit emptying.

6.6.3.1 Mud funnel

The density of drilling mud can be classified according to how much dilution is required before it flows through a funnel [Sugden, S., pers comm, May, 2011], however pouring, diluting and mixing faecal sludge would introduce unnecessary health risks. It may instead be possible to estimate flow rate from the time taken for the funnel to empty, and relate this to sludge density.

6.6.3.2 Bearing capacity test

The design of shallow foundations in clay-based soils uses plasticity theory to relate the ultimate failure stress, q_f, to clay shear strength (s_u), weight (γ) and embedment depth (h) [CUED, 2011]: $q_f = s_c . d_c . N_c . s_u + \gamma . h$ where s_c and d_c are shape and depth correction factors and $N_c = 2 + \pi$.

A simple test could therefore be designed whereby an object of known weight were placed on a plate of known size, and the depth to which it sank is recorded. The size of plate and weight of object could be fixed to estimate the depth at which the suction limit of a particular pit emptying technology is reached. This would allow a pit emptier to estimate what volume of sludge they could remove, and therefore how long it would take and how much it would cost their customer.

The shear stiffness of the sludge could also be estimated from the plate settlement under a known load and then a correlation applied to determine shear strength. This may be particularly useful for the stronger 'Class A' or 'B' sludges.

The plate could be made using scrap sheet metal and a string attached to one corner to recover it from the sludge after testing. The necessary contact with faecal sludge to clean and reuse the plate may, however, discourage pit emptiers from testing the contents of the latrine.

6.6.3.3 Free-fall penetrometer

Ballistic penetration tests [Kuo, M, *pers, comm,* May 2011] are used in the offshore drilling industry to determine strength profiles with depth. A similar procedure could be used to estimate sludge strength from the penetration depth of a small heavy object dropped from a known height above the sludge surface. A ball bearing or bolt may prove suitable, and a string should be attached to recover it after the test.

6.6.3.4 Manual estimation

An experienced geotechnical engineer or geologist is often able to estimate the strength of a clay by manual tests [BS14688]. Although the health hazards would make this inadvisable with pit latrine sludge, using a stick to probe or stir the sludge would give the pit emptier a qualitative measure of its behaviour, which might be sufficient to classify it into the four strength classes presented here. This also has the advantage that the strength could be estimated at different depths to give an indication of the volume of each class of sludge found in a latrine.

7 Conclusions & Recommendations

A simple two-component synthetic sludge has been developed, which replicates the full range of strengths reported for pit latrine sludges. The strength of this sludge can be readily adjusted by varying water content, however its density was found to be significantly lower than that of pit latrine sludge.

A large increase of 23.5% water content was necessary to fluidise a uniform high strength sludge by dilution alone. However, a consolidated sludge with a very high peak strength was also rendered 'pumpable', with strength decreasing 30~80% due to air-blown remoulding at constant water content. This process was found to fluidise a conical zone of sludge, leaving an annulus of residual material at the bottom of the tank.

The increase in volume and solids content of the sludge removable from pit latrines after fluidisation could encourage illegal dumping into the surrounding environment if not carefully managed. Innovative payment mechanisms are recommended whereby the pit emptier is paid on delivery of sludge for treatment rather than on extraction from the latrine.

The following recommendations are made based on the findings of this investigation:

- Pit latrine sludge should be physically characterised according to its undrained shear strength and density.
- Different classes of pit latrine sludge should be defined according to the limits of what can be removed from a standardised pit using different emptying technologies.
- Pit latrines designed for mechanical emptying should have suction hose attachments at the top and bottom of the pit to facilitate fluidisation.
- Vacuum cleaners should be considered as a low-cost alternative to sliding-vane pumps in pit emptying technologies.

8 Further work

8.1 More representative synthetic sludge

Compost was used in the synthetic sludge developed here due to its ready availability and previous use in the UN-Habitat trial. However its low density and the presence of unwanted twigs and plastic make it far from the optimum material to use. Clay-stabilised soils such as murrum, which are prevalent in sub-Saharan Africa have a maximum dry density exceeding 2000kg/m^3 [Kumar, 2010], and could therefore readily achieve the required density range for synthetic sludge.

If dry clay is unavailable it may be necessary to substitute it for naturally occurring moist clay. This would complicate mixing of the sludge, although it may be possible to first form a slurry by dilution, before adding the required amount of the second solid component.

The changes that occur during the two week consolidation period used in this investigation cannot be considered representative of what happens in a pit latrine over a number of years. Sludges with lower initial strength should be left to consolidate for longer periods, perhaps under an applied pressure to accelerate the drainage process.

The material used in this study contains no extraneous matter and is therefore representative of what would be found in the proposed UN-Habitat pour-flush latrine. However, most latrines use a simple squat hole and contain rubbish that can cause blockages during emptying. Shredded newspaper, plastic bags or rags could be added to the synthetic sludge to investigate their effect on the fluidisation process.

8.2 Full-scale trials & validation

This investigation forms the first part of an ongoing UN-Habitat research project into improved pit latrine design for mechanical emptying. Full-scale validation of the results using real pit latrine sludge is expected to take place in the next few years. The system may be trialled at full scale on synthetic sludge at the 'Small Is' Festival run by Practical Action. This would confirm the effects of scale on the results presented here, whilst also raising awareness about the importance of pit latrine emptying.

8.3 'Plug-drag' emptying mode

The ability of low-airflow vacuum systems to operate under 'plug-drag' mode was discussed in §6.5.2 and Manus Coffey Associates recently designed a dedicated 'plug-drag' system. It is hoped that this device will be prototyped by Partners in Development and tested as part of their work on pit emptying in South Africa.

8.4 Sludge classification

The different classes of sludge proposed by this investigation correspond to the performance limits of the pit emptying technology used. Further tests using other devices are required to produce a wider range classes, spanning from heavily consolidated sludge that must be dug out manually, to thin supernatant liquid that behaves like water.

A number of procedures have been suggested in §6.6.3 for use in the field to classify pit latrine sludge. Significant further work is required to determine whether these tests are feasible, and to calibrate their results against more accurate laboratory based procedures.

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11 Appendix A – Supporting calculations

11.1 Conversion from viscosity to shear strength

The IRCWD viscosity data was recorded as 'scale reading at nominal speed', which is specific to the particular viscometer used in that study. According to the viscometer's manual [Haake, no date], shear strength is equal to the scale reading multiplied by 3.88. For a cylindrical spindle it can be shown that the shear rate at the spindle-sludge interface is twice the rotational speed [Brookfield, no date]. The reported viscometer speed of 45 rpm is therefore equivalent to a shear rate of 3π or 9.4/s.

11.2 Predicted suction required for a given soil strength

Pumping sludge can be modelled as the inverse of a soil bearing stress problem to provide a lower bound estimate of the vacuum required for a given shear strength, s_u. The ultimate bearing capacity for embedment depth of at least four diameters is given by [Skempton, 1951] $q_{f,net}=9.0 s_u$ If the suction hose is initially filled with sludge to the hydrostatic level then $q_{f,net}$ equals the required suction pressure.

In the IRCWD study the Poole tanker reached its suction limit at scale reading 11, corresponding to an undrained shear strength of 43Pa @ $9.4s^{-1}$. This would require a suction of less than 400Pa, just 1% of the pump's rated capacity. However, the calculation is complicated by the rate-dependance of sludge shear strength.

A modified power law [Abelev & Valent, 2009] was used to estimate the sludge shear strength in the suction pipe. The system's maximum airflow rate (2.3 m^3/min) and the suction hose diameter (100mm) have been combined with an assumed triangular velocity distribution which yields a shear rate[3] of $\dot{\gamma}=\frac{3\bar{v}}{R^2}$

Table A: Formula, data & estimates of suction required at low-low$^+$ viscosity boundary

$$s_u=s_{u,ref}\left(1+b_s\left(\frac{\dot{\gamma}}{\dot{\gamma}_{ref}}\right)^c\right)$$

b_s	0.31
$s_{u,ref}$ (kPa)	40
γ_{ref} (/s)	9.4
γ (/s)	5857

c	0	0.5	1.0
s_u (kPa)	0.04	0.35	7.8
Suction (kPa)	0.36	3.2	70.2
Suction (cf Poole)	1%	8%	176%

From Table A it is evident that the theoretical suction required to pump the sludge is of the same order of magnitude as that produced by the Poole tanker.

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[3] $\int_0^R 2\pi r v\,dr=\pi R^2\bar{v}$ where $v=v_{max}(R-r)$ hence $v_{max}=\frac{3\bar{v}}{R}$ → $\dot{\gamma}=\frac{v_{max}}{R}=\frac{3\bar{v}}{R^2}$

11.3 Statistical analysis of data

A regression ANOVA table was used to test the significance of changes in water content on sludge shear strength. Results are summarised in Table B below. The results of a two-sample t test for unrelated samples [Spiegel, 1961] are also included in Table B.

Table B: Results of statistical tests

Description	τ-WC, All samples	τ-WC, 80.3% incl.	τ-WC, 80.3% excl.
P-value	10%	10%	1%
D.o.f	30	5	4
F	1.57	0.88	72.4
$\mathbf{F_{crit}}$	2.88	4.1	21.2
Significant?	No	No	Yes

Description	Density – dif. of means
P-value	1%
Cohen's d	1.3σ
t'	6.1
$\mathbf{t_{crit}}$	2.47
Significant?	Yes

11.4 Dimensional analysis – scale effects

Parameters relevant to the dimensional analysis are given below in Table C.

Table C: Parameters relevant to dimensional analysis

Symbol	**Description**	**Dimension**	**Lab scale**	**Full scale**
D	Suction hose diameter	L	75mm	100mm
H	Initial sludge depth in pit	L	~0.35m	1m
L	Hose length ≈ Δ static head	L	2m/1.5m	(3.3m)
A	Pit x-sectional area	L^2	0.16m^2	1m^2
ρ	Sludge density	ML^{-3}	1200kg/m^3	1800kg/m^3
s_u	Sludge shear strength	$ML^{-1}T^{-2}$	~400Pa	~400Pa
p	Injection or suction pressure	$ML^{-1}T^{-2}$	0.3~0.45 bar	(0.9~1.35bar)
g	Gravitational acceleration	LT^{-2}	9.81m/s^2	9.81m/s^2
Q	Air or sludge flow rate	L^3T^{-1}	?	?

According to the Buckingham Pi Rule, at least six dimensionless groups should be formed – these are presented in Table D. Values in parentheses are estimated by dimensional analysis.

Table D – Dimensionless groups and comparative values

Group	$\frac{Q}{D^2\sqrt{2gL}}$	$\frac{L}{D}$	$\frac{p}{\rho g L}$	$\frac{D}{\sqrt{A}}$	$\frac{H}{\sqrt{A}}$	$\frac{p}{s_u}$
Lab scale	?	33.3	2.5×10^{-5}	0.2	0.9	75
Full scale	?	(33.3)	(2.5×10^{-5})	0.1	1.0	(225)

12 Appendix B – Risk Assessment Retrospective

The key hazards identified before starting the project were associated with the use of a low pressure vacuum pump and concrete mixer, and from manual handling of heavy samples. These were found to present low risk to the investigator and safe lab procedures further minimised the likelihood of an accident. No accidents or 'near misses' occurred during the investigation.

The vacuum tank apparatus was designed to fall below the 250bar-litre limit at which pressure vessels require certification with a volume of ~100L and maximum pressure of 0.45 bar. Safety release valves for both pressure and vacuum were also included for additional safety. A hand pallet truck was used to transport heavy sludge samples around the laboratory and minimise manual handling risks.

Inhalation of clay powder was identified as an additional hazard and a personal respirator and dust extraction hood were both used when working with dry clay. The actuator used to drive the ball penetrometer presented a risk of crushing the fingers of other lab users. It was therefore placed in an inaccessible position and was not operated if anyone was within reach of the device.