TACKLING THE CHALLENGES OF FULL PIT LATRINES

Volume 2: How fast do pit toilets fill up? A scientific understanding of sludge build up and accumulation in pit latrines

Report to the
Water Research Commission

by

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The publication of this report emanates from a project entitled: *Understanding the sludge accumulation in VIPs, UDs and other on-site sanitation systems, and strategies to manage desludging in the future when pits are full* (WRC Project No. K5/1745).

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EXECUTIVE SUMMARY

The South African government has designated the Ventilated Improved Pit latrine (VIP) as the basic sanitation option that supports the rights of all South Africans to safe and decent sanitation. More than two million of these toilets exist in South Africa, with many more rudimentary home built latrines also in use which may or may not meet the criteria for basic sanitation. While on-site sanitation such as pit latrines avoids many of the issues, costs and logistical challenges of providing waterborne sewerage to rural or densely built areas, the unavoidable reality is that the pits of on-site systems sooner or later will fill up. This report is the second volume in the series *Tackling the challenges of full pit latrines* which addresses this issue. The other volumes in the series are:

- *Volume 1: Understanding sludge accumulation in VIPs and strategies for emptying full pits.*
- *Volume 3: The development of pit emptying technologies.*

Current research indicates that many of the VIP systems delivered by the South African government over the past decade can be expected to reach capacity in the very near future. Many municipalities have not yet put the necessary strategies, policies and budgets in place to maintain these on-site systems and are unable to predict how often they will need to be serviced. If municipalities are taken by surprise when pits reach capacity and do not have the necessary budget, manpower and equipment in place to respond, households will effectively find themselves without sanitation, a situation which compromises both public health and dignity, the driving forces behind South Africa's commitment to basic sanitation for all.

To accurately determine the lifespan of pits within a municipality, both social factors (such as demographics and user behaviours related to pit latrines) and geophysical and biological factors (such as the interaction between pit design, water table and soil)must be considered. Municipalities can impact a number of these variables directly through education, system design and service delivery in order to optimise the functioning of on-site systems. For example, where municipalities have provided water to households but have not provided for disposal of greywater, householders may use the pit for this purpose, impacting the aerobic and anaerobic conditions in the pit. And by putting a reliable solid waste collection programme in place, municipalities can reduce the use of the pit for solid waste disposal, dramatically decreasing the pit filling rate and the frequency at which pits need to be emptied. This study explores a number of these variables and models the aerobic and anaerobic zones and degradation processes occurring in the pit. A pit filling model is provided which can be used by municipalities to predict the rate at which its pits will fill based on the specific characteristics of the area.

Previous studies of on-site systems indicate a wide range of accumulation rates for wet (septic tank) systems (22 ℓ/c.a to 95 ℓ/c.a) as well as for pit latrines (19 ℓ/c.a to 70 ℓ/c.a). Filling rates for pit latrines observed in this study ranged from 21 ℓ/c.a to 64 ℓ/c.a. It was found that pits typically filled at a rate ranging from 200 ℓ/annum to 500 ℓ/annum regardless of the number of users. For pit design, using a figure of 40 ℓ/c.a meets household requirements, while basing pit emptying programmes on a figure of 60 ℓ/c.a ensures that pits do not reach capacity before the commencement of the planned emptying cycle.

Some municipalities have turned to products marketed to slow or halt accumulation in the pit in the hope that this will significantly reduce the frequency at which they will need to be serviced or eliminate the need altogether. In order to investigate the efficacy of these products, the Water Research Commission has tested approximately 20 pit additives in field and laboratory trials. To date none have been found to be effective in reducing pit filling rates. It is vital that municipalities do not spend their sanitation budgets on products with no proven benefit, leaving inadequate funds to service their on-site sanitation systems with tried and tested methods when these products fail.

Few municipalities have been proactive to date in terms of developing sanitation management programmes which integrate pit design and pit maintenance and where pit filling is monitored. As a result, many are likely to face a critical situation in the near future when pits reach capacity and they are ill prepared to respond. It is imperative that municipalities put programmes in place which are based on a sound understanding of the behaviour of users, geophysical characteristics of the area and system design so that they can manage the maintenance of systems efficiently and without compromising public health.

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1 INTRODUCTION

This document represents the second in a series of three publications covering research undertaken by Partners in Development and the Pollution Research Group at the University of KwaZulu-Natal for the Water Research Commission (Project K5/1745). Additional funding was provided by Irish Aid. The project was initiated in response to the fact that the VIP toilets which municipalities across South Africa have built to meet the need for basic sanitation are approaching capacity and few municipalities have a clear understanding of how fast their pits are filling, what challenges they will face in emptying them and potential solutions to these challenges, or what options exist for the use of sludge which has been removed from pits. The goal of this project was to contribute a clearer understanding to the questions of how fast pits are filling, what challenges they will face in emptying them and potential solutions to these challenges, or what options exist for the use of sludge which has been removed from pits. This document investigates pit filling rates and the factors which influence them, with the goal of providing municipalities with strategies for matching the pits under their jurisdiction with an appropriate maintenance cycle.

In a survey conducted for this study investigating the management of VIP toilets, Water Services Authorities (WSAs) in South Africa indicated that there were over one million VIPs within their jurisdiction[1]. They estimated that 85% of these are older than 5 years and that most pits need to be emptied every 5 to 9 years.

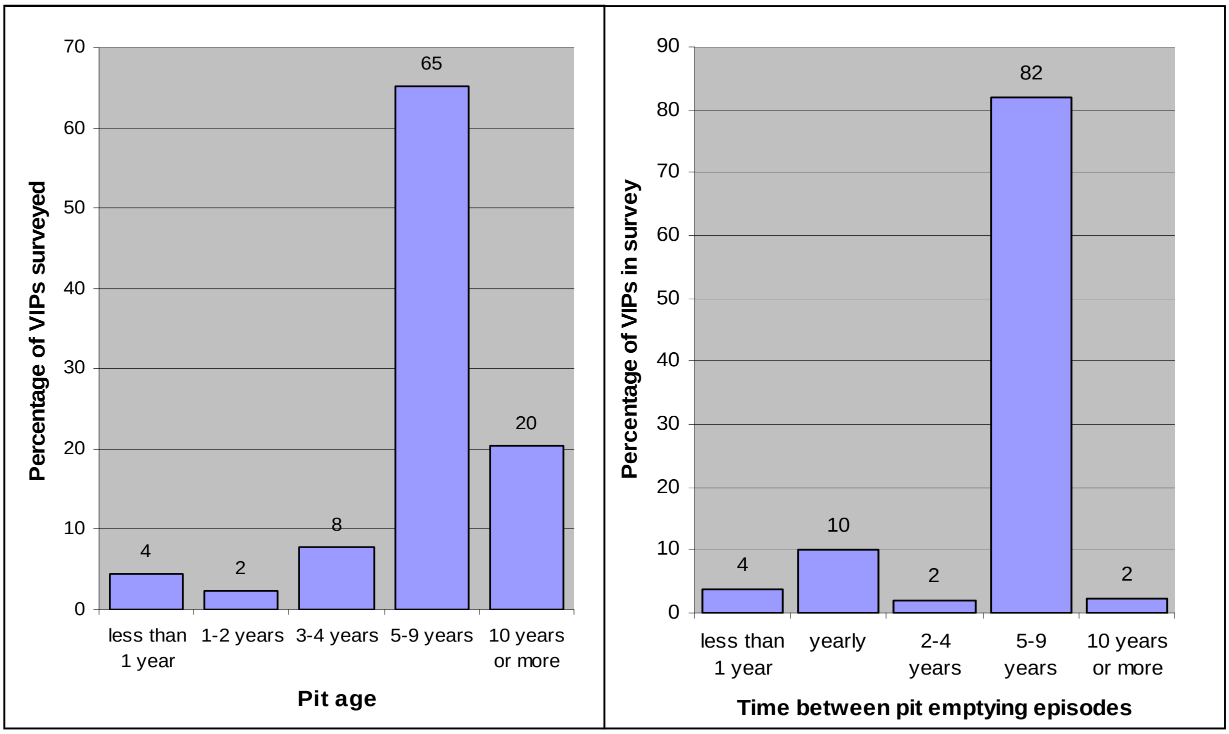


Figure 1.1 Age of VIPs and pit emptying frequency in WSAs surveyed (PID, 2009)

[1] The full report on this survey can be obtained from the Water Research Commission, Project K5/1745. A detailed summary of the survey is included in Volume 1 of this report series.

This suggests that pits are filling up more rapidly than was initially anticipated and that within the next few years WSAs which do not already have a plan, budget or programme in place for emptying pits will find themselves facing a crisis when pits reach capacity. To avert such a crisis, WSAs need to be able to accurately predict the rate at which pits will become full and require emptying and rapidly develop the capacity for emptying large numbers of pits.

A number of social, geophysical and biological factors impact the key processes within a pit which determine the rate at which it will fill: the addition of new material into the pit, the transfer of water into and out of the pit, biological transformations, and bacteria die-off (Buckley et al., 2008). A standard pit generally contains a range of materials, including faeces, urine, anal cleansing material and general solid waste. In the pit, the surface of the sludge has contact with the air, allowing aerobic degradation to occur. As sludge is covered over with fresh material and no longer has contact with the air, anaerobic degradation takes over. Understanding the interaction of these variables will not only enable municipalities to predict filling rates with greater accuracy but also to manipulate these variables in order to optimise both their pit designs and their pit servicing programmes.

2 FACTORS AFFECTING SLUDGE ACCUMULATION RATES

Pit design determines the holding capacity and drainage capacity of an on-site system and can limit or facilitate various methods of sludge extraction. User behaviour affects the make-up of faeces, the amount of urine that goes into the pit, the presence of solid or liquid waste in the pit and the presence of chemical or biological agents in the pit which could suppress or enhance degradation. A range of geophysical factors and biological processes influence the processes of accumulation and degradation in the pit.

2.1 Design of on-site sanitation systems and chamber size

On-site sanitation systems range from rudimentary home-built pit latrines to the sophisticated indoor urine diversion toilets now becoming fashionable in some affluent societies such as Sweden. Every on-site system has some kind of chamber or receptacle for holding faeces which will eventually become full. In addition to the number of users and their various behaviours which determine what goes into the receptacle (for example diet, anal cleansing material, use of the toilet for disposal of liquid or solid waste), the size of this chamber is a key factor determining how soon the chamber will fill. Systems designed to divert urine will produce sludge with a different nutrient and moisture content than systems which combine faeces and urine. In South Africa, the recommended pit size for VIPs is 2 to 3 m^3, while in some countries, such as Tanzania, pits may be as large as 10 m^3. The amount of water that enters the pit (flushing water, greywater or rain) in combination with the drainage capacity of the pit (affected by the lining of the pit, soil conditions and water table) also influence the filling rate. Unless the pit is sealed much of the moisture in the excreta leaches away, and the remaining organics slowly break down. Depending on the soil conditions, a pit must be reinforced in order to prevent the top structure from collapsing into the pit (Figure 2.1). Typically, pits are reinforced by lining them with bricks or blocks, laid with open vertical joints to allow for drainage.

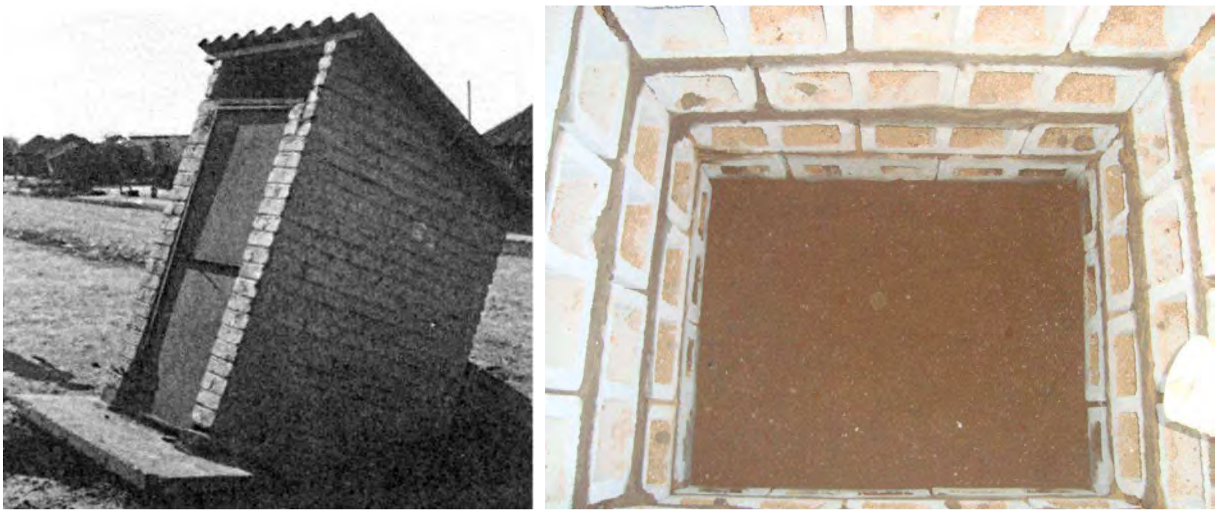


Figure 2.1 Left: An unlined or unreinforced pit cannot support a heavy top structure. Right: A pit lined with blocks laid with open vertical joints, allowing drainage through the bottom and sides of the pit.

If seepage into the surrounding soil is considered undesirable due to the proximity to drinking water sources, such as a village borehole, then the pit should be sealed. A sealed pit that is unable to drain is in essence a conservancy tank. Depending on the size of the tank, the number of users and whether any greywater is added to the pit, conservancy tanks typically fill within days or months.

The design of the toilet as a system must be considered in order to determine sludge accumulation rates. A key consideration in the design of the pit should be how to achieve filling rates that do not exceed the planned emptying cycle.

2.2 User related factors

❖ Number of users

In broad terms, the number of users of a pit obviously plays a key role in sludge accumulation rates. An individual produces between 0.12-0.40 litres of faeces and 0.6-1.5 litres of urine per day (Buckley et al., 2008). Averaged over a year, this amounts to 110 litres of faeces and 440 litres of urine per person per year: a total volume of 550 litres of excreta per person per year.

Accurately calculating the average number of users and their relative contribution to the contents of a pit over its lifetime can prove extremely difficult, however. The household size may have increased or decreased over the period that the pit has been in use, some members may have been away from the home during the day or week and have contributed far less to the contents of the pit than others, and children contribute less than adults to the pit. The current lifecycle of the pit may pre-date the current occupants of the house, who may have no knowledge of the household size or user behaviour of the former occupants who contributed to the pit during the first years of filling. As a result, studies frequently do not indicate a strong relationship between household size and the rate at which the pit fills. Bakare (2012) showed that there was no correlation between available data for pit filling rates and reported number of users and concluded that this was due to uncertainty in the pit filling rate data and confusion surrounding the interpretation of *average number of pit users*.

❖ Anal cleansing material

In Asian cultures “washing” is preferred over “wiping” as the anal cleansing method, which results in more water entering the pit. Most South Africans are “wipers.” If toilet paper is unaffordable then newspaper, and sometimes other materials such as plastic bags or maize cobs, will be used for anal cleansing. As these materials represent different volumes and biodegradability, they can have very different impacts on filling rates.

❖ Solid waste

Pits are often used for disposal of rubbish and greywater if the municipality has not provided alternative means of disposal. Solid waste content varies widely in terms of volume and biodegradability, impacted also by cultural and economic factors such as whether kitchen scraps are fed to animals, the amount of packaging that enters the home with purchases, whether plastic packets are provided free at shops, and the extent to which things are re-used rather than passed on. Families with a higher socio-economic status typically produce more rubbish. On-site systems with offset pits which operate with a flush tend to limit the disposal of rubbish into the pit to a large extent. While user education programmes attempt to discourage householders from disposing of rubbish in a pit, if there is no discreet alternative for disposal of personal items such as sanitary pads or condoms, or safe alternative for the disposal of hazardous waste, these are likely to continue to be disposed of in the toilet, whatever design it may be.

- **Ownership**

In South Africa, a toilet is usually owned by an individual family, and the public ownership model that is common in Africa (WHO/Unicef, 2006) and India (Cotton et al., 1995) is rarely used. Since basic sanitation is part of the Free Basic Water Services programme, toilets are usually provided at no expense to the household. As less value is sgenerally placed on something that is offered free of charge, owners are sometimes required to contribute their labour during the construction of the toilet, with the idea that “sweat equity” may increase the householders’ sense of ownership and responsibility for a system that they did not pay for. Generally, when users lack a sense of ownership, or are not satisfied with the system they have been given, they are less willing to maintain the system properly.

- **User education**

The provision of toilets by government without concurrent education programmes has sometimes failed to improve sanitation in a community. As a result, sanitation provision is most effective when it is understood to include infrastructure, maintenance and health and hygiene education (Department of Water Affairs, 2003). In South Africa, health and hygiene programmes have increasingly become part of sanitation delivery, and 40% of the municipalities with VIPs now have ongoing programmes which are often run through the schools or community meetings. When India introduced pour-flush latrines the systems failed in some communities due to misuse and home conversion of the systems to pit latrines. In response, the Kerala Water Authority added an education and follow-up programme as a component of subsidised latrine provision. Community members served on Ward Water Committees which facilitated the introduction of sanitation and inspected household latrines to ensure proper use (Kurup, 1996).

2.3 Geophysical and climactic factors

The conditions surrounding the pit, such as soil, slope and the interaction of the water table with the pit, impact the rate of accumulation in the pit in a number of ways.

- **Substrate and soil type**

Clay soils slow the drainage of liquids from pits, while sand provides effective drainage and allows pit contents to dehydrate, provided that little water is added by users. An impermeable substrate or sub-formation and shallow soils may limit drainage from pits and increase the rate of filling (Pearson, 2002). Wherever possible the lining of pits should be permeable in order to allow the liquid content to percolate into the surrounding soil, reducing volume in the pit.

- **Elevation, slope and water table**

If pits are extended below the water table, water will tend to drain into, rather than out of the pits. While higher moisture content may assist the decomposition process in the sludge, flooding of pits can render them unusable and a health hazard. While there is a perceived risk of pathogens and nitrates in the sludge contaminating the groundwater, the literature indicates that this does not occur unless there is a highly permeable aquifer formation with a significant groundwater flow (Still, 2002).

❖ Evaporation, rainfall and seasonal temperatures

Some loss of moisture from latrine pits occurs through evaporation – moisture is lost as vapour into the air. The rate at which this occurs will be affected by temperature and humidity, with higher losses occurring under warmer, drier conditions. Where precautions are not taken to prevent runoff of rainwater from the surrounding area into the pit, it may fill with water after heavy rain.

2.4 Biological activity in the pit

Fungal organisms and other biota such as maggots, roaches and worms in the pit also play a role in making the organic material more amenable to bacterial break down (Kele, 2005). The temperature, pH, ammonia level and water content in a pit may affect microbial activity.

❖ Aerobic and anaerobic degradation

While matter cannot be created or destroyed, matter that enters the pit can exit the pit through evaporation and transportation of dissolved particles into the surrounding soil, as discussed above, and through the degradation of organic matter by bacteria present in the pit into liquids and gases (primarily methane, carbon dioxide, ammonia and nitrogen) which can then exit the pit. During this process the sludge becomes more stable (less prone to further changes) due to the decrease in organic matter. Given enough time, all *biodegradable* matter in the pit will eventually be converted to inorganic products that are either soluble or gaseous and a small amount of non-degradable organic residue. The soluble and gaseous components will "disappear" from the pit through leaching and gas evolution. As the complex range of degradation processes each depend on particular bacteria, the populations of those bacteria will grow until they are in balance with their environment. As the biodegradable material is depleted, the micro-organisms die and themselves degrade.

Where sludge in the pit has contact with air (oxygen), aerobic digestion takes place. In this process, bacteria dependent on oxygen use the nutrients in sludge and the oxygen available at the sludge surface to grow, converting sludge to biomass (more bacteria) in the pit and to carbon dioxide which then exits the pit. Figure 2.2 below illustrates the area where aerobic digestion takes place where the surface of the sludge is in contact with air. If the pit is unlined or has open joints, aerobic digestion may also take place to a limited extent at the sludge/soil interface where bacteria can utilise oxygen found in unsaturated soil.

Aerobic processes proceed fairly rapidly in comparison to anaerobic processes, which are orders of magnitude slower. Where no oxygen is available, bacteria which do not require oxygen convert sludge to additional biomass (more bacteria) and methane and CO_2, which escape from the pit. The anaerobic region of the pit is shown in Figure 2.2b.

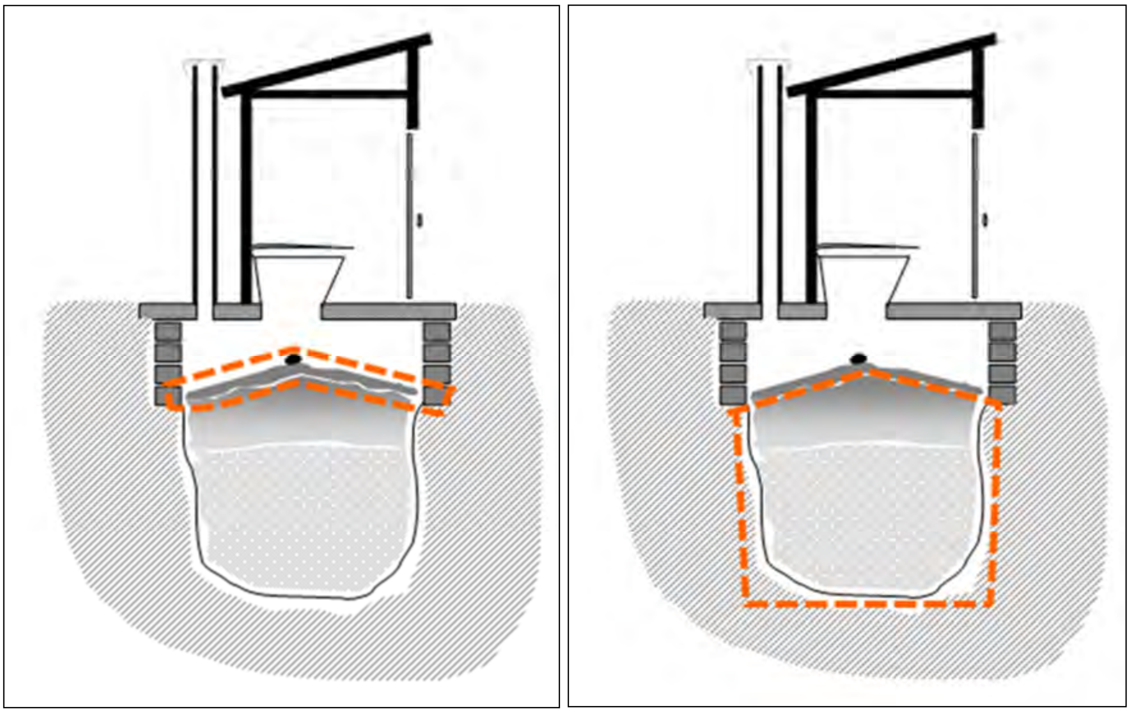


Figure 2.2 Left (a): Areas in the pit where the sludge is in contact with air and aerobic digestion occurs. Right (b): Areas in the pit where the sludge is not in contact with air and anaerobic digestion occurs.

Anaerobic degradation has a much lower yield of biomass than aerobic processes; for each g COD of substrate consumed, only 0.05-0.10 g COD becomes more biomass and the remainder is converted to methane, whereas in the case of aerobic digestion the conversion to bacteria is 0.50 to 0.70 g COD biomass/g COD organics and the remainder is converted to CO_2. With time the biomass thus generated aerobically or anaerobically breaks down and becomes substrate for other bacteria, such that the biodegradable material is all eventually removed. However, the growth of micro-organisms converts a portion of biodegradable organic material to non-degradable organic cell components. These accumulate with time in the pit and do not break down further.

Both aerobic and anaerobic processes will contribute to the breakdown and removal of biodegradable organic matter in pit sludge. It is hypothesised that the greater the contribution of aerobic processes to biodegradation, the more rapidly the material in the pit will stabilise, but because of the relatively higher growth yields that are exhibited during aerobic digestion, a greater amount of non-degradable residue is generated and eventually accumulates in a pit latrine. This may partially explain why it is reported in the practitioner's literature that wet pit contents (which are predominantly anaerobic due to the occlusion of air by the water content) accumulate more slowly than dry pit latrines.

This concept is presented graphically in Figure 2.3: It is assumed that the material added to a pit latrine has the following characteristics: organic biodegradable content 54.5%; biodegradable bacterial cell mass 28%; organic unbiodegradable content 5%; inorganic content 12.5%.

Only the first two categories are degradable. If we assume that the aerobic cell yield is 67% on a mass basis and that the generation of unbiodegradable COD as a result of growth is 15%, ultimately 14.7% of the original mass of material is added as unbiodegradable organics. However, if the same feed material undergoes anaerobic digestion with an anaerobic cell yield of 8% on a mass basis and the same unbiodegradable generation factor of 15%, the unbiodegradable organic fraction that accumulates is eventually 10.2% of the original mass added. Thus for only aerobic conversion, the final amount of material remaining after soluble and gaseous components have left the pit is around 27% of the original mass, while the corresponding value for anaerobic digestion is around 21%. In the case of aerobic digestion 73% of the original mass is converted to carbon dioxide, while in anaerobic digestion 79% of the original mass is converted to methane. Note that this is a dramatic simplification of what occurs since the original material may pass through many compounding growth-death-growth-death cycles which have been represented here by a single growth yield for each route and one organic residue generation term.

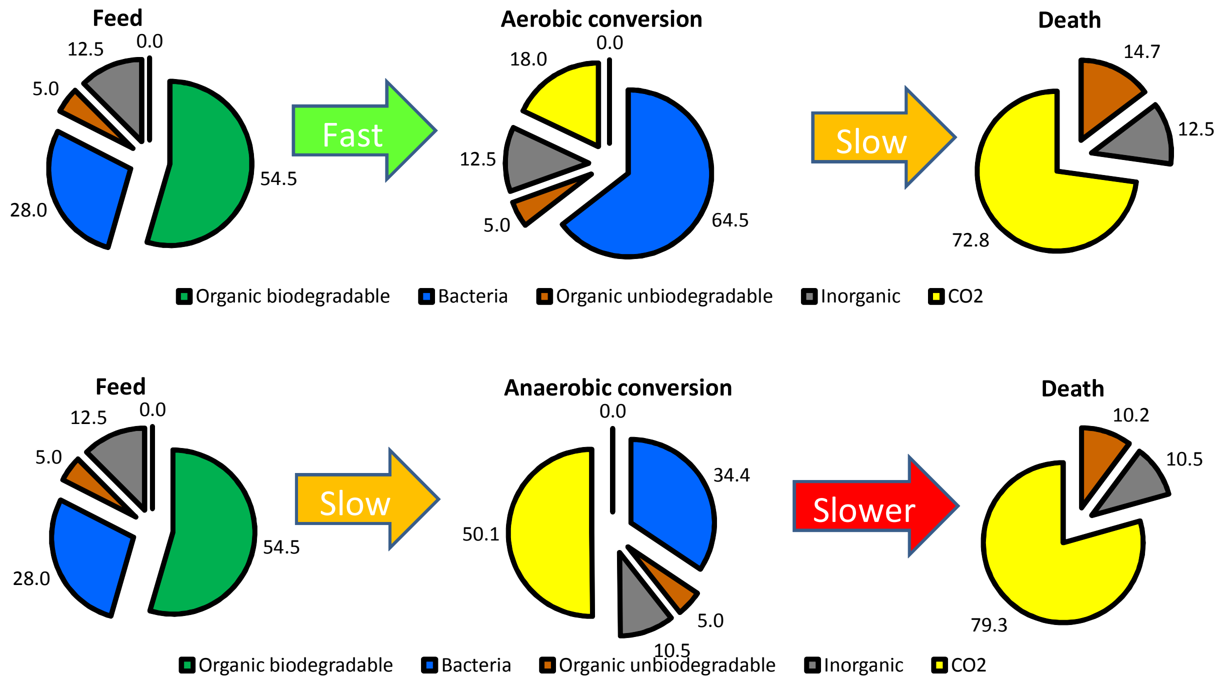


Figure 2.3 Aerobic versus anaerobic conversion

As illustrated in Figure 2.4, the zone of aerobic digestion is much smaller than the anaerobic digestion zone. This means that the bulk of pit contents at any time in pit are anaerobic. However, the much faster aerobic degradation rate on the pit surface may result in a relative contribution of aerobic digestion to the overall stabilisation process that is much larger than the volume ratio of the aerobic zone. Buckley et al. (2008) found that up to 50% of COD may be degraded under predominantly aerobic conditions on the surface of the pit. Further research is currently underway to quantify the rate of autodegradation of faeces on a pit surface.

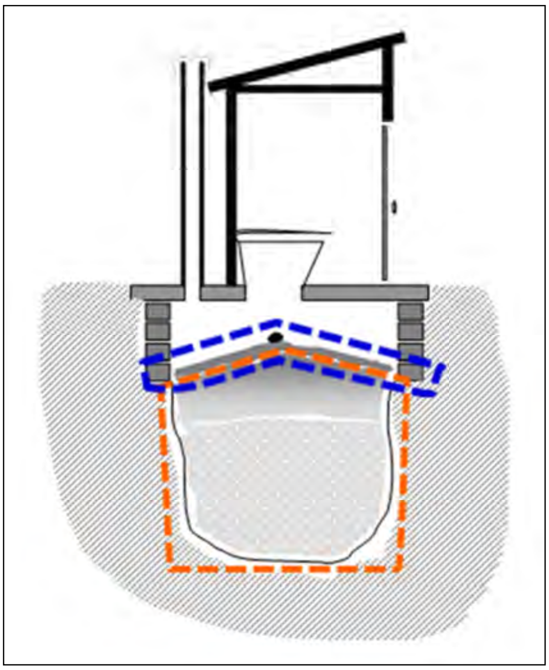


Figure 2.4 Zones of aerobic digestion (blue) and anaerobic digestion (orange) in the pit

2.5 The effect of substances added to inhibit/enhance biological activity

Products that are added to the contents of pit latrines fall into two broad and opposed categories: those added to reduce odours and insect activity, and those added to improve sludge degradation and reduce the rate of filling.

Nwaneri et al. (2007) mention that household bleaches and disinfectants such as Jik and Domestos (containing sodium hypochlorite), or Jeyes Fluid are often added to pit latrines to reduce odours. These products have known microbiocidal properties, and may inhibit the functions of bacteria active in sludge degradation, and therefore increase the rate of sludge build up. Organophosphates and pyrethroid insecticides may be added to reduce the activity of fly maggots, which will also therefore reduce the rate of sludge break down.

Substances containing active biological agents have also been developed to enhance the biological activity in the pit. There are currently dozens of products marketed in South Africa with the claim that they will prevent pits from filling up or reduce the rate at which they fill by enhancing the degradation of sludge. The assumption driving the development of pit additives is that digestion is not already occurring as efficiently as it could be in the pit. However, faecal sludge contains a wide range of naturally occurring bacteria which increase in proportion to the available nutrient load and are effective in digesting the sludge. These natural processes have already been found to work optimally in the treatment of waste water: when a septic tank or a waste water treatment works is commissioned, no seeding of the plant with appropriate bacteria is needed as the necessary bacteria arrive with the incoming waste stream.

While it may be possible to manipulate the conditions in the pit to optimize bacterial activity, it is impossible for even the optimal bacteria under the optimal conditions to empty a pit completely: as discussed in Section 2.4, not all matter can be transformed into gases or liquids which can then exit the pit. Aerobic bacteria consume sludge more quickly than anaerobic bacteria but (it is hypothesised) ultimately leave more non-biodegradable mass in the pit.

Some pit additives claim to add aerobic bacteria to the pit, thereby increasing the aerobic conditions in the pit. However is the amount of oxygen that determines whether conditions are aerobic or anaerobic, and this cannot be manipulated in any way by adding a substance to a pit.

In a survey conducted for this study, 20% of the Water Service Authorities in South Africa which have VIP toilets reported that they supply pit additives to householders or promote their use. Some are using their sanitation budgets for pit additives rather than for emptying pits in the hope that these products will prevent the need to empty pits or dramatically reduce the rate at which they fill. A typical pit additive treatment costs R20 to R30 per month, representing a cost of R1 200 - R1 800 over a five year period to allegedly slow – but not stop – accumulation of sludge in the pit. In contrast, a five year old pit can be completely emptied and the sludge disposed of by manual or mechanical means for between R500 and R1 500.

Investing in pit additives which may not be effective can therefore seriously compromise the capacity of municipalities to maintain their on-site systems. As no formal protocol exists in South Africa for testing the effectiveness of pit additives, the Water Research Commission has undertaken to test approximately 20 pit additives in order to investigate whether any empirical evidence could be found that any of these products actually do reduce filling rates.

2.5.1 Scientific investigation into the efficacy of pit additives

In 2007, the Water Research Commission tested a commercially available pit additive on nine VIP pits over a period of three weeks using blind controls. No sludge reduction was observed (Foxon et al., 2008). In 2009, laboratory tests were carried out on nine more products. None of the additives had a statistically significant effect on the rate of mass loss from the sludge samples (Foxon et al., 2009). Figure 2.5 combines the results for seven of the additives, comparing them against a control and also against samples to which only an amount of water was added. As can be seen, the rate of mass loss from the controls is no different to the rate of mass loss from the samples in which pit additives were used.

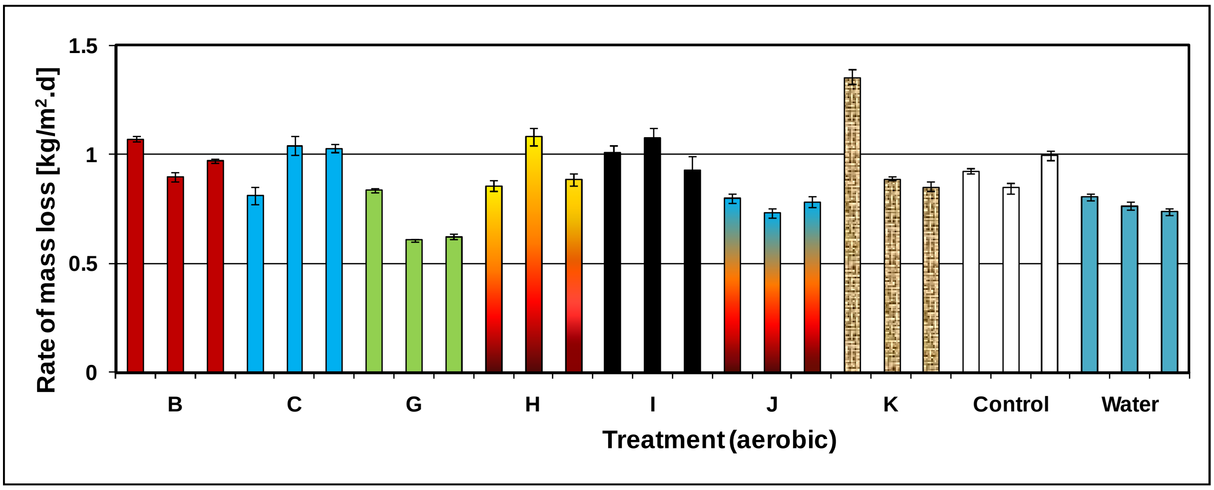
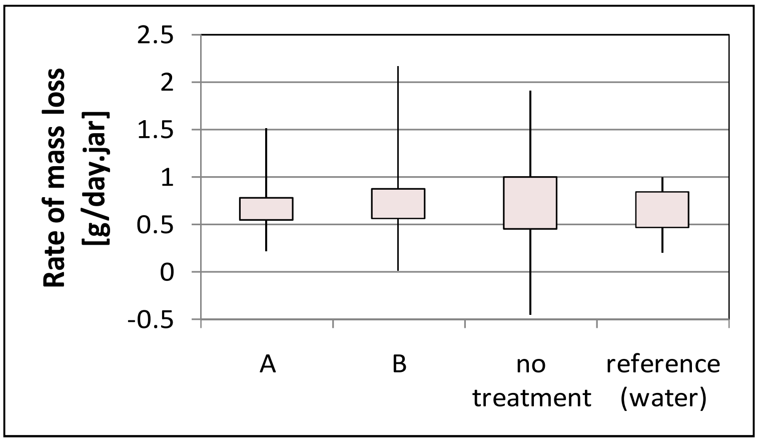


Figure 2.5 Rate of mass loss in laboratory tests of pit additives

Further laboratory trials and field trials were conducted in 2009/2010. For laboratory trials, fresh samples of two different pit additives were mixed with samples of VIP contents taken from the surface of the pit beneath the pit pedestal and incubated for 30 days. Tests were performed in three or five replicates and two reference treatments (or controls) were included for comparative purposes: (i) no addition of water or chemicals (control); (ii) addition of water (water reference). It was found that while there was significant variation in the measurement of mass loss rate in these experiments, there was no significant difference between the rate of mass loss for each of the four treatments and the controls.

Figure 2.6 Rate of mass loss from honey jar samples of pit latrine sludge subjected to different treatments.



For the field trials, the two pit additives used in the laboratory trial were used to dose eight pit latrines each, with reference and control groups of seven pit latrines each. Since the manufacturers advised that the additives be added with water to the pits, the reference experiment aimed to isolate the effect of adding water to pit contents on the sludge accumulation rate. In these pits, 10 ℓ of water was added to each of the reference pits on a weekly basis. The rate of pit sludge accumulation was determined by taking three measurements of the distance between the pedestal and pit surface for three locations directly under the pedestal using a laser distance measure. These measurements were averaged to give an indication of the distance between the top of the sludge heap and the pedestal.

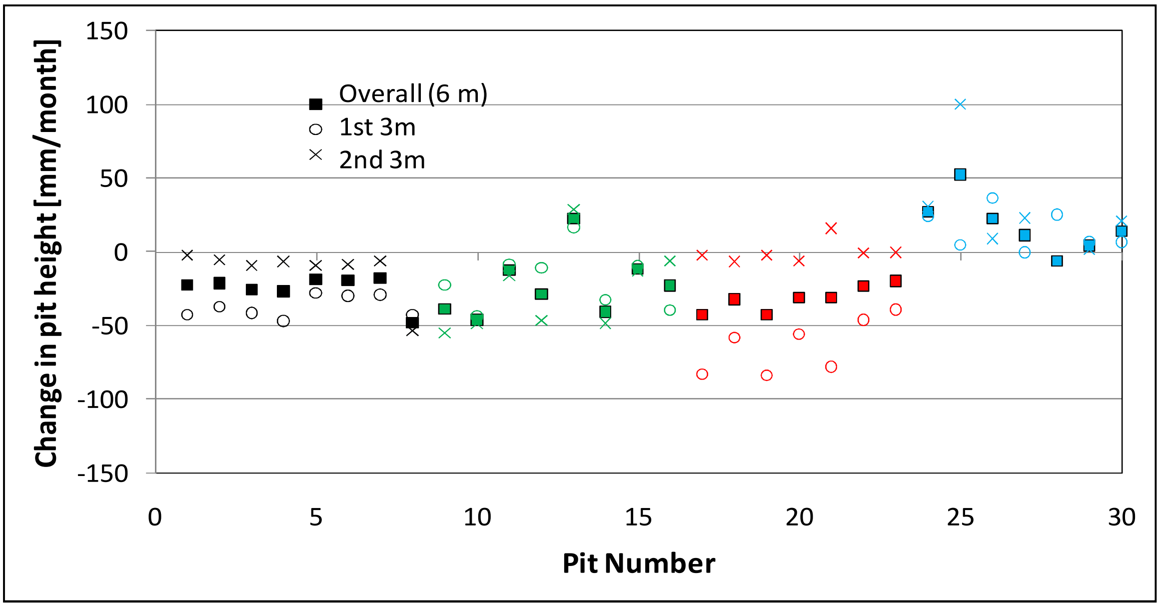
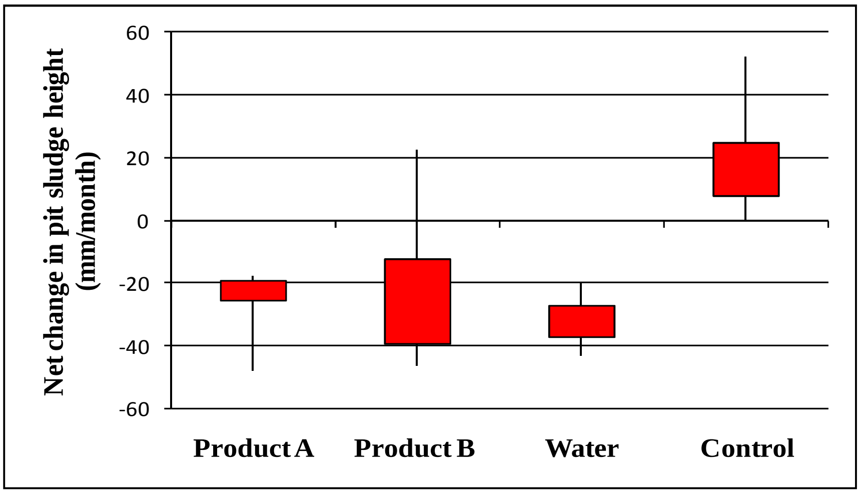


Figure 2.7 Change in height of pit contents over 6 months (laser measurement of height)
KEY: Black – Pit additive A. Green – Pit additive B. Red – Water only C. Blue – Nothing added D

Over the six month period there was no evident difference in the sludge accumulation rate whether pit additive A, pit additive B or simply plain water was added. There was however a noticeable difference between treatments which involved the regular addition of water, and the control where nothing was added. In this regard it is notable that the results for Treatments A, B and C were very similar despite the very different amounts of water involved (10 litres every second month for A and 10 litres every week for B and C). The results are summarised in Figure 2.8.

Figure 2.8 Change in height of pit latrine contents over 6 months (using laser measurement of height). The box for each data set represents the range of the 95% confidence interval on the mean, while the whisker shows maxima and minima from within each data set.



These results suggest that the pit additives in themselves do not bring about a reduction of pit contents but that some reduction in sludge accumulation rate can be achieved by the addition of water alone. Whether the addition simply levels the heap, bringing about an apparent reduction, or enhances biodegradation is not clear from these measurements.

To clarify the mechanism of measured accumulation rate reduction stereographic imaging was used to map the surface of the pit contents. This map was used to estimate the volume change of pit contents over the 6 month period as opposed to the change in pit contents height. The results are presented in Figure 2.9.

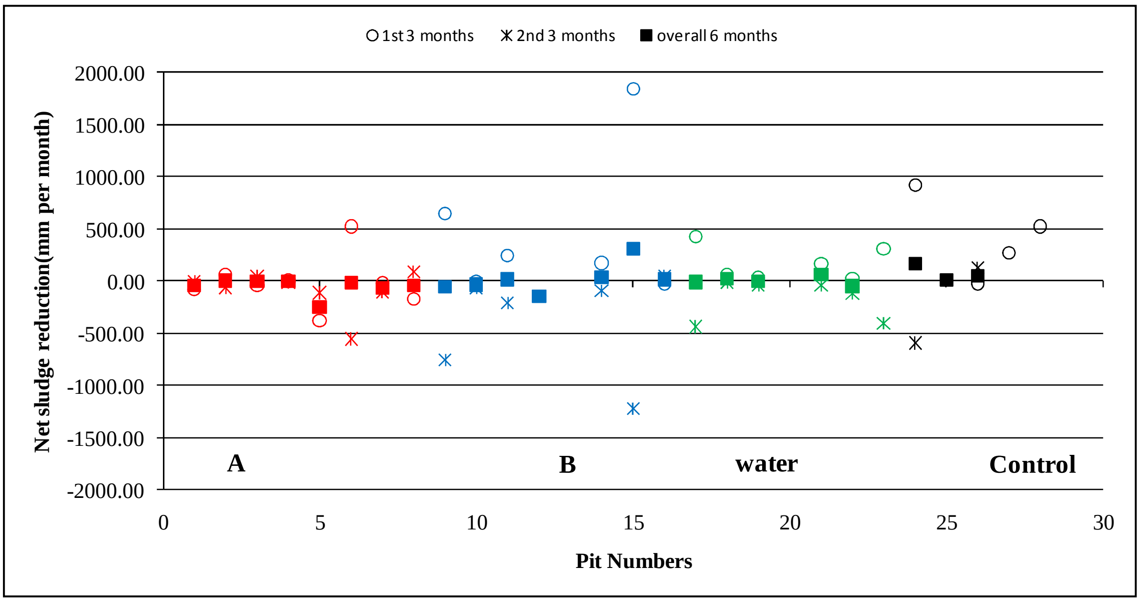


Figure 2.9 Change in height of pit contents over 6 months (stereographic determination of volume)

KEY: red – Pit additive A. blue – Pit additive B. green – Water only C. black – Nothing added D

In Figure 2.9, it is seen that there is no significant difference between the results from any of the treatments. This suggests that the difference between the control and other treatments in Figure 2.7 was due to changes in the shape of the pit contents as a result of the addition rather than to the actual volume rate of accumulation. The results are summarised in Figure 2.10.

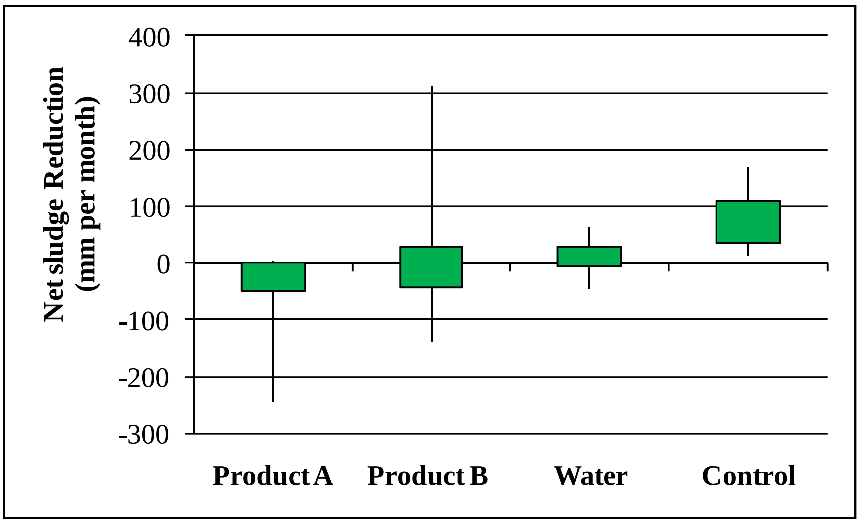


Figure 2.10 Box and Whisker plot showing change in height of pit latrine contents over 6 months (stereographic measurement of volume).

Also in 2009, the University of KwaZulu-Natal and Partners in Development (PID) were approached by a pit additive manufacturer and requested to test their product. Forty actively used pits were selected for the trial and divided into four treatment groups which were dosed with the additive, coloured water, a water and molasses mix or nothing. Over the period of the trial the median sludge height for the control group increased 39 mm, while the median height for the group dosed with coloured water increased 38 mm. The median increase for the latrines which had the molasses water mix added was 55 mm, and that for the group that was given the additive was 78 mm. The group that was given the additive not only showed no reduction in the rate of sludge accumulation, but it in fact showed an increased rate of sludge accumulation.

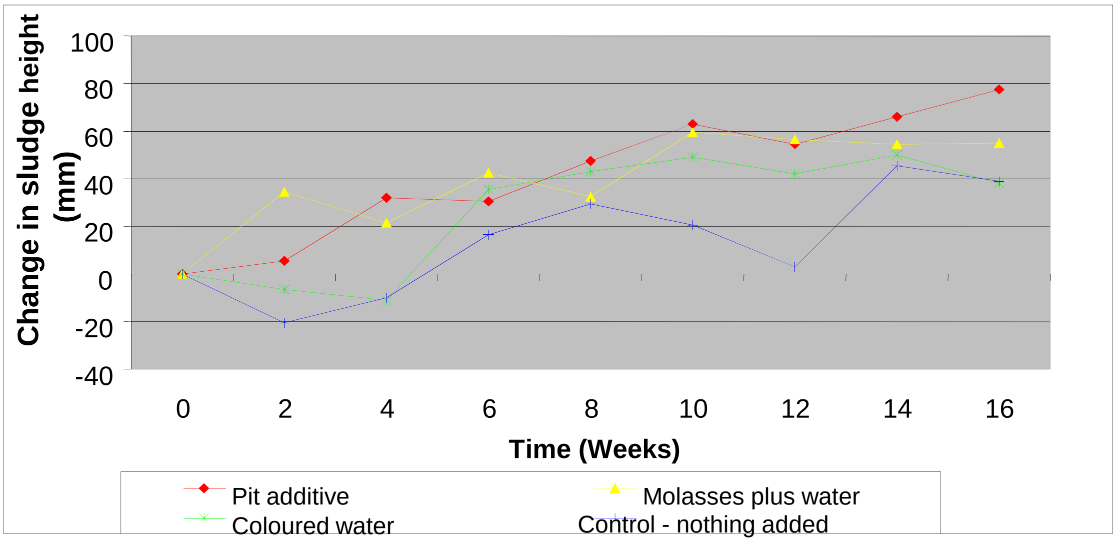


Figure 2.11 Median cumulative increase in sludge level

If these increases were extrapolated across the full 2.4 m^2 surface area of the pit they would equate to pit filling rates of between 300 and 600 litres in one year. These rates are within normal observed ranges, but are higher than the rates at which these pits were observed to have filled over the three years from the construction to the start of the trial, where the median increase was in fact 307 litres per year. However an examination of the *offset* sludge height measurements showed that the pit sludge height increase during the time of the trial was negligible on the sides in all cases, although once again the increase for the set of latrines which were being dosed with the additive was the highest (Figure 4.8). It is likely that sludge in a pit does not increase in height at a uniform rate over the area of the pit, but builds in the centre and then slumps to the outside in a repeating cycle. For this reason, while short studies of this nature may be of use for testing the efficacy of an additive, they are of limited use for determining long term pit filling rates.

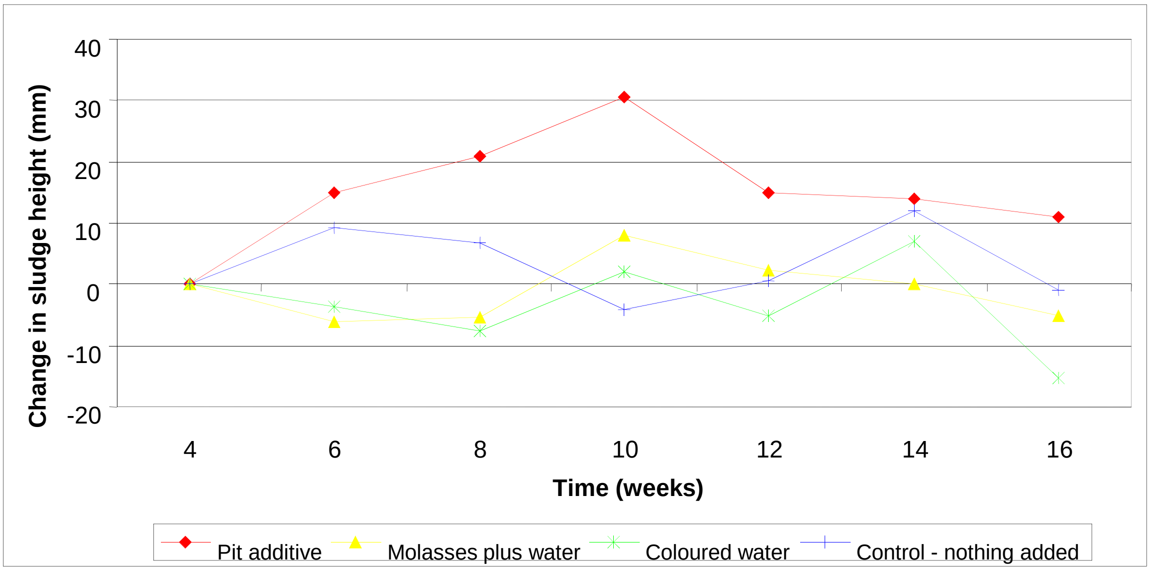


Figure 2.12 Median changes in sludge height from four 0.5 metre offset measurements

While sludge accumulation occurred at an irregular rate and with great variation between pits, the filling rates observed in this study showed that the pits were filling at approximately the same rate at which they had been filling during their first three years of use. The range of filling rates for that period was 46 to 638 litres per annum, with a mean of 339 litres per year and a median of 307 litres per year. The data does not indicate that the pit additive brought about any reduction in the accumulation rate of sludge in these latrines, even with a doubling of the dosage over the second half of the trial.

2.5.2 Conclusions

In all trials undertaken to date by the Water Research Commission, no evidence has been found that any of the pit additives tested made any difference to sludge build up. While one trial suggested that the addition of large amounts of water might reduce sludge build up, this result was not seen in the laboratory trials. This implies that the addition of water (or water and pit additive) probably did not increase biodegradation rates but that reduction in height was more likely due to the flattening of the surface by water, which possibly also increased leaching from the pit. This was confirmed by using imaging techniques to determine the volume change of pit contents.

These studies do not prove that all pit additives are ineffective, but that no evidence was found that a number of products on the market provide any measurable benefit. Clearly there is an urgent need for a standardised laboratory test protocol that is able to investigate the effects of pit additives under optimised, controlled and repeatable conditions. Until a standard test protocol is developed and put into force, the onus should be placed on manufacturers to demonstrate where and under what circumstances their products have worked. A laboratory protocol for testing pit additives was published by Foxon et al. (2009). Appendix B contains the requirements for a field testing protocol.

3 OBSERVATIONS OF SLUDGE ACCUMULATION RATES

The factors affecting filling rates are many and complex. It is therefore critical to have data of actual observed filling rates against which to test any theoretical models. The literature contains far more data on sludge build up in septic tanks than in pit latrines. This should not be surprising given the greater role of septic tanks as a sanitation solution for the more affluent.

3.1 On-site faecal sludge accumulation rates quoted in the literature

❖ Septic tanks

Table 3.1 gives some of the data from international studies on the filling rates of septic tanks. As can be seen the quoted rates vary from 22 ℓ/c.a to 95 ℓ/c.a. With so wide a range, unless one knows where the observations were made and under what circumstances, interpretation is impossible. For example, ambient temperature has an effect on sludge digestion rates, and user behaviour also has an effect.

Table 3.1 Filling rates of septic tanks (Norris, 2000)

Country	Reference	Mean filling rate litres/capita.annum
Not specific	Hill and Ackers, 1954	94.9
South Africa	Drews, 1985	32.9
USA	Wiebel, Stub and Thomas, 1949	21.9
India	Ensic, 1982	76.7
Australia	Sewards and Fimmel, 1982	29.2
Canada	Brandes, 1978	65.7

As a result the Water Research Commission conducted detailed field studies of filling rates of septic tanks in South Africa during the late 1990s. These results, which are summarised in Table 3.2, show that in South African conditions the lower end of the range (27 to 37 ℓ/c.a) is applicable.

Table 3.2 Observed filling rates of septic tanks in South Africa (Norris, 2000)

Location	Type of system	Number of measurements	Range of observations litres /capita.annum	Mean filling rate litres /capita.annum
Marselle, Eastern Cape	5 litre flush, septic tank, linked to wash trough	24	27.0 to 51.1	36.9
Umbumbulu, KwaZulu-Natal	1 litre flush, 1 m^3 septic tank, no sullage added	117	7.3 to 70.4	27.0
Ivory Park, Gauteng	1 litre flush, 1 m^3 septic tank,	15	20.1 to 44.9	30.3
Warden, Free State	Conventional flush, 4 m^3 septic tank with sullage	140	11.0 to 135.1	54.4

❖ Pit latrines

Because the sludge in a septic tank retains more moisture from the inflow of flushing water, despite continual leaching of liquid from the pit, septic tank studies do not provide a reliable guideline for estimating the filling rates of dry sanitation systems.

Unlike the case for septic tanks, the literature contains very little data on pit filling rates. Wagner and Lanoix (1958) used data gathered by the World Health Organisation in the 1950s. They found that sludge accumulation was approximately 40 litres per person per year. In wet pits and where solid anal cleansing material was used, they recommended that 60 litres per person per year be allowed for dry pits, and up to 50% more if large amounts of solid material (grass, stones etc.) are used for anal cleansing. These figures are still given as guidelines to calculate the life of pits by bodies such as WEDC and EAWAG (see Franceys et al., 1992 and Heinss et al., 1998), yet the original authors emphasised that pit filling rates should be developed for each country.

A study commissioned by the Water Research Commission (Norris, 2000) estimated the accumulation of sludge in pit latrines at 24 litres per capita annum. The study was carried out in Soshanguve in Gauteng. At this rate a family of 6 would accumulate 144 litres per annum, and hence a 2.5 m^3 pit would last approximately 17 years.

In 2009 the WRC published the research report *Basic Sanitation services in South Africa: Learning from the past, planning for the future* (Still et al., 2009). This report refers to the work by Norris and includes new data from a number of other field studies, which is reproduced in Table 3.3.

Table 3.3 Observations of pit filling rates (Still, 2009)

Location	Reference	Age of latrines	Number of sites monitored	Number of visits	Avg. pit volume m^3	Range of filling rates observed ℓ/c.a	Mean filling rate ℓ/c.a
Soshanguve	WRC Report	approx 3 years	11	14 over 28 months	1.96	13.1 to 34.0	24.1
Bester's Camp	City of Durban	four years	159	2 or 3 over 25 months	3.16	18.3 to 120.5	69.4
Mbila	New data	approx 5 years	11	1	2.83	10.0 to 33.2	18.5
Gaborone, Dar es Salaam	WHO Paper, 1982	not stated	not stated	Not stated	not stated	25 to 30	27.5 (implied)
Mbazwana	New data	11 years	19	1	3.40	14 to 123	29 (median)
Inadi	New data	11 years	25	1	2.00	14 to 77	34 (median)

Data from Brazil (Franceys et al., 1992) suggests that accumulation rates range from 40 ℓ/c.a where water was used for anal cleansing in a pit which is above the water table, to 90 ℓ/c.a where solid anal cleansing material is used and where the groundwater penetrates the pit. Shrestha et al. (2005) described a double vault urine diversion system (i.e. no urine entering the vault) with a 0.5 m^3 bucket filled every 6-7 months by 6 family members – a filling rate of 150 ℓ/c.a. This rate of filling is likely to be higher than for a pit latrine due to the lack of drainage and the addition of materials such as sand and ash. Brouckaert et al. (2005) suggested that drying of faeces in the filling phase of a double vault UD only takes place at the surface. Filling rates would be equivalent to the faeces produced per capita per annum less the loss of gases through decomposition.

3.2 New observations of pit filling rates

Further analysis was done of the data from the Besters Camp study conducted by Durban Corporation during the 1990s and the Mbazwana study conducted by Partners in Development more recently and new field studies have been conducted in a number of villages in Limpopo province and KwaZulu-Natal.

3.2.1 Besters Camp, 1995 (City of Durban)

Besters Camp is a peri-urban settlement in what is now the eThekwini Metropolitan Municipality. VIPs in the area studied were built between September 1991 and October 1992. The pits in the survey ranged from 2.55 to 3.82 m^3 in volume. The depth of the sludge below the pedestal was measured in

November 1993, and again in January 1995 (in some pits) and December 1995. The sludge in the pits was heaped, and measurements were taken approximately half way down the heap.

The calculated filling rates up to the first time of measuring (November 1993) showed a very wide range, and the maximum values seemed impossibly high (Table 3.4). The data collected during the two year monitoring period thereafter (to December 1995) showed a filling rate per person per annum ranging from a negative value (sludge volume decreasing) to a maximum value of 259 ℓ/c.a, which again are improbable figures. However, calculated for the period from construction to November 1995, the means were 354 ℓ/a and 70 ℓ/c.a, and the median filling rate was 64 ℓ/c.a. These figures, calculated from the original pit volume, and the measurements taken at the end of the study, seem far more realistic. It is likely that the initial measurements were seriously flawed, and the calculated filling rates for the two year study period would have also been affected by these. For the purposes of further comparisons, the rates calculated for the overall period from construction to November 1995 were used (i.e. the right hand column in Table 3.4).

Table 3.4 Filling rates calculated from unselected data, City of Durban, 1995

	Sludge accumulation rate (ℓ/a)			Sludge accumulation rate (ℓ/c.a)		
Period	To Nov '93	Nov '93 - Dec '95	to Dec '95	to Nov '93	Nov '93 - Dec '95	to Dec '95
Mean	512	271	354	104	42	70
Median	467	254	340	85	40	64
Max	2001	929	696	654	259	230
Min	99	-233	-23	25	-86	-3
Std Dev	251	199	145	78	45	42

The Besters figures point to the difficulty in obtaining accurate measurements for pit contents. They also suggest that the filling rates in peri-urban areas may be considerably higher than the Soshanguve study (see Table 3.3) indicated. Figure 3.1 below shows the wide range in the pit filling rates calculated from the Besters data.

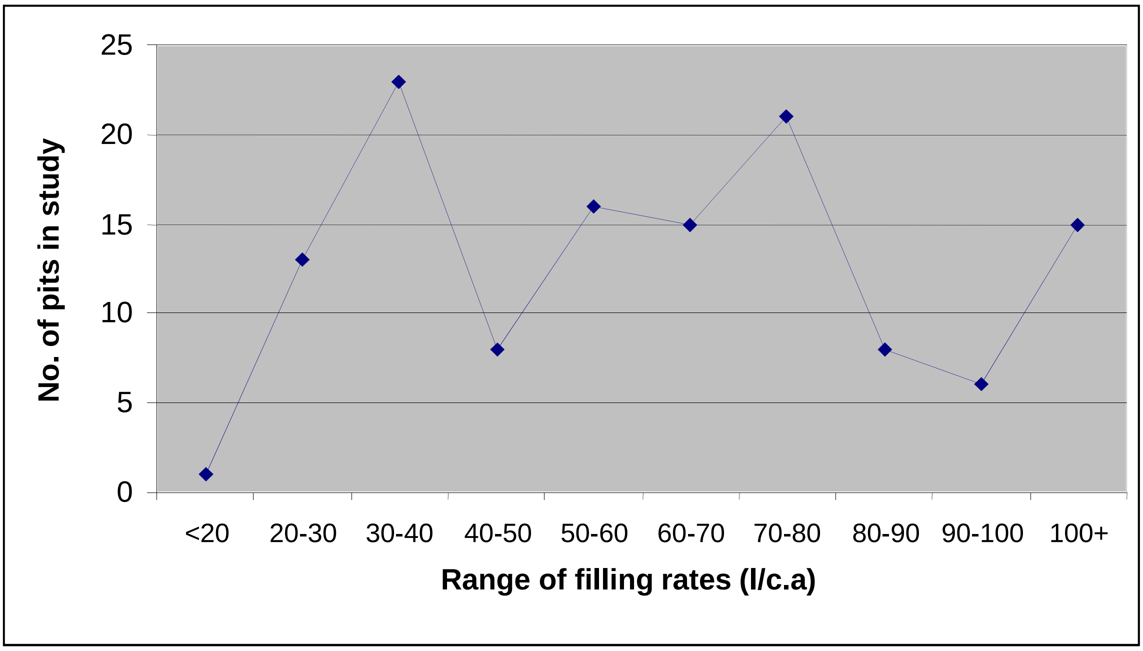


Figure 3.1 Distribution of pit filling rates in Besters study

3.2.2 Mbazwana (2000 and 2006)

Studies conducted by Partners in Development in 2000 and 2006 in Mbazwana in northern KwaZulu-Natal show pit filling rates which are closer to those for Soshanguve, with the median in the earlier measurements under 20 ℓ/c.a and 27 ℓ/c.a for the later study. Pits filled at median rates of 186 and 219 ℓ/a for the earlier and later measurement periods respectively.

Table 3.5 Filling rates calculated from Mbazwana

	Sludge accumulation rate (ℓ/a)	Sludge accumulation rate (ℓ/c.a)	Sludge accumulation rate (ℓ/a)	Sludge accumulation rate (ℓ/c.a)
Pit age	5 years (2000)		11 years (2006)	
Mean	185	19	221	31
Median	186	18	219	27
Max	305	33	376	78
Min	106	10	109	14
Std Dev	69	6	61	16

3.2.3 Limpopo (2009)

In 2009 as part of this study Tsogang (an NGO involved in rural water and sanitation) measured the sludge depth in 100 pits of known dimensions distributed over five villages. The pits ranged in volume from 4.32 m^3 to 6.48 m^3. They were built between 1997 and 2000, in rural villages in the Limpopo province. The results of this investigation are shown in Figure 3.6 below.

Table 3.6 Filling rates calculated from Limpopo Province

	Sludge accumulation rate (ℓ/a)	Sludge accumulation rate (ℓ/c.a)
Mean	301	43
Median	296	39
Max	585	109
Min	3	1
Std Dev	110	20

The mean sludge accumulation rate was 301 ℓ/a, and 43 ℓ/c.a. The median values were 296 ℓ/a and 39 ℓ/c.a. The data did not exhibit the extreme values found in the Besters study. Eight pits showed accumulation rates below 20 ℓ/c.a, and 7 showed values over 80 ℓ/c.a. The distribution of filing rates is shown in Figure 3.2.

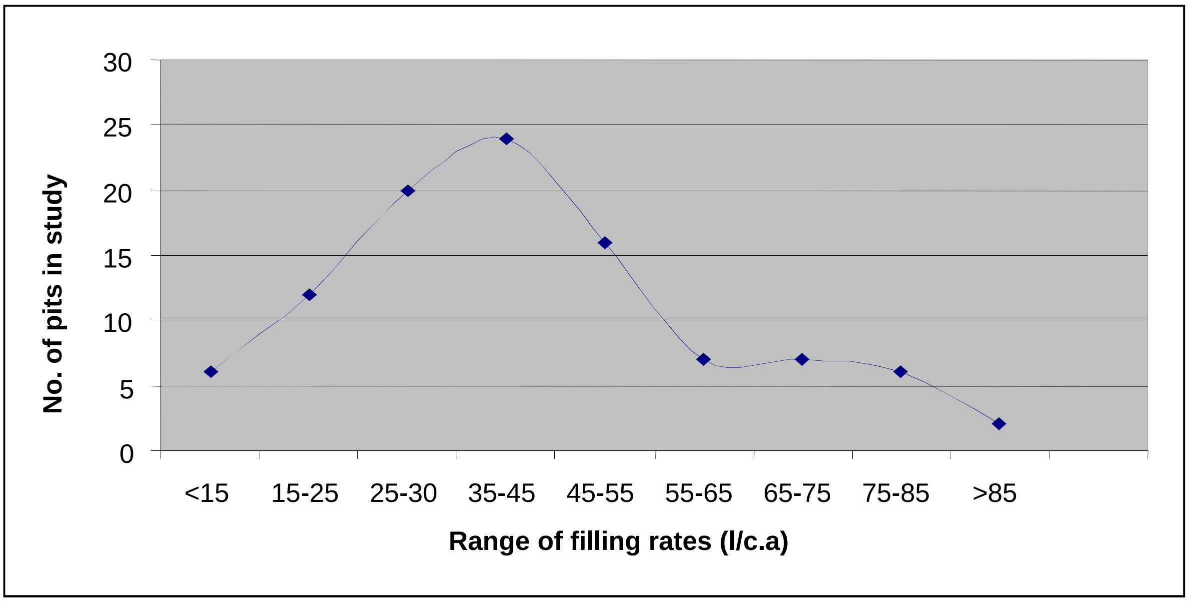


Figure 3.2 Distribution of pit filling rates in Limpopo study

3.2.4 Mafunze (2009)

In 2009, Partners in Development calculated sludge accumulation rates in VIPs in Mafunze, a rural settlement near Pietermaritzburg. The pits were built in 2006 and were fully lined, with a pit volume of 4.2 m^3. Sludge accumulation was calculated for the period September 2006 - September 2009.

Table 3.7 Filling rates calculated from Mafunze, KZN

	Sludge accumulation rate (l/a)	Sludge accumulation rate (l/c.a)
Mean	352	48
Median	307	42
Max	638	146
Min	46	11
Std Dev	172	29

The pits in this study were subjectively assessed for the amount of non-faecal matter in the pits. In some pits there was a large amount of newspaper, while others contained plastic bags and other non-biodegradable material. The pits were rated on a three point scale, from 1 (no rubbish) to 3 (high rubbish content). Half of the pits in the study fell into the latter category, and the median filling rate in this group was 50 ℓ/c.a against 33 ℓ/c.a in the medium or low rubbish group. When calculated as pit filling rates, these figures were 476 ℓ/a for the high rubbish pits and 248 ℓ/a for the others. The lowest rubbish group had a median value of 229 ℓ/a. This suggests that rubbish thrown into pits almost doubles their filling rate, and this may explain why municipalities find that pits are filling at a higher rate than was anticipated. In other words, the use of pit latrines to manage solid waste is significantly reducing the useful lives of much of our dry on-site sanitation infrastructure.

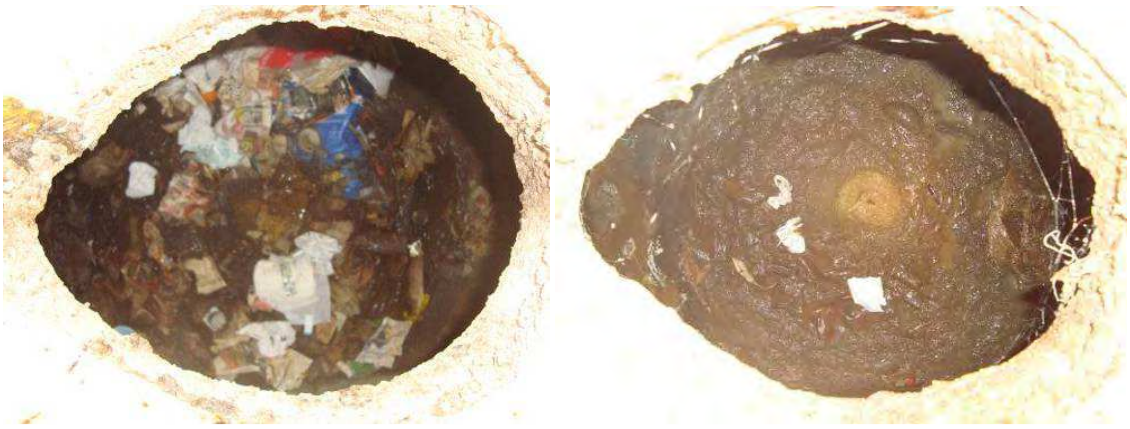


Figure 3.3 Two pits from the Mafunze study, showing high and low rubbish levels

A frequency distribution for the filling rates (see Fig. 3.4) suggests a bimodal distribution for the data, probably due to variation in user behaviour with respect to disposal of solid waste.

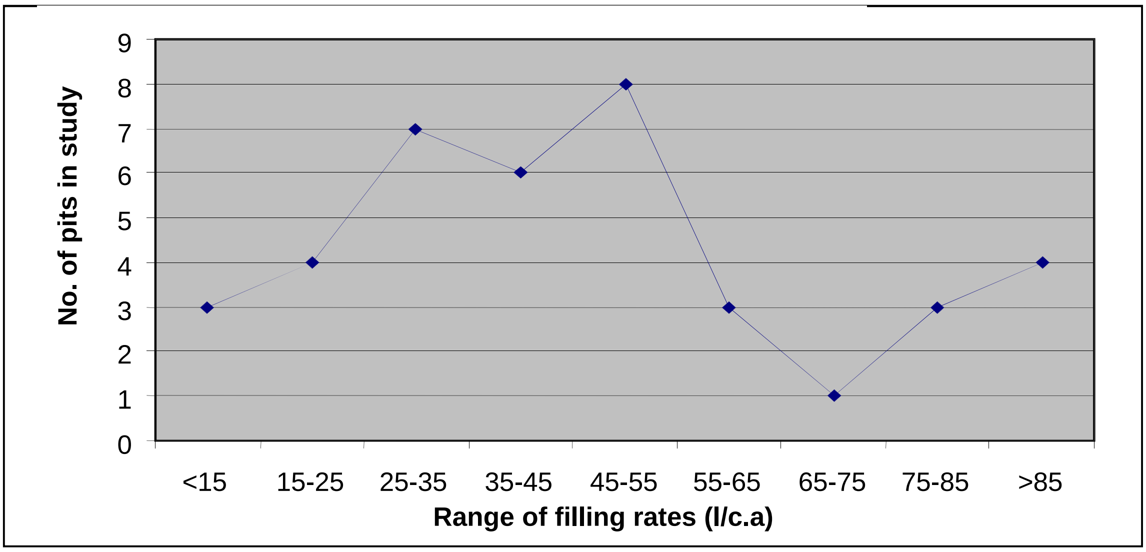


Figure 3.4 Distribution of pit filling rates in Mafunze study

3.2.5 Ezimangweni, KZN (2009)

The contents of VIPs were measured during a pit emptying programme carried out by eThekwini Municipality. A sample of 40 VIPs was assessed and the filling rates appeared to be much lower than those in the Besters study (see section 3.2.1 above). The median of the values for sludge accumulation was 109 ℓ/a 21 ℓ/c.a.

Table 3.8 Filling rates calculated from Ezimangweni (UKZN)

	Sludge accumulation rate (ℓ/a)	Sludge accumulation rate (ℓ/c.a)
Mean	115	27
Median	109	21
Max	255	164
Min	24	5
Std Dev	52	27

3.2.6 Further eThekwini data

VIP latrines from four different low cost housing communities in eThekwini Metro Municipality were studied by either estimating the volume of pit contents using pit height measurements and pit design data, or by recording the amount of sludge removed during pit emptying. The communities investigated were Savana Park, eFolweni, eZimangweni Area 1 and eZimangweni Area 3. The VIPs were lined single pits and were approximately 1.5 m deep. A summary of the sludge accumulation rate results obtained from the four communities is presented in Table 3.9. The sludge accumulation rate is calculated as litres per person per year ± 95% confidence interval on the mean.

Table 3.9 Pit sludge accumulation rates from four communities in eThekwini Municipality

Location	Number of pits	Average no. of users	Accumulation rate (ℓ/c.a)
Savana Park	12	6.2	31 ± 21
eFolweni	15	7	44 ± 46
eZimangeni 1	40	6.6	28 ± 10
eZimangeni 2	8	5.4	22 ± 7

The average accumulation rate for pit latrine sludge in communities served with VIP latrines was between 21 and 44 ℓ/c.a. The overall average sludge accumulation rate obtained for all the four communities in which a total number of seventy six pit was investigated was 31 ± 10 m^3 ℓ/c.a.

3.3 Discussion

Table 3.10 Filling rates averaged across studies

Location	Reference	Age of Latrines	Number of sites monitored	Avg. pit volume m^3	Range of filling rates observed ℓ/c.a	Mean filling rate ℓ/c.a
Soshanguve	WRC Report	approx 3 years	11	1.96	13.1 to 34.0	24.1
Bester's Camp	City of Durban	four years	159	3.16	18.3 to 120.5	69.4
Mbila	New data	approx 5 years	11	2.83	10.0 to 33.2	18.5
Gaborone, Dar es Salaam	WHO Paper, 1982	not stated	not stated	not stated	25 to 30	27.5 (implied)
Mbazwana	New data	11 years	19	3.40	14 to 123	29 (median)
Inadi	New data	11 years	25	2.00	14 to 77	34 (median)
Limpopo	Tsogang study 2009	9-12 yrs	100	5.4	1 to 109	39 (median)
Mafunze	PID, 2009	3 years		4.2	11 to 146	48 (median)
Ezimangweni	eThekwini Municipality, 2009	14 yrs	40		5 to 164	21 (median)
eThekwini	PRG, 2010	10-14yrs	35	2.25	3 to 264	19

These studies show a range of median pit filling rates, from as low as 109 ℓ/a and 21 ℓ/c.a in the Ezimangweni area, to as high as 340 ℓ/a and 64 ℓ/c.a in Besters. Both of these settlements are in the eThekwini area, but two differences are i) that Besters is a very dense settlement, and ii) the Besters data was collected when the latrines were still in the early stages of filling. It is possible that the pits in Besters were poorly drained and part of what the observers were reporting as sludge was in fact just retained water, accounting for the fact that the data was significantly higher than that observed in the other seven studies.

Pit accumulation rate data is typically reported in units of volume accumulated per person per year. Therefore data from these and other studies is obtained by measuring the amount of material accumulated in a pit, dividing this value by the period of time the pit has been in use, or the time since it was last emptied, and dividing again by the average number of users as reported by the household.

When the respondent is asked how many people use the toilet, they are in fact being asked how many people on average throughout the year use the toilet, across the years that sludge has been accumulating in the pit. This question is difficult to answer accurately. Children will contribute less to the pit than adults, and typically some members of the household will only use the toilet in the morning and at night as they are away from the home during the day, while other members of the household are home all day. Men may urinate outdoors rather than in the toilet. Over the years that sludge has been accumulating in the pit some members of the family may have moved away and others may have been added to the household. In addition, there may have been previous occupants at the house who contributed to the current contents of the pit representing a different number of users responsible for a portion of the sludge. Because of the complexity of this question, it is difficult to ensure that it is correlated accurately to data obtained on pit filling rates.

When calculated pit filling rate is plotted against the number of users in a household, an interesting result is obtained: there is a definite reduction in the per capita user rate as the number of users increase. This is shown using the data obtained by the research into accumulation rates undertaken as part of this project in Figure 3.5. Similar effects have been seen from other data sets (Still et al., 2010)

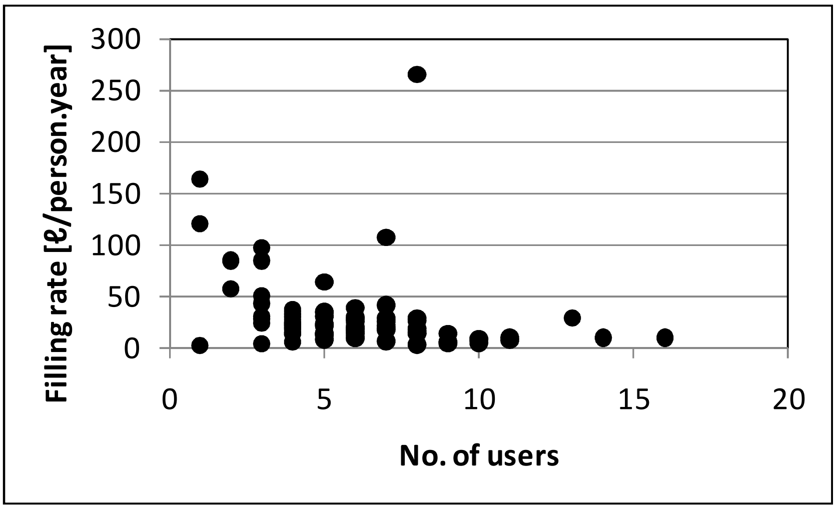


Figure 3.5 Per capita filling rate as a function of number of users for the eThekwini 2010 study

This result gives rise to conjecture about the nature of biological processes and the habits of users at high usage rates. However, when the data is plotted as filling rate per pit, it is observed that the data indicates that the per pit filling rate is not dependent on the number of users (Figure 3.6)

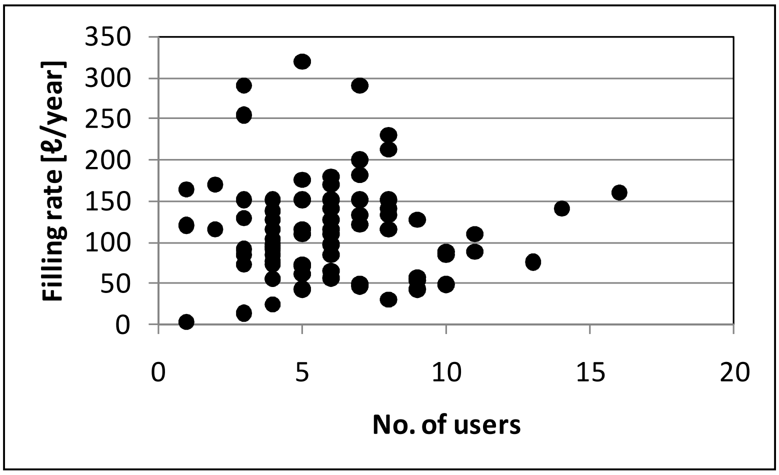


Figure 3.6 Per pit filling rate as a function of number of users for the eThekwini 2010 study

When the data is presented in this way, it suggests that the filling rate is not a function of reported number of users, but rather depends on a range of other factors not recorded, or more likely that the reported number of users does not represent how many people on average throughout the year use the toilet, across the years that sludge has been accumulating in the pit as described above, and therefore does not correlate well with the sludge accumulation rate.

To test whether this is a likely explanation, the statistical characteristics of a large set of accumulation rate data and corresponding reported number of users were analysed (average, distribution type and variance). From this information, a random number set was generated using the same average and distribution type and variance as the accumulation rate data, and another *independent* random number set was generated with the same statistical properties as the reported number of users data. When the two sets were plotted against one another, the plot showed the same decreasing trend as in Figure 3.5. This result indicates that the apparent decrease in per capita filling rate with increasing number of users is a mathematical artifice of dividing an approximately constant property by an increasing one, and specifically, that the data on number of users is not different to a completely random number set. This suggests that the reported number of users in any study is not a particularly trustworthy data type. It also suggests that the per pit filling rate is a more useful design factor then the per capita filling rate which in any case would require that the designer estimate the probable number of users, a figure which is likely to prove to be as variable as the historical number of users of an existing pit.

Regardless of user numbers, in the studies assessed most pit filling rates were between 200 and 500 litres per annum, and many from the eThekwini studies were below these values. The data in these studies suggest that 40 ℓ/c.a is a good figure to work with for design purposes. Figures of up 60 ℓ/c.a are not unusual, however, and planning for large scale pit emptying programmes should take the higher figures into account.

In the case where the municipality is to manage the emptying programme (i.e. householders not responsible for emptying) the desired pit volume can be calculated as follows:

t = Frequency of emptying (assume 5 years)

r = Design filling rate for emptying at a frequency of t (assume 60 ℓ/person.year)

n = Average number of users in household (assume 6 people)

The desired useful pit volume is calculated as

$$V = r \times n \times t$$

For the assumed values,

$$\begin{aligned} V &= 60\ \ell/\text{person.year} \times 6\ \text{people} \times 5\ \text{years} \\ &= 1\,800\ \ell \\ &= 1.8\ \text{m}^3 \end{aligned}$$

Note that a pit typically does not fill evenly, but rather in a heap, so when calculating a pit volume at least the top half metre of the pit height should be discounted. A related consideration is that a pit toilet which is near full is more likely to smell and is more likely to be visually offensive, so the top portion of the pit should be thought of as freeboard.

Thus if the pit is designed to have width and length of 1.0 m and 1.2 m, the depth (d) of the pit should be

$$d = \frac{V}{1.2\ m \times 1.0\ m} + 0.5\ m = \frac{1.8\ m^3}{1.2\ m \times 1.0\ m} + 0.5\ m = 2\ m$$

The removal of sludge from pits deeper than 1.5 metres is impossible using manual methods (unless the emptier climbs inside the pit, which is a serious health risk), and difficult using vacuum tankers (due to the high suction pressures involved). For this reason some advocate the use of smaller and shallower pits which should be emptied more frequently (e.g. every three years) rather than large pits to be emptied less often.

4 MODELLING OF PIT FILLING RATES

If it is assumed that the average person produces approximately 110 ℓ of faeces every year (Section 2.2), and that in addition to faeces, other solid material including anal cleansing material and possibly other household solid waste enters the pit, it is clear that the rate of material entering a pit is much greater than the average accumulation rate of 40 ℓ per person per year (Section 3.3). This clearly indicates that a *significant* degree of volume reduction occurs in a pit latrine as a result of biological breakdown, compaction and leaching.

A study was undertaken to develop a model of the breakdown and accumulation of sludge in a pit latrine. The study is presented in detail in Appendix A. This section presents a summary of the results of the modelling exercise.

Four processes occur within a pit that will impact the rate at which it will fill: the addition of new material into the pit, the transfer of water into and out of the pit, biological transformations, and pathogen die-off (Buckley et al., 2008). The pit contains a range of substances including faeces, urine, anal cleansing material, and general solid waste. The contents of a VIP have an aerobic surface layer, but anaerobic conditions prevail in deeper layers. Thus the exposed surface of pit contents, especially newly added material, will be subject to aerobic biological processes. As the pit contents are covered over and oxygen supply is limited, conditions in the pit become anaerobic, and anaerobic biological processes will dominate. The amount of time faecal sludge spends under aerobic conditions depends on the rate at which material is added to the pit, and pit dimensions (Buckley et al., 2008).

A simple material-balance model of the filling and degradation processes occurring in a pit latrine was developed, and compared with field measurements. The model divided the contents into three fractions: biodegradable organic matter, matter that was originally un-biodegradable when deposited into the pit, and un-biodegradable matter formed by the biodegradation process. The originally un-biodegradable material is conceptualised as a combination of the un-biodegradable fraction of faecal material and any other un-biodegradable household rubbish. Because of the heterogeneous origin of the material, the model is formulated on a volume basis, to avoid complexities associated with density variations.

The model uses a single degradation rate and a single feed addition rate, and describes the relationship between age, location and composition of material in a pit latrine at a particular time after the pit was first commissioned.

It was found that the model was able to adequately describe changes in composition with depth in the pit assuming that the starting material was the same as the characteristics measured on the surface of the pit. The model did not describe the changes that occur on the surface of the pit immediately after new material is deposited as these occur under aerobic conditions and at a different rate to processes within the bulk of the sludge.

Figure 4.1a shows the variation of COD in the pit latrine with increasing depth. It can be seen that for the pits modelled, the COD rapidly decreases with depth to a depth of approximately 1 m below the surface of the pit. Thereafter, the COD content remains approximately constant. This indicates that the material below 1 m is relatively well stabilised and does not undergo any further degradation.

In contrast, the model was not able to accurately predict moisture content as a function biological reaction (Figure 4.1b)

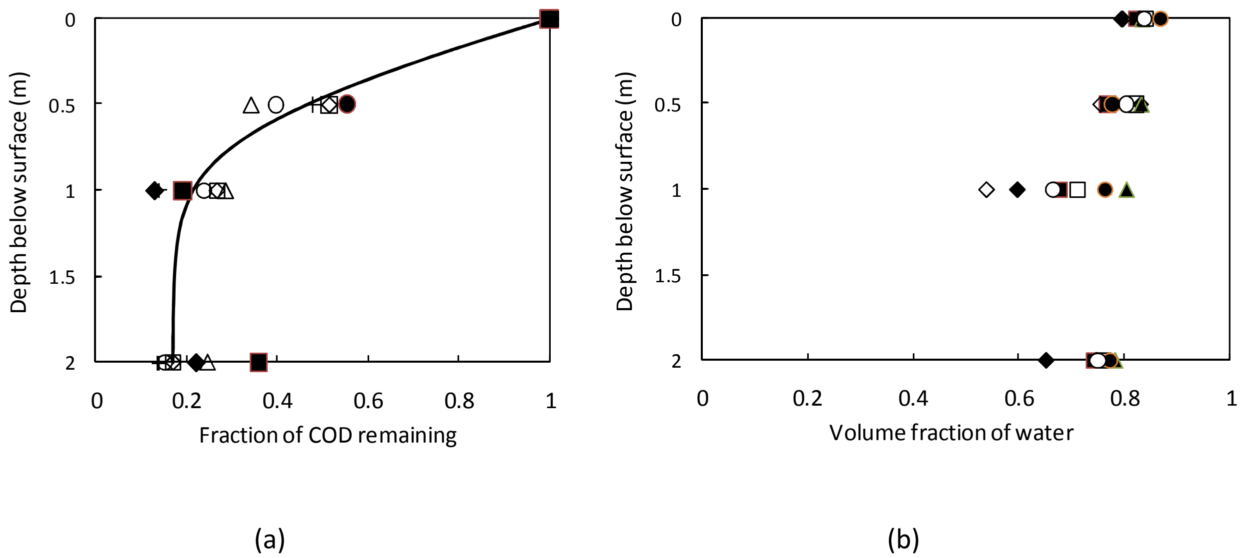


Figure 4.1 Variation of COD and moisture content with increasing depth

The data clearly showed that water is not conserved in the pit, and indeed it would be surprising if it were, since the pits are not sealed. There is an exchange of water between the pit and the surrounding soil that cannot be characterised from the data measured in this study. To get around lack of knowledge about the water movement, the model was compared with the measured compositions on a water-free basis. However, the volume of pit contents must reflect the volume of water, so the modelled volumes of dry material were scaled up using the average measured value for the water content of the pits.

The purpose of developing the pit filling model is primarily to assist municipal planners to formulate strategies for managing low cost sanitation services based on pit latrines. If the model is accepted as the best estimate available for a process filled with uncertainties, the following scenarios illustrate how it might be used to evaluate strategies for designing a sanitation service based on pit latrines. Figure 4.2 considers how the volume in the pit will vary with time for various proportions of un-biodegradable material in the feed (these proportions are on a water-free basis, whereas the volume is based on the average water content). The solid black line (20%) corresponds to the parameter values that fitted the pit data of this investigation. The 7.8% line is calculated for zero ash content, and represents an asymptotic (but improbable) case. The model clearly shows the impact of increasing the amount of non-biodegradable material in the pit on the filling rate: increasing the unbiodegradable fraction from 15% to 25% will reduce the amount of time required to accumulate a volume of 1.5 m^3 by more than 5 years. This highlights the importance of keeping solid waste out of pit latrines to maximise pit life-span. Figures 4.3 and 4.4 examine the characteristics of pit contents averaged over the entire volume, representing what would be taken out the pit when emptied, assuming that the stratified contents would become mixed during emptying. Figure 4.3 shows the volume fraction of material that is still biodegradable, and Figure 4.4 its ash content. These plots indicate that the longer material is left in a pit, the greater the degree of stabilisation of the pit contents when it is exhumed. Using the parameters obtained from the model fitting exercise (biodegradable:unbiodegradable volume addition ratio = 3.8:1) the average fraction of biodegradable material in accumulated pit contents would reduce from nearly 80% to less than 40% over a 10 year period. Depending on the final fate of the pit sludge, this information might be important for designing pit size and emptying frequency to ensure that the exhumed sludge has appropriate characteristics for burial, composting etc.

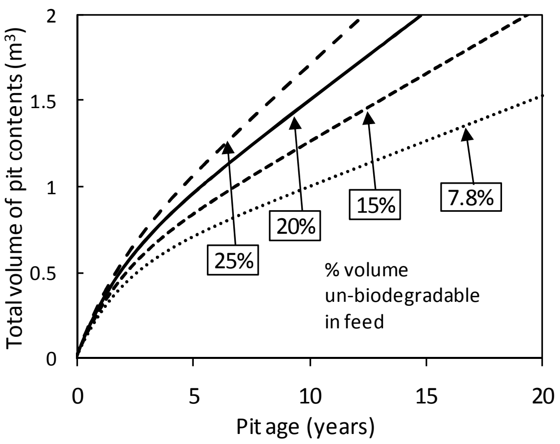


Figure 4.2 Volume of pit contents for four different scenarios.

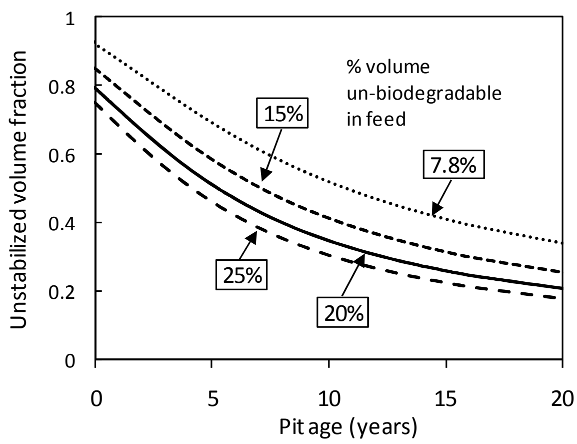


Figure 4.3 Overall biodegradable content of pit for four different scenarios.

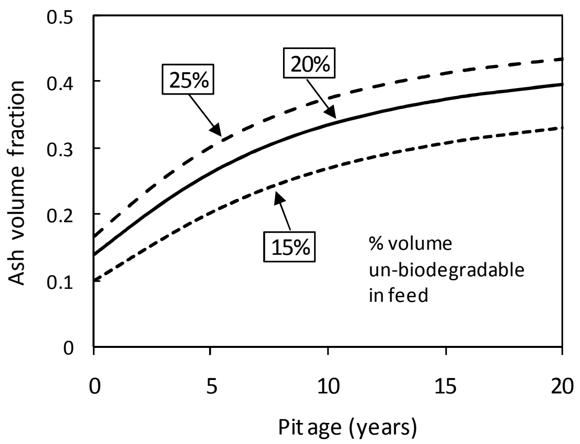


Figure 4.4 Average ash content of pit for various scenarios.

Given the uncertainties involved, it seems unlikely that the design of a pit latrine based sanitation service would be driven primarily by the factors described by the model, but rather by considerations of logistics, human resources and cost. However, the model may be useful to estimate some of the implications of any chosen system design. Nevertheless, the following conclusions may be drawn from the results of the modelling study:

- ❖ The quality of the data obtainable from sampling pit latrines is by nature very scattered, such that more sophisticated modeling of the processes in pit latrines *is not justified.*
- ❖ There appears to be a systematic variation of organic content and ash with depth, in that at least 7 of 18 pits showed decrease in COD with corresponding increase in ash content relative to surface samples with increasing depth.
- ❖ The model predicts that the influence of the addition of non-degradable material on the filling rate is significant. Thus, if the intention of the system design is to maximise the life of the pit or to minimise the pit filling rate, an effective solid waste management system must also be implemented within the community.

- The average biological stability of the pit sludge increases with time. Pit design and emptying frequency may be designed around the required stability of the sludge when the pit is emptied.

If we accept that the model gives a reasonable prediction of pit filling rates under the conditions for which it is calibrated (dry pits – no free liquid surface, KwaZulu-Natal coastal climate) then it is possible to predict how long it will take for pit latrines to fill up under a range of conditions. The following table shows the time required to fill a pit to within 0.5 m of the top for three different pit sizes, 1 m^3, 1.5 m^3 and 2 m^3, for three different filling rates (4 people per household, 7 people per household, 12 people per household) and for three different rubbish addition rates (low rubbish estimated as 12% un-biodegradable material in feed, medium rubbish estimated as 20% unbiodegradable material in feed and high rubbish at 28% unbiodegradable) in the feed. Thus the entry corresponding to the pits examined was for a 2 m^3 pit for a household of 7 people with medium rubbish addition.

Table 4.1 Pit filling time [years]

	Slow addition (4 people)			Average addition (7 people)			Fast addition (12 people)		
Pit size [m^3]	Low rubbish	Med rubbish	High rubbish	Low rubbish	Med rubbish	High rubbish	Low rubbish	Med rubbish	High rubbish
1	16	12	10	7	5	5	3	2	2
1.5	27	21	17	13	10	8	5	4	4
2	38	29	24	19	15*	12	9	7	6

*model calibrated using data for this condition

Note all values other than the one for which the model was calibrated should be regarded as predictions only as they make use of a number of assumptions. For example it was assumed that the amount of rubbish entering the pit was directly proportional to the number of users; this is probably not accurate as bulk items like nappies, blankets, kitchen waste are probably characteristic for a household, rather than the number of users, and the relationship between amount of rubbish and number of users would probably not be directly proportional. However, this table provides a clear illustration of the relationship between the number of users, rubbish content and pit size and may be useful for informing decisions relating to design of pit size and municipal emptying programme.

Using the simple design equation in Section 3.3 we find that the data for the medium rubbish entries corresponds to average filling rates of 18 ℓ per person per year for the slow addition scenario (4 users), 22 ℓ per person per year for the medium addition scenario (7 users) and 30 ℓ per person per year for the fast addition scenario. These numbers are lower than the general values of 40 m^3 proposed in Section 3.3, but match the numbers measured during a pit filling rate study in eThekwini which yielded a 95% confidence interval for pit filling rate in the areas studied of 21 ℓ per person per year to 41 ℓ per person per year. Thus the numbers presented in Table 4.1 apply to the conditions found in the eThekwini study. It is likely that the numbers for other regions may be higher due to different user practice, and also slower degradation rates expected at lower ambient temperatures.

This study suggests that a pit filling rate of 40 ℓ per person per year is reasonable, and that designing the emptying cycle for a maximum of 60 ℓ per person per year is conservative, but will ensure that virtually no pits are completely filled during the emptying cycle unless through gross abuse on the part of the users.

5 CONCLUSIONS

If no degradation occurred within a pit at all, an average sized pit (2.5 m^3) would fill in approximately 3 years. With active aerobic and anaerobic degradation processes occurring within the pit, however, it could take as long as 25 years to fill, if the content of non-degradable solids is low. Analysis of sludge at different depths shows that almost all the degradation takes place within the first 4 years that material is in the pit, with a decrease in COD and an increase in ash content relative to surface samples with increasing depth. The stabilized material in the bottom of the VIP (containing stabilised faeces and non-biodegradable solids) reduces to about a quarter of the volume of fresh excreta. Water leaching from the pit carries the majority of the soluble components out of the bit before reaching the bottom of the pit. For this reason it is critical that the pit walls are constructed in such a way that this leaching can take place.

In practice, about a quarter of the pit volume is composed of non-biodegradable household solid waste. Allowing for this, a pit can be expected to fill in 10 years or less depending on the size of the pit, the number of users and the amount of rubbish put into the pit. It is vital that municipalities understand the role that an effective solid waste management programme has in determining the lifespan of pit latrines and therefore the frequency at which pits will have to be emptied. By providing householders with reliable rubbish collection and emphasising the importance of keeping rubbish out of pits, municipalities may be able to extend the lifespan of pits by at least 50%.

A number of products are marketed in South Africa with the claim that they will slow or halt accumulation of sludge in pits, significantly reducing the frequency at which they need to be emptied or eliminating the need to empty altogether. The Water Research Commission has tested approximately twenty of these products in either field or laboratory trials using testing protocols developed by the Pollution Research Group at the University of KwaZulu-Natal. To date, none of the products tested have had any measurable impact on pit filling rates. It is important that municipalities understand that the efficacy of these products has not been demonstrated. There is an urgent need to establish independent testing of these products. Until a product has been demonstrated to have a significant impact on filling rates, it is advisable that municipalities dedicate their operations budgets to methods for servicing pits that have been proven to be effective and sustainable.

It is vital that municipalities take a proactive approach to pit maintenance. If pits reach capacity and the municipality does not have the necessary resources, methods and technologies in place to service pits, households will eventually be without sanitation, a situation which would gravely compromise both public health and human dignity. The model developed in this study shows the relationship between filling rate and the amount of rubbish that is added to a pit latrine. Pit filling rates across South African communities typically range from 200 litres per annum to 500 litres per annum. This translates into approximately 40 litres per person per annum. Ideally, municipalities should develop an integrated on-site sanitation management programme in which pits are designed with a capacity that matches the pit emptying cycle. While designing for a pit capacity of 40 litres per person per year, planning a pit emptying programme around a figure of 60 litres per person per year will ensure that pits that have higher numbers of users than they were designed for will still be accommodated within the emptying cycle.

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APPENDIX A: MODELLING THE FILLING RATE OF PIT LATRINES

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INTRODUCTION

The Ventilated Improved Pit latrines (VIPs) in eThekwini Metro Municipality are lined single-pits and include the four necessities of a VIP: a pit 1.5 m deep (or deeper), a foundation and cover slab, a superstructure and a vent pipe with a fly screen (Mara 1984). The pit is for the collection of excreta, the superstructure provides shelter and privacy, the foundation and cover slab prevent collapse and the vent pipe reduces odour by providing airflow and reducing the presence of flies by trapping them in the pit and attracting them away from the toilet entrance.

Of the approximate 3.3 million inhabitants in the eThekwini municipality, about 206 000 households are without basic sanitation (EWS 2011). Most of these households are located in informal settlements in the suburbs. Just outside major economic centres, the level of development drops quickly and poverty is prevalent. Despite these statistics and the recent urban development in localized areas, approximately 100 000 households in the eThekwini municipality currently use pit toilets as their primary mean of human excreta disposal, although many of these are user-built rudimentary pits that do not qualify as adequate sanitation. eThekwini Municipality has undertaken the task of emptying all pit latrines on a 5 year cycle. During the first round of emptying, it was found that the average age of the pits was approximately 14 years, and many of the pits were full or overflowing and in urgent need of emptying. The municipality proposed that a 5 year cycle should be used for emptying since this was possible from an organisational point of view, and most pits are expected to require more than 5 years to fill. In addition, 5 years is the amount of time that a standard pit servicing an average family (5.5 people per household) will receive a volume of material equal to the holding volume of pit, or, in other words, the average pit will fill completely in 5 years if no degradation of pit contents occurs. The cost of emptying a pit, depending on removal method, content disposal location, accessibility of pit, and terrain, ranges between R 600 and R 1 000 per pit (WIN-SA 2006 values). The cost of pit emptying is more closely aligned to the number of pits emptied than to the volume of pits emptied. Thus, from an economic point of view, a better understanding of pit filling rates would assist in more cost-effective design of the pit emptying program.

Four processes occur within a pit that will impact the rate at which it will fill: the addition of new material into the pit, the transfer of water into and out of the pit, biological transformations, and pathogen die-off (Buckley et al., 2008). The pit contains a range of substances including faeces, urine, anal cleansing material, and general solid waste. The contents of a VIP have an aerobic surface layer, but anaerobic conditions prevail in deeper layers. Thus the exposed surface of pit contents, especially newly added material, will be subject to aerobic biological processes. As the pit contents are covered over and oxygen supply is limited, conditions in the pit become anaerobic, and anaerobic biological processes will dominate. The amount of time faecal sludge spends under aerobic conditions depends on the rate at which material is added to the pit, and pit dimensions (Buckley et al., 2008).

MATERIALS AND METHODS

Overview

A simple material-balance model of the filling and degradation processes occurring in a pit latrine was developed, and compared with field measurements. The model divided the contents into three fractions: biodegradable organic matter, matter that was originally un-biodegradable when deposited into the pit, and un-biodegradable matter formed by the biodegradation process. The originally un-biodegradable material is conceptualised as a combination of the un-biodegradable fraction of faecal material and any other un-biodegradable household rubbish. Because of the heterogeneous origin of the material, the model is formulated on a volume basis, to avoid complexities associated with density variations.

Two pit latrines were examined for this study: the pits were located in the same community (Savana Park) in the eThekwini Municipality, and had very similar user profiles, geography, climate, design and construction. Both VIPs selected were filled to within 0.2 m of the top of the pit, the reported average number of users of each pit was 7 and the pits were located on slopes. VIP 1 was on the top of a steep slope while VIP 2 was on the hillside. Both pits had the same concrete block construction and were in approximately the same condition with an intact superstructure. Neither pit had ever been emptied previously. Samples were collected at the top of the pit, after the top 0.5 m of material was removed, (0.5 m down), 1.0 m down and the bottom of the pit, approximately 2.0 m below the original pit content level.

Since there is a great deal of uncertainty about the filling process over the history of the pits, the results from these two pits were compared to less intensive data from a study by Bakare (2012) from a further 16 pits located in various settlements in the eThekwini area in order to assess to what extent the results could be considered typical or anomalous.

PIT FILLING MODEL

Consider a volume of material which initially consists of v_{b0} m^3 that is biodegradable and v_{u0} m^3 that is un-biodegradable. Each m^3 of biodegradable material degrades to form k m^3 of new un-biodegradable material. The volume of new un-biodegradable material is represented as v_n m^3, with initial value $v_{n0=0}$.

The rate of degradation is given by , $\frac{dv_b}{d\vartheta} = -r \cdot v_b$

Then, after the material has remained in the pit for time θ, the un-biodegradable material formed by degradation is $v_n(\theta) = kv_{b0}\left(1 - e^{-r\theta}\right)$, and the original un-biodegradable material present is $v_u(\theta) = v_{u0}$

The total volume present at age θ is

$v(\theta) = v_b(\theta) + v_n(\theta) + v_u(\theta) = v_{b0} \cdot e^{-r\theta} + k \cdot v_{b0}\left(1 - e^{-r\theta}\right) + v_{u0} = v_{u0} + k \cdot v_{b0} + (1-k)v_{b0} \cdot e^{-r\theta}$

The ratio of the total volume present to the volume of originally un-biodegradable material is:

$$\phi(\theta) = \frac{v(\theta)}{v_u(\theta)} = \frac{v(\theta)}{v_{u0}(\theta)} = 1 + k\frac{v_{b0}}{v_{u0}} + (1-k)\frac{v_{b0}}{v_{u0}}e^{-r\theta} \quad \text{.... (1)}$$

The fraction of biodegradable material present is:

$$\beta(\theta) = \frac{v_b(\theta)}{v(\theta)} = \frac{v_{b0} \cdot e^{-r\theta}}{v_{u0} + k \cdot v_{b0} + (1-k)v_{b0} \cdot e^{-r\theta}} = \frac{\frac{v_{b0}}{v_{u0}}e^{-r\theta}}{1 + k\frac{v_{b0}}{v_{u0}} + (1-k)\frac{v_{b0}}{v_{u0}}e^{-r\theta}} \quad \text{.... (2)}$$

Ash content is measured on a mass fraction basis, and is a sub-fraction of the originally un-biodegradable fraction. Assuming that the ash fraction has density ρ_a and the remainder of the material in the pit has density ρ_0, and the volume fraction of ash in the originally un-biodegradable material is F_a, then the volume of ash associated with volume $v(\theta)$ is $F_a v_{u0}$, and is mass is $m_a = \rho_a F_a v_{u0}$. The mass contained in volume $v(\theta)$ is:

$$m(\theta) = \rho_a F_a v_{u0} + \left[(1 - F_a)v_{u0} + k \cdot v_{b0} + (1-k)v_{b0} \cdot e^{-r\theta}\right]\rho_0$$

The mass fraction of ash is then

$$\frac{m_a}{m}(\theta) = \frac{\rho_a F_a v_{u0}}{\rho_a F_a v_{u0} + \left[(1-F_a)v_{u0} + k \cdot v_{b0} + (1-k)v_{b0} \cdot e^{-r\theta}\right]\rho_0} = \frac{F_a \frac{\rho_a}{\rho_0}}{F_a \frac{\rho_a}{\rho_0} + \left[(1-F_a) + k \cdot \frac{v_{b0}}{v_{u0}} + (1-k)\frac{v_{b0}}{v_{u0}} \cdot e^{-r\theta}\right]}$$

.... (3)

The fraction of the organic material present that is biodegradable is:

$$\frac{v_b}{v_b + v_u}(\theta) = \frac{v_{b0} \cdot e^{-r\theta}}{v_{b0} \cdot e^{-r\theta} + (1-F_a)v_{u0} + k v_{b0}\left(1 - e^{-r\theta}\right)} = \frac{\frac{v_{b0}}{v_{u0}} \cdot e^{-r\theta}}{(1-F_a) + k \cdot \frac{v_{b0}}{v_{u0}} + (1-k)\frac{v_{b0}}{v_{u0}} \cdot e^{-r\theta}}$$

.... (4)

It is assumed that this ratio will be the same whether expressed in volume, mass or COD units, since the biodegradable and un-biodegradable organic fractions have the same density and COD.

The age distribution of material in the pit is determined by the history of when it was deposited and the reaction transformations that consumed or generated it. However, the age distribution of the originally deposited un-biodegradable material depends only on the deposition history, as it undergoes no transformations.

This originally un-biodegradable material in the pit will have a residence time distribution (RTD) density function $f_u(\theta)$ where θ is the age of the material (the time since it was deposited). $f_u(\tau)$ is defined by $f_u(\tau) = \frac{dF_u(\tau)}{d\tau}$ where $f_u(\tau)$ is the fraction of originally un-biodegradable material which has age $t < \tau$.

The total volume of the originally un-biodegradable material is given by:

$V_u(T) = \int_0^T R_u(t)dt$, where $R_u(t)$ is the rate of addition of un-biodegradable material at time t (m^3/d), and T is the time since the pit started filling. The RTD function $F_u(\tau)$ is the given by

$$F_u(\tau) = \int_0^\tau R_u(t)dt \bigg/ \int_0^T R_u(t)dt$$

For the case where the rate of addition is constant,

$R_u(t) = R_u, \quad V_u(T) = R_u \cdot T, \quad F_u(\tau) = \frac{\tau}{T}$, and $f_u(\tau) = \frac{1}{T}$

Equation 1 implies that a volume dv_u of originally un-biodegradable material of age between τ and $\tau + d\tau$ will be associated with a volume $\phi(\tau)dv_u$

Thus the total volume of material in the pit is:

$$V(T) = \int_0^T R_u(\tau) \cdot \phi(\tau)d\tau$$

For a constant addition rate this becomes:

$$\begin{aligned} V(T) &= R_u \cdot T \int_0^T f_u(\tau) \cdot \phi(\tau)d\tau = R_u \cdot T \int_0^T \frac{1}{T} \cdot \phi(\tau)d\tau = R_u \int_0^T \phi(\tau)d\tau \\ &= R_u \int_0^T \left[1 + k\frac{v_{b0}}{v_{u0}} + (1-k)\frac{v_{b0}}{v_{u0}}e^{-r\tau}\right]d\tau \\ V(T) &= R_u\left[\left(1 + k\frac{v_{b0}}{v_{u0}}\right)T + \left((1-k)\frac{v_{b0}}{v_{u0}}\right)\frac{(1-e^{-rT})}{r}\right] \end{aligned}$$ .... (5)

Equation 5 applies to the entire contents of the pit at age T since the pit started filling, and can be used to calculate the height of pit contents (given pit dimensions) when the pit has been in use for a time period of length, T.

In order to establish a profile of age vs. level below the surface, consider the volume with ages between t and T where $0 < t < T$

$$V(t,T) = R_u \cdot T \int_t^T f_u(\tau) \cdot \phi(\tau)d\tau = R_u\left[\left(1 + k\frac{v_{b0}}{v_{u0}}\right)(T-t) + \left((1-k)\frac{v_{b0}}{v_{u0}}\right)\frac{(e^{-rt} - e^{-rT})}{r}\right]$$

... (6)

Since material of age T corresponds to the bottom of the pit, equation 6 can be used to calculate the level in the pit of material of age t. The fraction of biodegradable material at this age or level can be calculated using equation 2.

In this form, the model assumes that the feed characteristics and feed addition rate are constant and that biodegradable material all degrades at a single constant rate.

Experimental procedure

Samples of sludge from the Savana Park pit latrines were collected in May 2010. During pit emptying, it was recorded that approximately 25% of the contents was non-faecal matter, a value similar to other studies (Still, 2002). Samples were dug out of the vault through the back top slab using rakes and spades. The top layer sample was collected from the very first shovel-full taken from the surface of the pit contents, and probably contained some material less than a day old. The depth of the pit was measured with a graduated rod, with 0.5 m, 1.0 m and 2.0 m noted. When the centre of the pit reached the next marked height, another sample was taken. The emptying process disturbed the layering of the material, and frequently the pit content collapsed around holes as they were dug. While sampling, the emptiers attempted to maintain as much order in the sludge layers as possible. Nevertheless it was estimated that the uncertainty of the depth measurement was approximately 300 mm for the levels of the middle two samples. This uncertainty in depth did not apply to the top or bottom samples, but it was probable that the sample removed from the bottom of the pit was contaminated by samples from higher up the pit. The samples were screened to remove large, obvious, non-faecal material, such as plastic bags, cloth and broken glass, which meant that the samples did not represent the rubbish content of the material. Samples were stored in pre-labelled, sanitized and lined plastic containers with lids.

The samples were analysed for total solids, moisture content, volatile solids, alkalinity, pH, COD fractions, free and saline ammonia (FSA), Total Kjeldahl Nitrogen (TKN), total phosphate and orthophosphate. All analyses were performed according to Standard Methods (APHA 1995). All analyses were performed in triplicate. The mass measurements were recorded to 1 mg precision, and the volume measurements to ±1 ml. Due to the heterogeneous nature of the pit contents, it is expected that significant differences between samples from within the same layer will exist. To obtain an indication of the average composition of material from each layer, a 50 g composite sample was prepared by collecting smaller masses of material from different parts of each sample. Data for fresh faeces from Buckley et al. (2008) and Nwaneri (2009) were compared with the measurements from samples of the surface layer in the pits.

Interpreting experimental data in terms of the model

The distribution of material in the pit is determined by the entire history of what was disposed into it. This depends on the history of the users' behaviour, about which we have almost complete ignorance. Modelling the process therefore inevitably involves sweeping assumptions, such as considering the rate of deposition of material into the pit and its characteristics to remain constant for the entire period. Furthermore, even if detailed information were available, more detailed assumptions probably would not be particularly useful, since they would only be applicable to the specific pits investigated. In view of these uncertainties, one can only expect a rough correspondence between the model and measured data.

Two issues were evident in the experimental data that could not be directly accounted for in the model:

The first was the observation that the COD/volatile solids ratio of fresh faeces from Buckley et al. (2008) was more than twice that of the surface material. This means that either (i) non-faecal organic matter disposed of in the pit has a much lower COD than faeces, therefore the COD content of pit sludge is diluted relative to that of faeces; or (ii) that the faecal matter loses a significant fraction of COD in the interval during which it is exposed to air before being sampled; or (iii) the faeces of the users of the pit latrines studied had a lower COD concentration than those used in the study by Buckley et al. (2008). Given the semi-solid state of pit sludge, it is believed that a combination of (ii) and (iii) are responsible for the differences observed. Without any way of determining to what extent the difference was due to a high rate of degradation on the surface, the surface degradation was not modelled in this study. Rather the characteristics of the material on the surface of the pit (the top sample characteristics) were considered to be the effective feed to the pit.

The second issue was the fate of water in the pit. The data clearly showed that water is not conserved in the pit, and indeed it would be surprising if it were, since the pits are not sealed. There is an exchange of water between the pit and the surrounding soil that cannot be characterised from the data measured in this study. To get around lack of knowledge about the water movement, the model was compared with the measured compositions on a water-free basis. However, the volume of pit contents must reflect the volume of water, so the modelled volumes of dry material were scaled up using the average measured value for the water content of the pits. For this study, 16 sets of rough measurements (from Bakare, 2012) and 2 sets of detailed measurements (this study) were used. Figure 1 shows the volume fraction of water (moisture content on a volume basis) for 7 of the 18 pits that seem to fit the assumptions of the model relatively well.

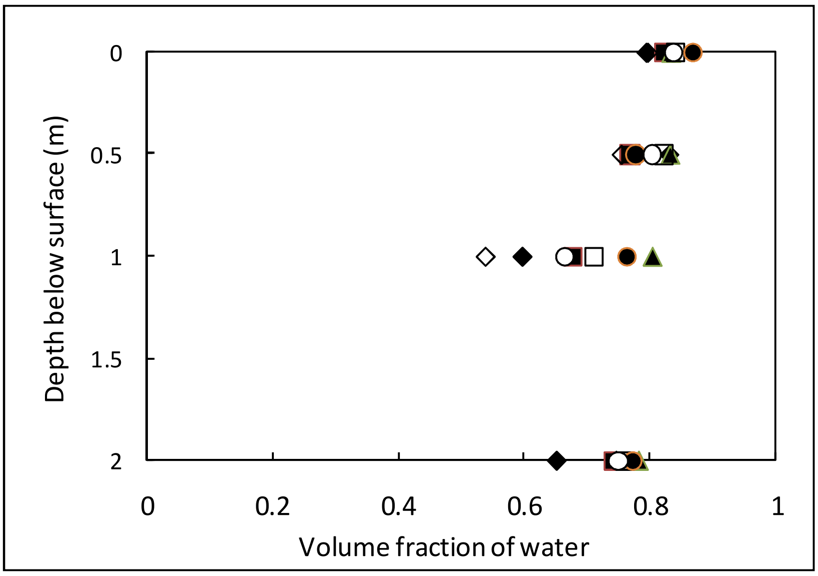

Figure 1 Volume fraction of water data for 7 pits.

Parameter estimation
The model parameters that were adjusted to fit the data were:

- The rate of addition of un-biodegradable material: $R_u = 3.964 \times 10^{-5}\, m^3/d$ (dry basis)
- The ratio of biodegradable to un-biodegradable material fed: $\frac{v_{bo}}{v_{u0}} = 3.8315\, m^3/m^3$
- The fraction of un-biodegradable material that is ash: $F_a = 0.6748\, m^3/m^3$
- The yield of un-biodegradable organic material from degradation of biodegradable material: $k = 0.1\, m^3/m^3$
- The rate constant for bio-degradation: $r = 0.0025\, d^{-1}$
- The density of the ash was assumed to be 2500 kg/m^3, and all other material (including water) to be 1000 kg/m^3 , giving $\frac{\rho_a}{\rho_0} = 2.5$
- The average water content of the pits was taken as $0.8064\, m^3/m^3$.
- COD was assumed to be directly proportional to the organic volume (whether biodegradable or un-biodegradable).

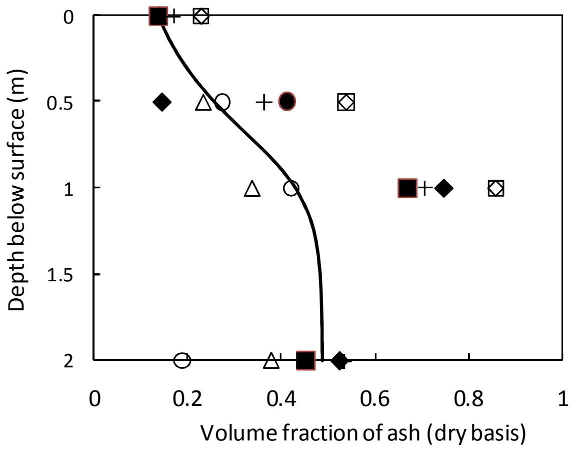

Figure 2 Distribution of ash with pit depth.

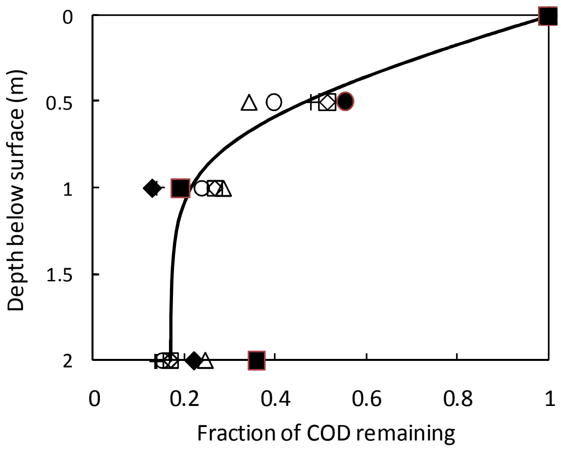

Figure 3 Distribution of COD with pit depth.

Figures 2 and 3 show the fit of the model to measured data for the same 7 pits as in Figure 1. The fraction of COD remaining is calculated as the ratio of the COD measured at a depth over the COD at the surface. The filled symbols represent the 2 pits in Savana Park which were used in determining the model parameters, and the open symbols are for 5 of the other 16 pits. These 5 are those that seemed to correspond reasonably well to the assumptions of the model. The equivalent data for the remaining 11 pits is shown in figures 4 and 5.

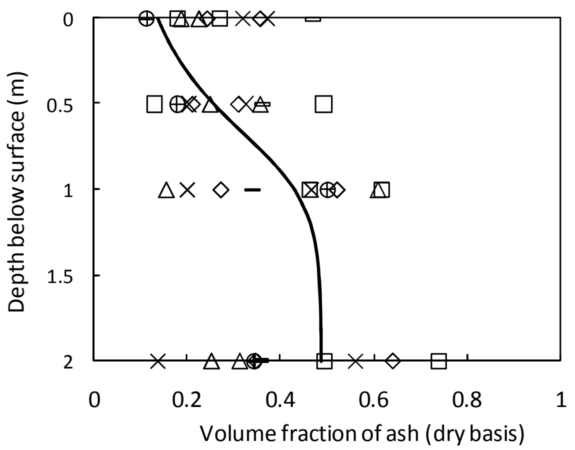

Figure 4 Distribution of ash with pit depth.

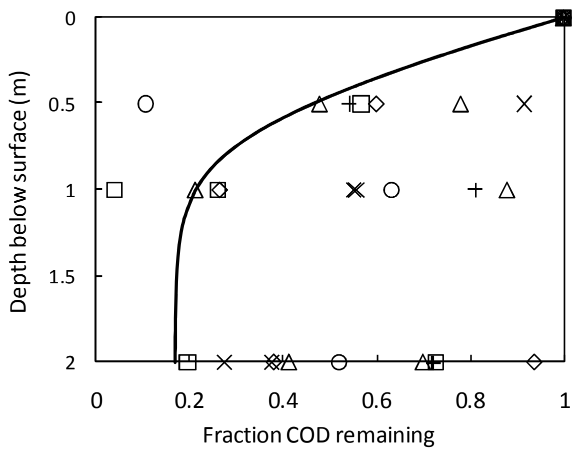

Figure 5 Distribution of COD with pit depth.

DISCUSSION

The purpose of developing the pit filling model is primarily to assist municipal planners to formulate strategies for managing low cost sanitation services based on pit latrines. However, it is necessary to examine its applicability carefully, given its sweeping assumptions and limited fit to the experimental data. It is also necessary to consider the limitations of the data themselves.

It may be concluded from the consideration of the measured data that the model shows a reasonable correspondence with a substantial proportion of pits in the eThekwini area (7 out of 18 in the sample considered), but more than half do not fit the model. However, the data for those that do not fit the model show no discernable trend at all, and might merely reflect unpredictable user behaviour. It is possibly significant that all but two of this set of pits have ash contents at the surface that are substantially higher than those which were used to determine the model parameters, indicating that the pits may have been used for disposal of material other than excreta and toilet tissue that may have influenced the filling rate and general characteristics of the pit samples..

Since the sampling procedure excluded large objects such as plastic bags, cloth and glass, their volume is not properly accounted for in the model. Thus the model deals with the accumulation of material which is visually approximately homogeneous, with a maximum particle size of about 5 mm. However, the disposal of larger objects into the pit is a completely independent process, which needs to be estimated separately on an entirely different basis in any case.

A similar argument applies to water content, since the movement of water into and out a pit depends on site-specific factors. Since water occupies about 80% of the pit volume, it does have to be accounted for, but there does not seem to be any better option than using the average value. It should be noted that researchers with experience of pit latrines in Asia and other parts of Africa consider those found in eThekwini to be unusually dry, so the average value used in this study probably needs to be adjusted for other localities.

The assumptions of uniform feed composition and uniform degradation rate over the life of the pit are clearly unrealistic in themselves, but there is no way that they could be improved in practice, and probably no advantage for policy planning that could be derived from a more detailed treatment.

There is good reason to believe that there is a much higher rate of biodegradation of material on the surface of the pit where conditions are aerobic than for material that has become submerged. However the measured data do not provide any information which could be used to estimate this. For this reason the surface material was taken as the effective feed to the pit, ignoring any processes taking place on the surface. As a result, the filling rate cannot be directly related to the actual input but has to be inferred from the level in the pit and the time that it has been in operation. However, a separate investigation found no correlation between filling rates estimated from pit-emptying records and the reported number of users per household, so it appears that there may be no better approach to the problem than the one adopted here.

If the model is accepted as the best estimate available for a process filled with uncertainties, the following scenarios illustrate how it might be used to evaluate strategies for designing a sanitation service based on pit latrines. Figure 6 considers how the volume in the pit will vary with time for various proportions of un-biodegradable material in the feed (these proportions are on a water-free basis, whereas the volume is based on the average water content as discussed above). The solid black line (20%) corresponds to the parameter values that fitted the pit data of this investigation. The 7.8% line is calculated for zero ash content, and represents an asymptotic (but improbable) case. The model clearly shows the impact of increasing the amount of non-biodegradable material in the pit on the filling rate: increasing the unbiodegradable fraction from 15% to 25% will reduce the amount of time required to accumulate a volume of 1.5 m^3 by more than 5 years. This highlights the importance of keeping solid waste out of pit latrines to maximise pit life-span. Figures 6 and 8 examine the characteristics of pit contents averaged over the entire volume, representing what would be taken out the pit when emptied, assuming that the stratified contents would become mixed during emptying. Figure 7 shows the volume fraction of material that is still biodegradable, and figure 8 its ash content. These plots indicate that the longer material is left in a pit, the greater the degree of stabilisation of the pit contents when it is exhumed. Using the parameters obtained from the model fitting exercise (biodegradable:unbiodegradable volume addition ratio = 3.8:1) the average fraction of biodegradable material in accumulated pit contents would reduce from nearly 80% to less than 40% over a 10 year period. Depending on the final fate of the pit sludge, this information might be important for designing pit size and emptying frequency to ensure that the exhumed sludge has appropriate characteristics for burial, composting etc.

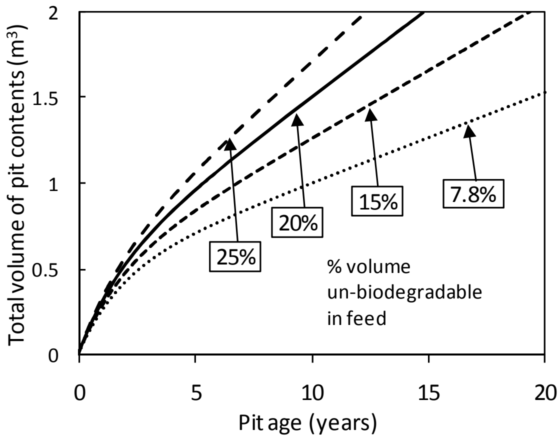

Figure 6 Volume of pit contents for four different scenarios.

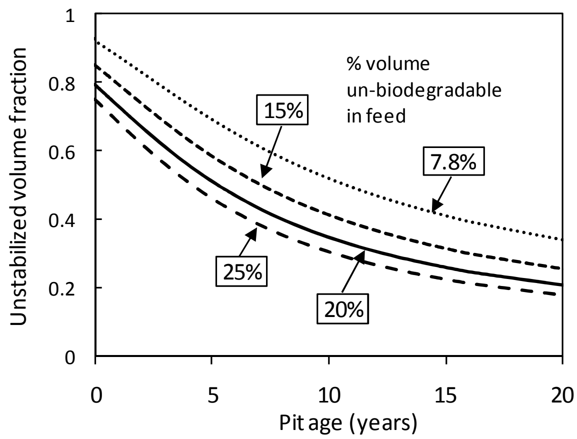

Figure 7 Overall biodegradable content of pit for four different scenarios.

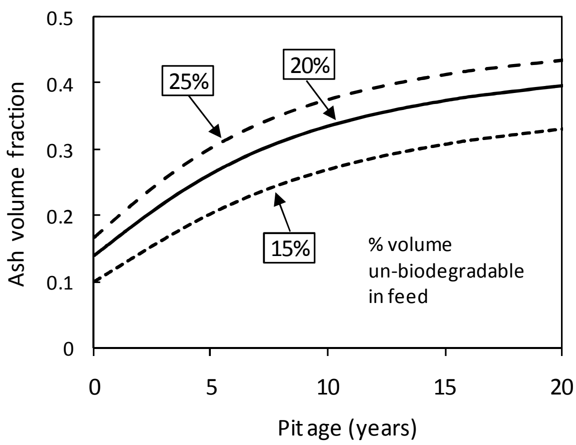

Figure 8 Average ash content of pit for various scenarios.

CONCLUSIONS

Given the uncertainties involved, it seems unlikely that the design of a pit latrine based sanitation service would be driven primarily by the factors described by the model, but rather by considerations of logistics, human resources and cost. However, the model may be useful to estimate some of the implications of any chosen system design. Nevertheless, the following conclusions may be drawn from the results of the modelling study:

- The quality of the data obtainable from sampling pit latrines is by nature very scattered, such that more sophisticated modelling of the processes in pit latrines is not justified

- There appears to be a systematic variation of organic content and ash with depth, in that at least 7 of 18 pits showed decrease in COD with corresponding increase in ash content relative to surface samples with increasing depth.

- The model predicts that the influence of addition of non-degradable material on the filling rate is significant. Thus, if the intention of the system design is to maximise the life of the pit or to minimise the pit filling rate, an effective solid waste management system must also be implemented within the community.

- The average biological stability of the pit sludge increases with time. Pit design and emptying frequency may be designed around the required stability of the sludge when the pit is emptied

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APPENDIX B: PROTOCOL FOR FIELD TESTING OF PIT LATRINE ADDITIVES

In a previous WRC project (*K5/1630 Scientific support for the design and operation of ventilated improved pit latrines (VIPS)*) methods were developed for testing the effect of commercial additives on pit latrine sludge under laboratory conditions. These were published in the final report for that project (Buckley et al., 2008) and in *Water SA* (Foxon et al., 2007). This protocol involved incubating additives at the per-surface-area dosage rate recommended by the manufacturer with a sample of pit latrine sludge collected from the top of a pit latrine still in use, and comparing the mass of rate loss in the samples to that in control units.

Buckley et al. (2008) concluded that *given the large uncertainty and variation that will be observed in field trials, there is a need for a standardised protocol for testing the performance of the additives under controlled conditions. It is simply not possible to replicate field conditions in a controlled manner. It is therefore a strong recommendation of the project team that conclusions about the efficacy of commercial pit latrine additives be based on controlled laboratory based experiments, rather than on field trials.*

However, these authors conceded that *there is a political and societal argument for field trials of pit latrine additives; however, these must be carefully designed to separate the effects of the additives and other factors through the implementation of appropriate control and reference experiments; furthermore, reliable methods of assessing volume change must be developed to measure the effect of the treatments on pit latrines since simple height measurements have been found to be subjective and do not provide an accurate measure of the volume changes in the pit.*

Pit latrine additives are marketed on their ability to reduce the sludge accumulation rate in a pit latrine or even to reduce the volume of pit latrine contents. A field testing protocol must therefore test the hypothesis that the addition of a pit latrine additive *significantly* changes the average rate of accumulation in a pit latrine.

There are a number of inherent difficulties associated with field trials. Buckley et al. (2008) summarise these as follows:

- *Due to the variation in latrine design, age, usage and number of users, the pits* (vary) *considerably in the volume, composition and ambient conditions of the sludge contents. Given that a number of parameters (e.g. pH, temperature, moisture content, available oxygen, inhibitory substances, etc.) influence biological/chemical enzymatic/catalytic activity, it should be expected that any effect of the additives will differ considerably in mechanism and extent between different pits.*

- *The pit contents usually do not present a flat surface; therefore measurement of the change in distance between the top of the heap and the pedestal with time does not translate directly into measurement in the change of pit content volume*.

- *The critical issue is to accurately determine the change in volume of pit contents; neither the distance to top of heap nor slope of heap directly does either. It is important that any kind of pit additive study has a very clear approach to measurement of the effect of the additive and takes these factors into account. It is possible that activities such as adding water or mixing pit contents (both beneficial in their own way to biological processes) have the added effect of reducing the cone steepness and therefore reducing the apparent volume of the pit contents.*

- *in order for trials to be meaningful, they must be undertaken on a large scale with a large number of different pits being subjected to the same treatments, and a large number of reference pits against which the treatments may be compared. These need to include control pits where no action is taken, and pits which are subjected to similar treatments as those with additives, but without the commercial product so that the effects of adding water or mixing may be observed. These tests must be performed with a sufficiently large sample (ideally 30 of each treatment) since the natural variations expected between pits will mask the effects of the treatments if the sample size is not sufficiently large.*

The minimum requirements for a meaningful field trial are:

- The trial must be undertaken by a recognised testing authority
- The trial must include a statistically significant number of observations of double-blind test and reference experiments
- The trial must include control experiments
- The measurement techniques must take into account changes in height and shape of the sludge pile in a pit latrine
- The trial must be conducted over a period of time in which it is possible to measure a significant change in the volume of pit latrine material.

In WRC projects K5/1630 and K5/1745 three different types of measurement were undertaken. These were:

- infra-red laser distance meter measurement of 5 points in the pit latrine
- stereographic imaging and data analysis of the pit surface
- automated laser scanner

In each case the measurement method acknowledges that in dry pits, the pile of pit contents is not flat and ultimately calculates an average change in pit content volume as the basis for comparing performance of pit additive.

PROCEDURE FOR TESTING PIT LATRINE ADDITIVES

Treatments

It is recommended that for each additive, three different treatments are applied in the test:

1. Test treatment: the pit latrine additive is applied at the rate recommended by the supplier
2. Reference treatment: any instruction relating to the application of the additive (such as mixing in water, stirring the pit contents with a stick, injecting the additive under the surface etc.) must be applied in the reference treatment using a non-active placebo that has the same appearance as the additive (e.g. bran, flour). The placebo should not add a significant organic load to the pit latrine contents, and should not enhance or inhibit biological activity.
3. Control: Control units are pit latrines located in the same area as the test and reference treatments to which no treatment is applied. In these pits, only the filling rate is measured.

Purpose of reference treatment

The purpose of the reference treatments is to determine whether the *method* of applying the additive has any impact on the measurement of pit latrine filling rate. An obvious example is in the case of an additive that is applied by mixing with water and pouring onto the surface of the pit latrine. Besides any potential biological action of the treatment, the addition of large volumes of water will result in flattening of the pile below the pedestal, and possibly compaction of materials such as toilet paper due to wetting. In addition, there may be enhanced biological activity due to the addition of water. All of these may result in an apparent reduction of filling rate relative to control units that are not attributable to the additive itself. To separate these effects from the contribution of the additive, the reference experiment must exactly replicate the conditions of the test, but without the biological additive.

These should be executed in a "double-blind" fashion with the test treatment; i.e. the householders should not know whether their pit latrine has test material or placebo. In addition, the field-worker applying the treatment and measuring the filling rate should also not know which treatment is applied to each pit latrine. This may be achieved by preparing the different treatments in advance by the principal experimenter, who is not the field worker, and identifying each treatment only by a identity number that corresponds to the pit treated and a central database. This precaution is to reduce the possibility that householders or field workers will treat test and reference pits differently in anticipation of the outcome of the test. It will also limit the possibility of the supplier being able to influence the outcome of the test.

It is possible to operate a pit latrine additive trial where no placebo is used in the reference treatments and only the application method is applied. However, in this case, the experiment will not be *double-blind* as the field worker will know which pits are test and reference pits, and therefore it is possible that the householder, and potentially the additive supplier will also know this information. The experimenter would therefore have to take precautions to ensure that there were no additional differences to the treatment of the pits by the users or third parties.

Purpose of control treatments

The control treatments may be regarded as the standard against which test and reference treatments are compared. Pit latrine filling rates vary widely between households, communities and seasons for a range of reasons beyond the control of the experimenter; thus the filling rate of the control group can only be regarded as an indication of the untreated rate of filling. However, assuming that users within a community have similar pit use habits, especially regarding the use of anal cleansing material and disposal of household refuse, then in order to conclude that an additive has a significant effect on the filling rate, the results from the test treatment group should be (statistically) significantly below the average filling rate **in the control group**. Should a number of additives be tested simultaneously, only one control group would be required; however, a different reference treatment group would be required for each additive addition method tested.

Number of replicates

Not less than 10 and not more than 30 pit latrines should be tested for each additive tested. A similar number of pits should form the reference treatment group and control group. Figure 1 demonstrates how a trial consisting of two additives, each with a different application procedure and using 10 replicates per treatment would be set up. This test would require 50 pit latrines.

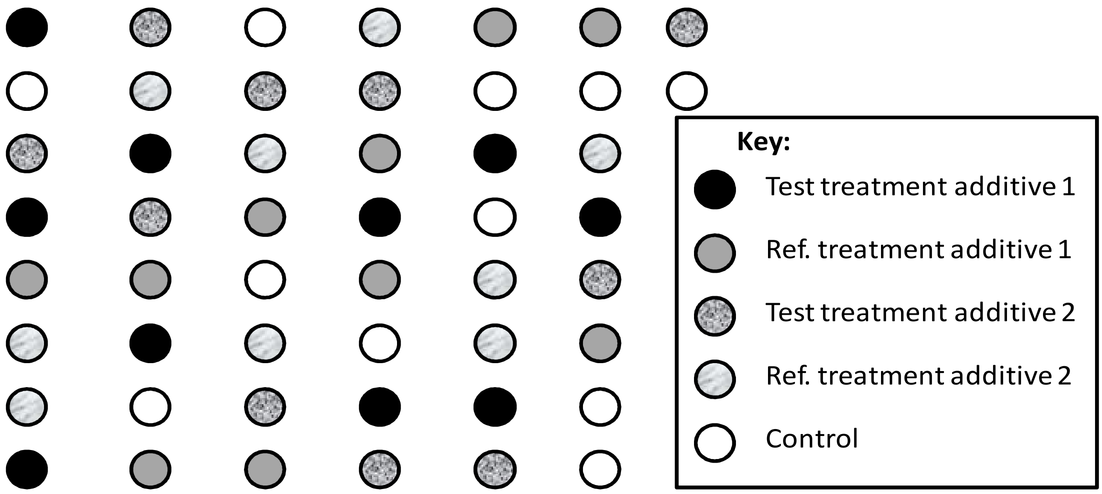


Figure 1 Test set up for a field trial for 2 pit latrine additives, with different application procedures and 10 replicate measurements for each treatment.

Duration of trial
The trial must span a period which is sufficiently long to be able to obtain a measure of the filling rate. The trial should thus be at least 3 months long and should not exceed 6 months.

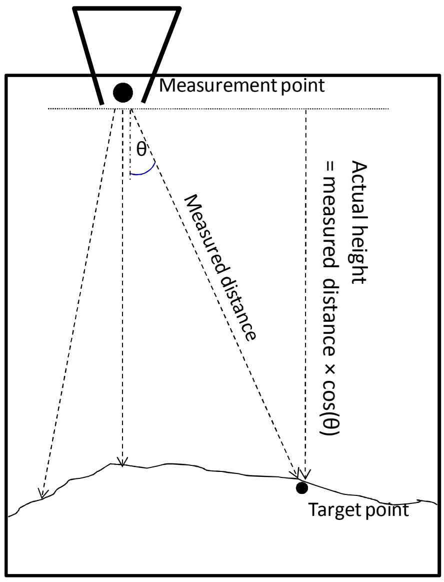
Number of measurements during the treatment
Due to the nature of pit sludge accumulation and the inherent uncertainty in any type of measurement, it is unlikely that measurements more frequently than at 3 monthly intervals will yield measurable filling rates. However, instructions for application of pit latrine additives often require weekly or monthly application. It is also inadvisable to leave the trial unobserved for an extended period in case field conditions change dramatically in the experimenters absence (e.g. flood, fire etc.) Thus it is recommended that measurements are made at least as often as the application rate (i.e. weekly or monthly) and not less frequently than 6 weekly.

EXECUTION OF PIT LATRINE FILLING RATE MEASUREMENT

Method 1: Laser distance meter technique
The first method involves measuring the distance between the top (or bottom) of the pedestal and the top of the pit latrine contents using a infra red distance laser meter (or equivalent distance meter). For this method, between 5 and 10 measurements of any observable portion of the pit contents should be made and the measurements averaged. This measurement should be repeated at known intervals (e.g. weekly).

The **accumulation** is calculated as averaged distance at time=0 (i.e. on the date of first measurement) less the averaged distance at a later time **t**. Accumulation [units of m] is plotted against time. The slope of a linear regression (best-fit straight line) through this graph will have units of height/time and is a surrogate for pit filling rate. The same technique should be applied across test, reference and control treatments. A positive result will be noted if the slope of accumulation vs. time for the test units is significantly *lower* than ***both*** the reference and control treatments as determined by a 95% confidence interval determination on the slope.

The main drawback of this method, is that the distances measured are between the point measured and the pedestal at a range of angles and thus are not actually height measurements as shown in Figure 2. In fact, the actual height measurement of each point ***h*** is related to the measured distance ***m*** by the angle of the measurement θ:



$$h = m \times cos(\theta)$$

There is no satisfactory way of correcting for this error, and this error will be more pronounced when the angles employed are greater (e.g. when the pit is fuller).

Therefore this method of measurement will not give an accurate measurement of the pit filling rate and should be used for comparative purposes only, where the results are compared to pits of the same internal construction and therefore size and which have a similar degree of fullness (e.g. nearly empty, half-full, nearly full)

Figure 2 Laser measurement technique: effect of angle of measurement on reported height.

Method 2: Stereographic imaging technique

The stereographic imaging technique uses a pair of stereoscopic digital photographs to measure the spatial coordinates of any number of points on the surface of the sludge in the pit latrine. These points are then used to map out the shape of the surface of the pit content in three dimensions. This technique makes use of specialised equipment to obtain images at precisely defined spatial positions (height, angle) and uses triangulation calculations to determine the distance between the camera and any point of the pit contents, as shown in Figure 3.

The vertical distance between the height (or z-co-ordinate) of all the points analysed may be averaged as an indication of the height of the pit contents or alternatively, the volume of headspace above the pit contents can be calculated by integrating the height measurements across the mapped surface. The accumulation rate is then the volume change of the headspace with time, or the change in distance between the average surface z-co-ordinate and the measurement point (as in method 1, except with more accurate representation of the average distance).

Method 3: Automated laser scanner

The automated laser scanner works on a similar principle to Method 2 in that the surface of the pit is mapped. However, the laser scanner is programmed to automatically scan for a large number of points on the surface and the output signal is automatically converted to a table of co-ordinates. This method is much easier to execute in the field than the stereographic method, and the data analysis can be automated, resulting in a much faster data processing time, with a more accurate result. An example of the output for this method is presented in Figure 4.

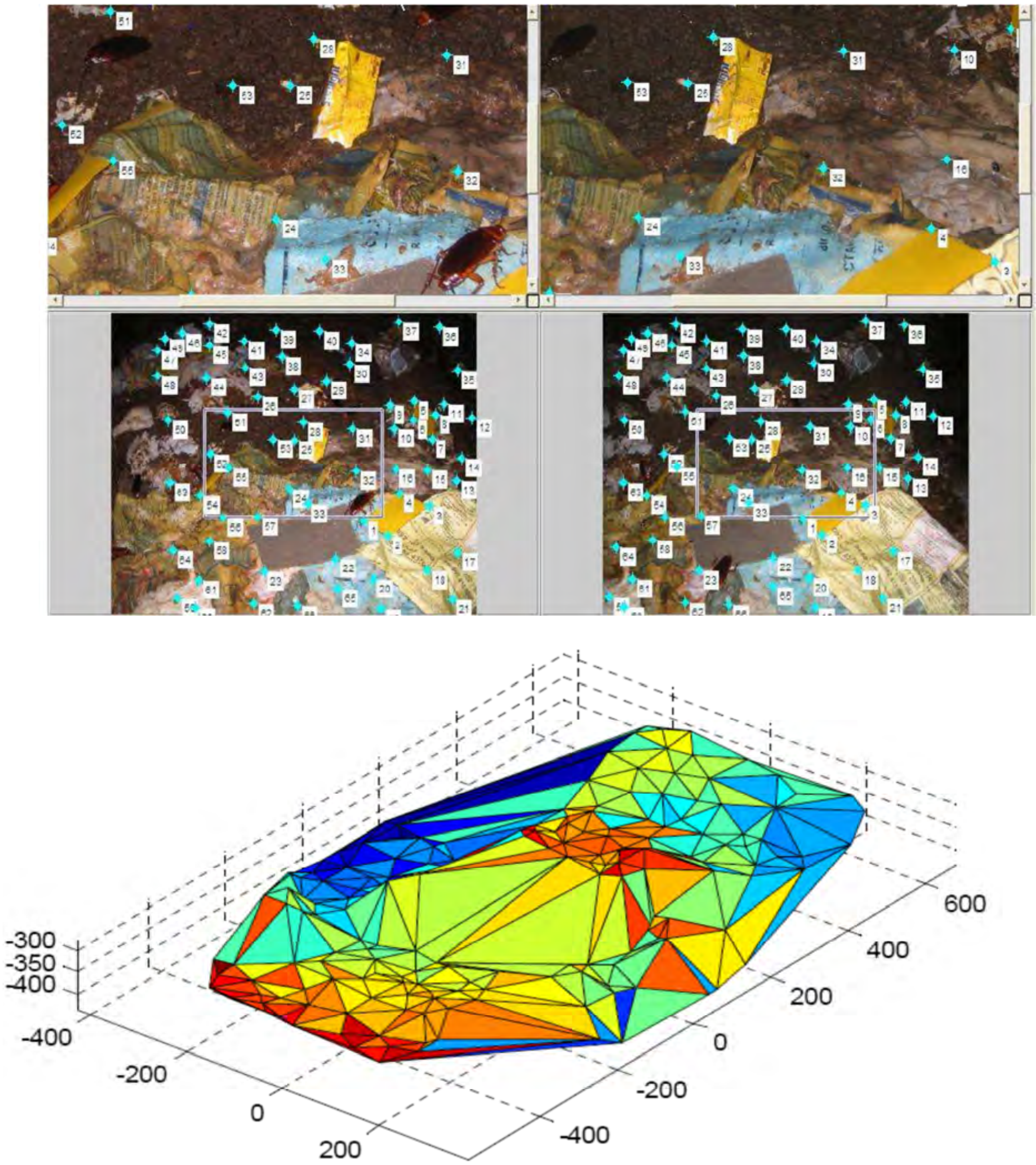


Figure 3 Images and calculated distances using the stereorgraphic imaging technique for determining the rate of accumulation in a pit latrine (Bakare 2012)

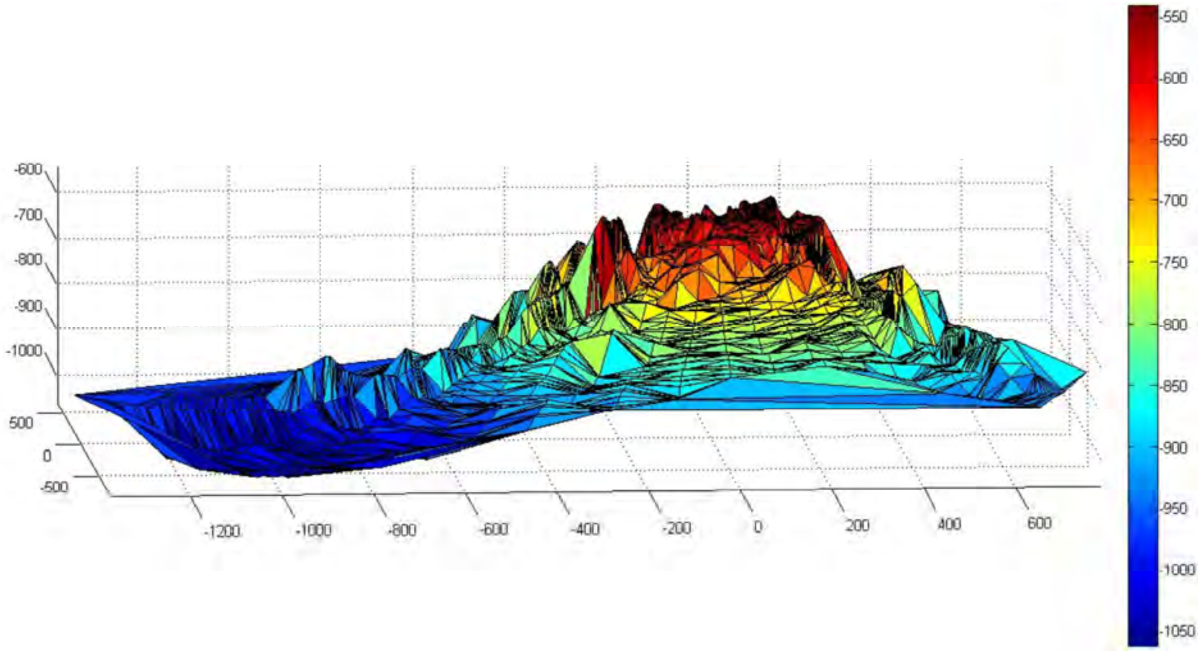


Figure 4 3-D modelling of the surface of pit latrine contents using an automated laser scanner (Dahmani, 2010) .

The output of this method is treated in the same way as for Method 2

Analysis of the 3 methods
Method 1 is the easiest of the methods to implement, requiring simple equipment and simple data interpretation techniques. However, the data obtained is the least accurate, and in fact is fundamentally compromised by the fact that distances measured at any angle not directly below the pedestal will be overestimated as a measure of height. However, the purpose of the testing protocol must be to prove the hypothesis that an additive can significantly reduce accumulation rate. If such a change cannot be detected by this simple method, than it can be safely concluded that any possible effect of the additive is not sufficient to reduce the sludge accumulation rate by a large enough factor to make the additive viable as a means of managing sludge accumulation in pit latrines. Thus, if no significant reduction of accumulation rate between test treatment and controls and reference treatments can be observed using this method, the hypothesis that the additive reduces accumulation rate is not supported.

Methods 2 and 3 require sophisticated equipment and extremely sophisticated data analysis techniques, which would not readily be available unless if developed for the purpose by a testing agency. However, these methods should give more reliable data with which to draw conclusions about the efficacy of a pit additive. The equipment costs for Method 2 are significantly lower than those for Method 3, but the data quality is lower and the analysis time considerable higher.

Whichever method is chosen, the data analysis must be carefully performed to ensure that the reported results take account of the fact that most pit latrine contents do not form a smooth flat surface and that the influence of additive on accumulation rate is isolated from influence of the method of application rate.

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