Australian Government
Department of Agriculture

AUSTRALIAN Pork™

Sludge Handling and Management

Final Report
APL Project 2012/1029

January 2014

FSA Consulting
Eugene McGahan
PO Box 2175
Toowoomba Qld 4350

When referring to this document the following reference should be used:

O'Keefe, MF, McDonald, SA, Yan, MJ, Davis, RJ, Watts, PJ, McGahan, EJ and Tucker, RW, 2013, 'Sludge Handling and Management', Project No. 2012/1029, Australian Pork Limited, Canberra, Australia, January 2014.

DOCUMENT STATUS RECORD

Client:	Australian Pork Limited
Document Title:	Sludge Handling and Management
Job No:	7887
Document File Name:	7887 APL Sludge Handling Report - Final Jan 2014.docx

Version No	Date of Issue	Description	Signatures		
			Author	Checked	Approved
1	2 Sept 2013	Draft	RJD/EJM	RWT	
2	11 October 2013	Draft	RJD/EJM	PJW	
3	30 November 2013	FINAL	RJD/EJM/PJW	PJW	
4	08 January 2014	FINAL	RJD/EJM/PJW	EJM	

Notes:

Version 1	This is a draft report for client comment.
Version 2	This is a draft report for client comment.
Version 3	This is a Final Report.
Version 4	This is a Final Report with final comments from client (APL) included.

Disclaimer:

1. Feedlot Services Australia Pty Ltd has taken all reasonable steps to ensure that the information contained in this publication is accurate at the time of production. In some cases, Feedlot Services Australia Pty Ltd has relied on information supplied by the client.
2. This report has been prepared in accordance with good professional practice. No other warranty, expressed or implied, is made as to the professional advice given in this report.
3. Feedlot Services Australia Pty Ltd maintains **NO** responsibility for the misrepresentation of results due to incorrect use of information contained within this report.
4. This report should remain together and be read as a whole.
5. This report has been prepared solely for the benefit of the client listed above. No liability is accepted by Feedlot Services Australia Pty Ltd with respect to the use of this report by third parties without prior written approval.
6. Where soil testing has been undertaken, it should be noted that soil conditions can vary significantly even over relatively short distances. Under no circumstances will any claim be considered because of lack of description of the strata and site conditions as shown in the report. In addition, the client or contractor shall be responsible for satisfying themself as to the nature and extent of any proposed works and the physical and legal conditions under which the work would be carried out, including means of access, type and size of mechanical plant required, location and suitability of water supply for construction and testing purposes and any other matters affecting the construction of the works.

This document should be cited as follows:

O’Keefe, MF, McDonald, SA, Yan, MJ, Davis, RJ, Watts, PJ, McGahan, EJ and Tucker, RW, 2013, ‘Sludge Handling and Management’, Project No. 2012/1029, Australian Pork Limited, Canberra, Australia, January 2014.

Copyright:

PO Box 2175
TOOWOOMBA QLD 4350

Acknowledgements

This project is supported by funding from Australian Pork Limited and the Department of Agriculture.

Abstract

Sludge accumulates in various waste management ponds at piggeries and cattle feedlots. Eventually, this sludge needs to be removed and handled. Many existing piggery ponds are reaching the point where sludge removal is becoming a pressing issue. Another issue has arisen recently with the use of covered treatment ponds to generate biogas. Sludge removal from covered ponds presents special difficulties. This report reviews the physical and rheological properties of pond sludge and the methods used to pump, remove, dewater and manage the wet sludge. The most important parameter that influences the ability to pump sludge is the total solids content. Sludge samples were collected at several Australian piggeries and feedlots. These samples were analysed for their physical properties.

Executive Summary

FSA Consulting was engaged by Australian Pork Limited and Meat and Livestock Australia to undertake project 2012/1029 – Sludge handling and management. This project covered a review of existing literature and practices on the pumping of sludge in intensive agriculture industries and other relevant areas.

Sludge accumulates in various waste management ponds at piggeries and cattle feedlots. Eventually, this sludge needs to be removed and handled. Many existing piggery ponds are reaching the point where sludge removal is becoming a pressing issue. Another issue has arisen recently with the use of covered treatment ponds to generate biogas. Sludge removal from covered ponds presents special difficulties.

Sludge is a mixture of water and solid materials (total solids (TS)). The TS component can be inorganic material (any materials such as debris, sand or rocks plus the ash component of organic wastes), slowly digestible organic material or dead microbial cell mass. The ratio of water to solids (TS content) can vary considerably. As the TS content increases, the sludge's characteristics and handling requirements change. The particle size and particle size distribution (PSD) can vary from very fine colloidal material to larger particles. Some particles can be cohesive (i.e. they tend to stick together) while other particles such as sand are non-cohesive. Rheology is the study of the flow of matter. This is an important feature in the design of sludge removal systems.

The term – sludge – is widely used for a range of materials. However, the handling and management options for "sludge" is heavily dependent on the TS content of the material. In this report, the following terms have been defined.

1. Effluent. This is material with a TS content of <5%. Effluent is a material that can be pumped and behaves like other Newtonian fluids, e.g. water.
2. Slurry. This is material with a TS content of 5-15%. These materials are "thick" but can flow. They behave in a non-Newtonian manner and require specialised pumping equipment.
3. Sludge. This is material with a TS content >15%. Essentially, this material is too thick to pump and must be handled with bulk mechanical methods.

The actual properties of sludges derived from different sources vary, even at the same TS content. Hence, the TS contents stated above are a general guideline for use in this report rather than a fixed rule. Care needs to be taken when reviewing other work as the definition of sludge used in the literature is highly variable.

The physical characteristics of the sludge or slurry is importantly in determining the appropriate pumping and handling methods. Particle size distribution (PSD) and bulk density are important but the rheological properties have the greatest influence. Several studies have been conducted into the rheological properties of raw and digested manure in sludge or slurry forms. Most researchers find that viscosity (i.e. resistance to pumping) increases with increasing TS content and decreases with temperature. Effluent with a TS content <2% can be pumped with centrifugal pumps. Slurries with a TS content of about 5-10% TS can be pumped with various types of positive displacement pumps. Sludge with a TS content greater than 15% is virtually impossible to pump.

When desludging ponds, there are three techniques depending on the operation and structure of pond, sludge physical characteristics and the frequency of desludging. Desludging can be broadly categorised into three groups:

- desludging dewatered ponds (after effluent removal)
- desludging an uncovered pond containing effluent
- desludging a covered pond.

Due to the high cost of desludging, for ponds with very old or thick sludge, it is often cheaper to remove the water layer first (i.e. dewater the pond) and then excavate the sludge with conventional earthmoving equipment such as an excavator and dump trucks.

However, it is usually more desirable to remove sludge from a pond without dewatering as this maintains the function of the pond. There are three basic methods of sludge removal from an operating, uncovered pond. They are:

1. Pumping. This uses a pump or vacuum tanker located on the bank of the pond. It may or may not include agitation of the sludge in the base of the pond.
2. Dredging. This involves the use of a system where the pump is within the pond and is mobile so that all sections of the pond can be accessed.
3. Mechanical Removal. This involves the use of a long-reach excavator or similar to remove the sludge without pumping.

Sludge removal from covered anaerobic ponds presents specific difficulties as the cover cannot be removed during the operational phase. There are essentially three methods of sludge removal from CAPs. They are:

1. In-situ desludging. In this approach, the solids settle to the base of the CAP and are removed by pumping via a pre-installed pipeline.
2. Suspension removal. In this approach, the solids are not allowed to settle. They are kept in suspension using agitators inside the CAP. The solids are removed as part of the effluent flow out of the CAP.
3. Life-time accumulation. In this approach, solids are allowed to settle but are not removed until the operational life of the pond cover is reached and the cover is removed. In this approach, a large sludge-accumulation volume is needed to be designed as part of the internal volume of the CAP.

Depending on the final utilisation method for the sludge or slurry, it may be desirable to dewater the removed sludge or slurry. This is particularly applicable if the final utilisation site is some distance from the source. There are several methods of dewatering (solid separation) for sludge and slurries. However, most of the available options are not suitable for dewatering sludge and slurries because:

- Removal efficiency is not sufficiently high to achieve a “dry” sludge.
- Capital, operating and maintenance costs are high.
- Capacity is too low for a large volume of sludge removed in a short period.

- High technical skills are required.

In reality, most sludge and slurries removed from ponds is dewatered using free drainage and/or evaporation in bays or tubes. The choice of dewatering method is site-specific. The methods include:

1. Long-term bulk storage.
2. Short-term drying bays.
3. Sedimentation and Evaporation Pond Systems (SEPS).
4. Geotextile tubes.

Samples of pond sludge were taken and analysed at several piggery and feedlot sites across Australia. The sludge was accumulated from different sources, had different ages and consequently had different rheological properties. Additionally, a sludge pumping test was undertaken measuring the pipe friction losses for the digested sludge in a covered anaerobic pond at different total solids contents.

The TS contents ranged from 3 to 16% TS. Bulk density ranged from 1020 to 1294 kg/m^3 indicating that the majority of the sample was water. Particle size distribution varied due to a range of source and age issues. In the pipe friction loss experiment, sludge with a TS content of about 3% had a low friction loss and could be easily pumped. However, as the TS content increased to 10%, the friction loss increased rapidly and the material was very difficult to pump. The VS:TS ratio of all sludge in this experiment was about 0.6 indicating that the material was well digested. This experiment would suggest that frequent removal of recently settled sludge (<3%TS) from the covered pond would be preferred over infrequent removal of densely settled sludge (>10%TS).

Further work is required in understanding the optimal sludge removal frequency from covered anaerobic ponds coupled with the correct design of the sludge removal pipeline system and correct selection of pump type.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PHOTOGRAPHS

GLOSSARY

Term	**Meaning**
Biochemical Oxygen Demand (BOD)	The quantity of oxygen used by bacteria while decomposing organic material
Chemical Oxygen Demand (COD)	A measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant.
Dissolved Solids (DS)	Materials contained in liquid that are less than 1 μm size.
Effluent	Wastewaters containing manure and with a TS <5% (see Figure 2*: Handling characteristics of manure at different moisture contents*)
Faeces	Solid animal excreta
Fixed Solids (FS)	The amount of the total solids remaining as ash or residue when a material is heated to 600°C for one hour. Variations in fixed solids represent variations in the levels of minerals contained in the diet.
Thickening	Increasing the total solids concentration of wastewater.
Manure	Faeces plus urine.
Settleable Solids (SS)	The total solids that settle in a predetermined period for a set sample depth.
Settling Velocity	Speed at which solids drop out of liquid.
Sludge	Material with a TS concentration of >15% (see Figure 2*: Handling characteristics of manure at different moisture contents*).
Slurry	Material with a TS concentration of 5-15% (see Figure 2*: Handling characteristics of manure at different moisture contents*).
Spadeable Solids	Manure with a total solids concentration of generally 15 – 20% (see Figure 2*: Handling characteristics of manure at different moisture contents*). Solid enough to be handled with a spade.
Stackable Solids	Manure with a total solids concentration of generally >20% (see Figure 2*: Handling characteristics of manure at different moisture contents*).
Suspended Solids (SusS)	Solids that can be removed from liquids by filtering or centrifuging. It is the quantity of unsettleable material captured utilising laboratory filtering techniques.
Total Solids (TS)	The sum of the dissolved, suspended and settled solids or the sum of the volatile and fixed solids. This is the residue remaining when the water is evaporated from a sample. It is also defined as Dry Matter. TS is the inverse of moisture content (wet basis), i.e. 10% TS is 90% moisture content.
Total Suspended Solids (TSS)	The sum of the dissolved and suspended solids.
Volatile Solids (VS)	The amount of total solids driven off as volatile (combustible) gases when a material is heated at 600°C for one hour.
Volatile Suspended Solids (VSS)	The amount of total suspended solids driven off as volatile (combustible) gases when a material is heated at 600°C for 20 minutes.

Wastewater	Any stream of water containing manure and or other waste products (feedstuffs, etc)

1. Introduction

1.1 Project Background

Pond desludging is a challenge for all pig producers with conventional sheds and effluent ponds. Over the years, FSA Consulting team members have been asked many times about the best way to desludge piggery ponds with limited options to offer. FSA Consulting recently conducted workshops on "Making Money from Manure Workshops: Part 1 – Soils and Nutrients" (2011/1015.331). During the course of these workshops, various participants asked for information on desludging techniques, managing removed sludge and reusing sludge, indicating that this is an important issue for industry.

The beef feedlot sector is also investigating the potential to install purpose-built covered anaerobic ponds (CAP) that will be loaded with manure to achieve biogas production. They will face the same challenges with desludging these systems and need to start investigating solutions now.

The number of CAPs will continue to increase as more producers realise the benefits of capturing biogas to replace fossil fuel derived power sources at piggeries. Desludging effluent ponds is particularly difficult for covered, lined ponds since agitators and excavators cannot be readily used. The majority of existing covered piggery ponds have in-situ pipes that extend from the pond base up through the banks so that sludge can be periodically removed using a pump or vacuum tanker. However, the effectiveness of this system is yet to be fully tested and understood, e.g. bridging or tunnelling in the settled sludge may result in incomplete sludge removal. There is a need to ensure that this system works for piggeries and feedlots and / or develop different desludging techniques. There is also a need to develop better management systems for the removed sludge, which is difficult to manage due to its moisture content and physical properties. However, it is rich in phosphorus and can be a valuable fertiliser. Currently, nutrient extraction is unlikely to be viable. Hence, there is a need to identify techniques to improve the handling properties of the sludge.

The design process for materials handling systems starts with physical characterisation of the material to be managed. This represents a knowledge gap for piggery and feedlot sludge. To date, bank breeching, excavators, vacuum tankers and in-situ pipes have been used to desludge ponds with varying degrees of success. Other industries (e.g. mining and municipal wastewater treatment plants) deal with sludge and may use different techniques and equipment that could be adopted. There is a need to look further afield to identify solutions. One of Australian Pork Ltd's 2012-13 environmental management priorities is innovation of best management practices. The current technical issues include the need for effective pond desludging and practical and environmentally sustainable options for the management and reuse of sludge. In finding an effective and practical way to significantly reduce GHG emissions (covered ponds with capture or destruction of biogas), desludging has become more difficult. There is a need to find innovative, effective solutions.

This project relates directly to APL Strategy 3 – Government Policy & Compliance Requirements under the Core Objective – Leadership, Preparedness, Stewardship since it is the increasing focus on climate change and associated government pressure that is driving the interest in covered ponds for reducing greenhouse gas (GHG) emissions and harvesting the biogas as an energy source.

1.2 Project Objectives

The project objectives, taken from the research contract, include:

- To characterise the physical properties of piggery pond sludge and feedlot sedimentation basin and pond solids.
- To review current practice and research pertaining to the properties of piggery and feedlot pond sludge, desludging and sludge management, including methods currently used by the pig and feedlot industries and also by other relevant industries.
- To provide a technical report and fact sheets containing recommendations for removing and managing the sludge from piggery and feedlot effluent ponds.

One of the original project objectives was to assess the performance of in-situ pipes, a pump and a Z-filter for desludging a covered, lined pond and dewatering the removed sludge. This objective was removed from the project in March 2013.

2 Sludge, Slurry and Effluent

2.1 Sources of Sludge

Sludge is a mixture of water and solid materials (total solids (TS)). The TS component can be inorganic material (any materials such as debris, sand or rocks plus the ash component of organic wastes), slowly digestible organic material or dead microbial cell mass. The ratio of water to solids (TS content) can vary considerably. As the TS content increases, the sludge's characteristics and handling requirements change. The particle size and particle size distribution (PSD) can vary from very fine colloidal material to larger particles. Some particles can be cohesive (i.e. they tend to stick together) while other particles such as sand are non-cohesive. Figure 1 shows the general properties of different sludge derived from different sources.

Sludge is generated in many industries including intensive livestock facilities, abattoirs and food processing plants, municipal waste treatment facilities and in mining. Due to the source and treatment of each waste stream, the sludge generated by each industry will have different characteristics. Hence, solutions for handling sludge in one industry cannot be necessarily transferred to another industry unless the characteristics of the sludge are similar.

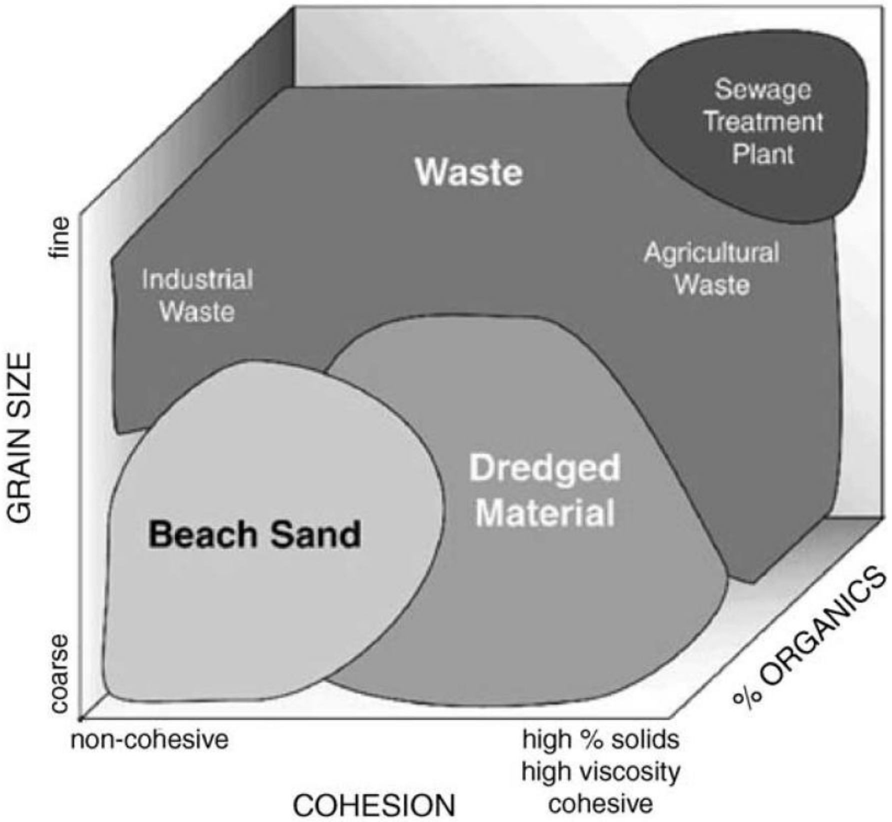


Figure 1: General properties of sludge from different sources

2.2 Rheology

Rheology is the study of the flow of matter, primarily in the liquid state, but also as 'soft solids' or solids under conditions in which they respond with plastic flow rather than deforming elastically in response to an applied force. It applies to substances which have a complex microstructure, such as muds, sludge, suspensions, polymers and other glass formers (e.g. silicates), as well as many foods and additives, bodily fluids (e.g. blood) and other biological materials or other materials which belong to the class of soft matter.

Newtonian fluids can be characterized by a single coefficient of viscosity for a specific temperature. Although this viscosity will change with temperature, it does not change with the strain rate (i.e. flow velocity). Only a small group of fluids exhibit such constant viscosity, and they are known as Newtonian fluids. This includes water. However, for a large class of fluids, the viscosity changes with the strain rate (or relative velocity of flow). These are called non-Newtonian fluids.

Rheology generally accounts for the behaviour of non-Newtonian fluids, by characterizing the minimum number of functions that are needed to relate stresses with rate of change of strains or strain rates. For example, tomato sauce can have its viscosity reduced by shaking (or other forms of mechanical agitation, where the relative movement of different layers in the material actually causes the reduction in viscosity) but water cannot. Tomato sauce is a shear thinning material, as an increase in relative velocity caused a reduction in viscosity, while some other non-Newtonian materials show the opposite behaviour: viscosity going up with relative deformation, which are called shear thickening or dilatants materials.

Since Sir Isaac Newton originated the concept of viscosity, the study of liquids with strain rate dependent viscosity is also often called non-Newtonian fluid mechanics. Within non-Newton fluids, there are two types. Homogenous fluids (e.g. hot chocolate or molasses) does not have solid particles that settle out. They can be pumped at low velocities. However, many agricultural slurries have settable particles which rapidly settle. These fluids must be pumped at a higher velocity or solids may settle in the pipeline, pipe fittings or pump intakes. An understanding of the rheological properties of a material is required for optimal sludge handling and management.

2.3 Definitions of Sludge, Slurry and Effluent

The term – sludge – is widely used for a range of materials. However, as will be shown in the report, the handling and management options for "sludge" is heavily dependent on the TS content of the material. Landry et al. (2002) simply distinguishes between solid and semi-solid manure (i.e. manure having a TS content >10%) and liquid manure and slurry. A better definition is required for this report.

For piggery waste, Figure 2*: Handling characteristics of manure at different moisture contents*
shows the range of total solids in a solid/water mixture and the characteristics and handling options of different ratios. Hence, some specific definitions are required. In this report, the following terms have been defined.

1. Effluent. This is material with a TS content of <5%. Kumar et al. (1972) studied the properties of animal waste slurries. They found that the viscosity of dairy cattle slurry

decreased with a decrease in TS and increase in temperature. They found that the flow of slurries was Newtonian at TS contents less than 5%. Hence, effluent is a material that can be pumped and behaves like other Newtonian fluids, e.g. water.

2. Slurry. This is material with a TS content of 5-15%. These materials are "thick" but can flow. They behave in a non-Newtonian manner and require specialised pumping equipment.
3. Sludge. This is material with a TS content >15%. Essentially, this material is too thick to pump and must be handled with bulk mechanical methods.

The actual properties of sludges derived from different sources vary, even at the same TS content. Hence, the TS contents stated above are a general guideline for use in this report rather than a fixed rule.

Care should be exercised when reviewing experimental and practical work undertaken on "sludge" as the TS content very strongly influences the outcomes. It should also be noted that a material can "move" between each definition by the addition or subtraction of moisture. By drying or dewatering, an effluent can become a slurry. Importantly, in a pond system, agitation of a sludge in the bed of a pond can change its characteristics from sludge to slurry to effluent.

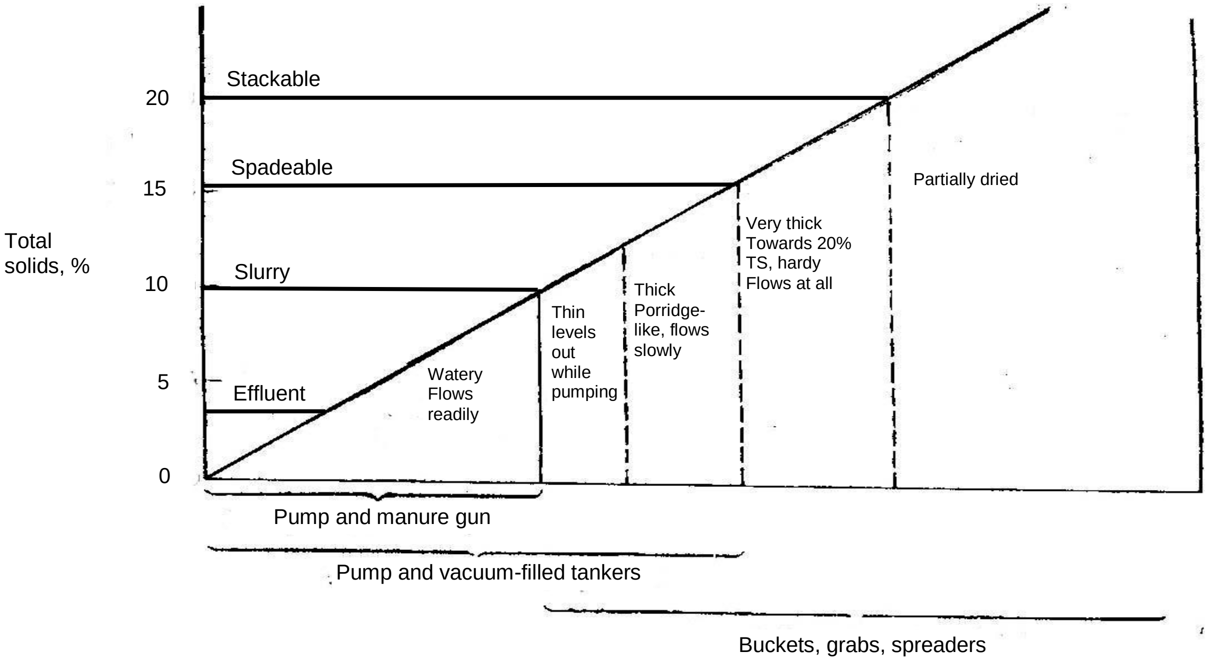


Figure 2: Handling characteristics of manure at different moisture contents

2.4 Components of Sludge, Slurry and Effluent

Sludge, slurry and effluent exhibits wide variations in their properties depending on origin and previous treatment. Their characterisation based on source only gives qualitative information. Many characterisation parameters have therefore been proposed and tests developed to measure specific properties in relation to particular methods of treatment.

Conventional characterisation parameters can be grouped into physical, chemical and biological parameters:

- physical parameters give general information on sludge and slurry processability and handlability
- chemical parameters are relevant to the presence of nutrients, salts and toxic/dangerous compounds, so they become necessary in the case of utilisation in agriculture
- biological parameters give information on microbial activity and organic matter/ pathogens presence, thus allowing the safety of use to be evaluated.

The characteristics that are important depend on the handling and disposal methods adopted. The most important parameters for handling and processing are the physical and rheological parameters.

The amount and type of solids present are important. Solid types can be divided into seven distinct groups:

1. Total Solids (TS)
2. Settleable Solids (SS)
3. Dissolved Solids (DS)
4. Suspended Solids (SusS)
5. Volatile Solids (VS)
6. Volatile Suspended Solids (VSS)
7. Fixed Solids (FS)

The physical characteristics of the solid component, especially particle size distribution (PSD) and bulk density, are important when designing handling equipment. Suspended solids are more likely to settle out under gravity, whereas DS and SusS will not. Some odour generating compounds (carbohydrate, proteins and fats) and organic nutrient elements are contained in the fine particles that are typically not removed by mechanical separation systems. These finer particles are more likely to be contained in the SusS, and contribute substantially to the VS fraction.

2.5 Physical Characteristics of Sludge, Slurry and Effluent

The physical characteristics depend on:

1. Original source material, particularly the ratio of organic to inorganic solid components (i.e. VS: TS ratio).
2. Pre-treatment, i.e. the method of solids removal prior to pond entry.
3. Treatment, i.e. organic (anaerobic or aerobic) treatment or chemical (flocculation).
4. Age, i.e. the time period over which the sludge has accumulated.

Clearly, the characteristics of a mining sludge that primarily comprises of settled sand and clay will be greatly different to a sludge formed at the base of a secondary, organic treatment pond.

2.5.1 Particle Size Distribution in Wastewater Solids

Research conducted by Payne (1984) concluded that piggery wastewater has a relatively uniform distribution of particle size, with the greatest variation reported in the particle size range of 0.5 to

1.4 mm. Most variance from the mean at 0.75 mm resulted from differences in the diet fed. Pigs fed whole grain masticate more, producing a greater proportion of small diameter particles in the faeces. However, in most Australian piggeries only cracked, ground or pelleted grain is included in diets. In one trial, particle size distributions in faeces were similar and smaller for diets incorporating whole or ground grain, whilst cracked grain was associated with larger particle size fractions (Payne 1986). The pig manure with the higher proportion of finer particles had a greater water retentivity (78% versus 70% for the low fibre ration), and the time required for drying was twice as long. Handling properties were different for the two manures, with slumping of solids occurring at 22% TS content for the high fibre diet, compared with 35% TS for the low fibre ration. Changing the fibre content of the feed ration also changes the particle size fractions in the wastewater. The concentration of, and the size class of particles present in faeces, determine the ease of dewatering and other physical handling characteristics. Objective comparisons of the performance of solids separation systems can only be made if the influence of the feed diet on particle size (and therefore handling characteristics) is considered.

Variations in particle size from NSW piggeries (Payne 1984) piggery wastewater from the United Kingdom (Pain et al. 1978) and flushing water (1% TS) from the “Berrybank Farm” piggery (Charles 2000) are shown in Table 1.

Table 1: Particle size distribution in piggery wastewater (% less than)

Size (μm)	**Payne, 1984**	**Pain *et al.*, 1978**	**Charles, 2000**
<750	76	75	98
<500	-	70	94
<180	51	62	80
<45	45	58	62
<25	-	43	51

The efficacy of mechanical solid separation systems (e.g. screens) depends on manure particle size. For a screen with a pore size of 1 mm, TS removal would vary from 8-22% (Payne 1984). Given the variation of the existing particle size distribution (PSD) data (Table 1) and the lack of experimental measurements of solids removal efficiencies in Australia, assumptions on solids removal from Australian piggeries are at best crude. This underpins a need to obtain particle size distribution for wastewater solids and solids removal efficiencies under Australian conditions.

Marcato et al. (2008) studied the PSD and trace element patterns in a full-scale anaerobic digestion plant treating piggery slurry. Analysis of PSD in raw and digested slurries (about 2%TS) showed a general shift in distribution towards larger sizes due to degradation of small and easily degradable particles as well as formation of large microbial filaments. Figure 2 and Figure 3 shows the PSD results of raw and digested piggery slurry taken from Marcato et al. (2008).

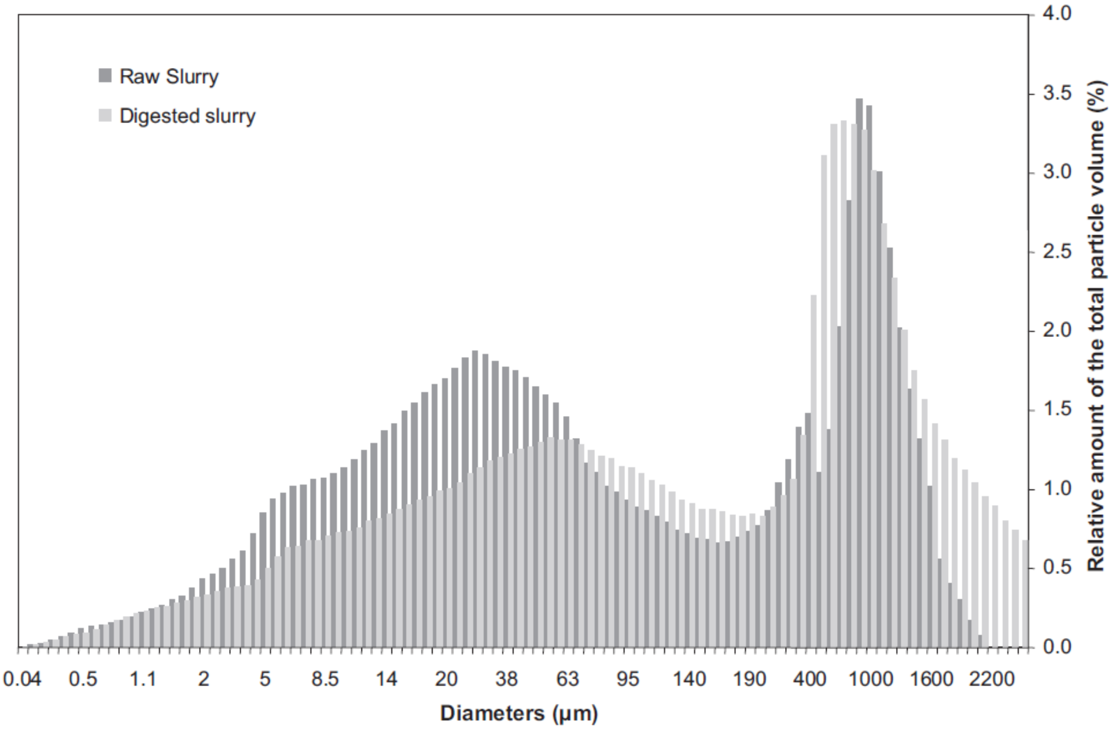


Figure 2: Distribution of relative volumes of the various size classes of particles in raw and digested pig slurry

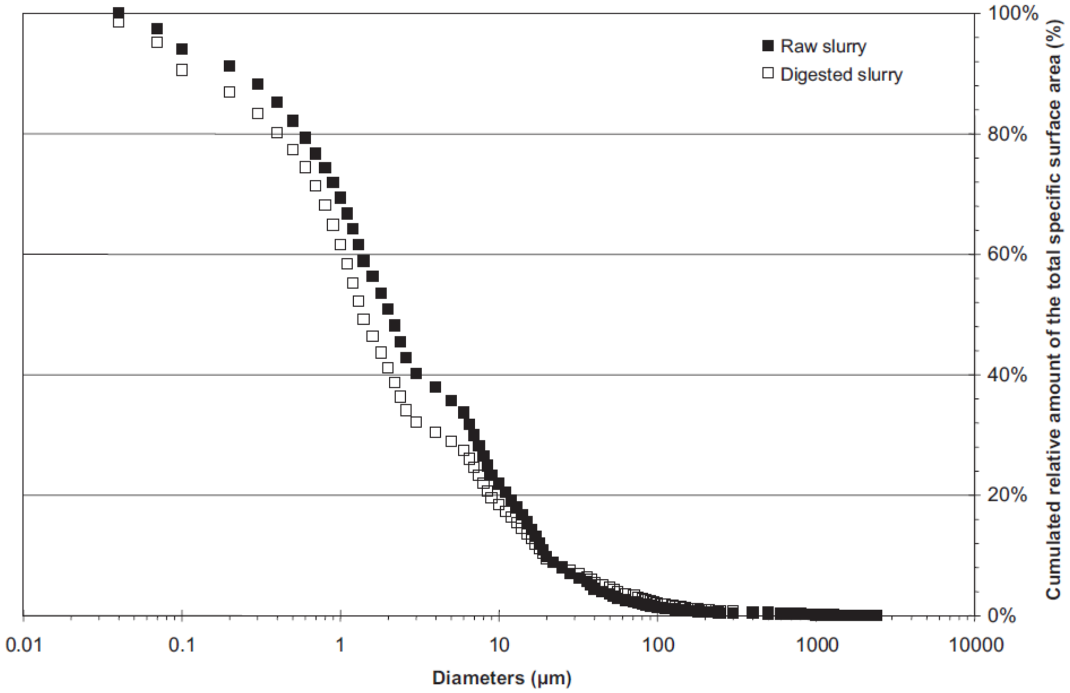


Figure 3: Cumulative relative distribution of specific surface area in raw and digested pig slurry

2.5.2 Rheological Properties of Sludge and Slurries

Numerous studies have been conducted into the rheological properties of manure at different TS contents. Density, rheological consistency index, flow behaviour index, specific heat and thermal conductivity of beef cattle manure were determined by Chen (1982) Density was measured for TS ranging from 1 to 99%. The results suggested that the density of manure increased as the total solids concentration increased for manure having TS below 16%. For manure with TS above 50%, the bulk density of the manure dropped much below the liquid manure density. Rheological properties where measured for manure having TS between 1 and 14% and based on the results obtained, beef cattle slurries were described as non-Newtonian pseudoplastic fluids, the deviation from Newtonian behaviour increasing with TS. Brambilla et al. (2013) provides a review of the rheological behaviour of slurries and provides rheological data on dairy manure, pig manure and wastewater slurries.

Chen and Shetler (1983) studied the effect of temperature on the rheological properties of cattle manure slurry. They tested manure with TS ranging from 2.5 to 19.3% at temperatures between 14 and 64°C. The results of this study confirmed previous findings by Chen (1982) to the effect that manure slurry is a non- Newtonian pseudoplastic fluid and that a power law could be used to describe its behaviour in the tested shear rate range.

Achkari-Begdouri and Goodrich (1992) studied the rheological properties of Moroccan dairy cattle manure with TS ranging from 2.5 to 12% at temperatures between 20 and 60°C. The rheological properties studied included the consistency coefficient, the flow behaviour index and the apparent viscosity. Their results showed that in the ranges of TS and temperature of the study, Moroccan dairy cattle manure behaved as a pseudoplastic fluid. Two equations based on TS and temperature, one yielding the consistency coefficient and the other predicting the flow behaviour index, were proposed.

Landry et al. (2002) and Landry et al. (2004) studies the physical and rheological properties of manure products including TS content, bulk density, PSD, friction characteristics, angle of repose and shear-strain- shear stress relationships for a range of different animal types.

Several researchers have determined a similar general behavioural aspect of animal slurries. Most researchers find that viscosity increases with increasing TS content and decreases with increasing fluid temperature (Baudez et al. 2012, El-Mashad et al. 2004a, El-Mashad et al. 2004b, Hasar et al. 2004, Kumar et al. 1972, Staley et al. 1973), although Chen and Hashimoto (1976) found that temperature had no effect. Figure 4 shows typical data showing the variation of shear stress (viscosity) as TS and fluid temperature are changed on fresh dairy manure slurry. Staley et al. (1973) used their viscosity measurements on fresh dairy slurry combined with conventional pipeline friction equations to calculate pipe friction losses for slurries of different TS contents at different flow rates (constant temperature of 20°C) (Figure 5). They confirmed this relationship in field measurements. This data illustrates the effect that increasing TS content has on pumping head requirements.

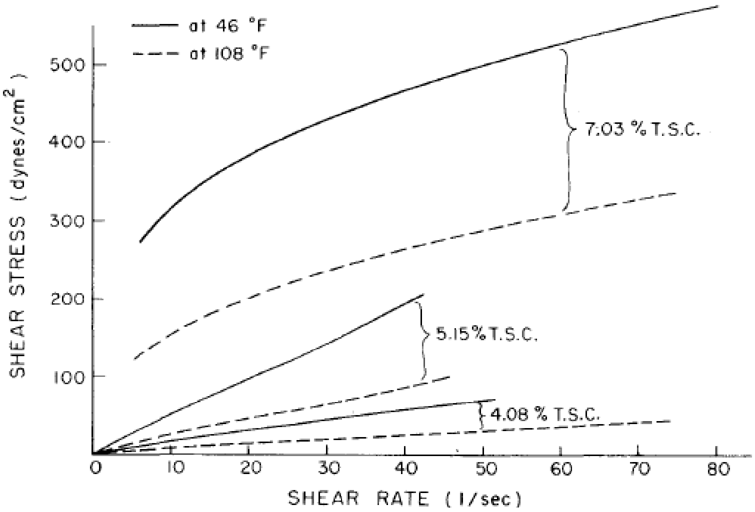


Figure 4: Effect of TS content and temperature on viscosity (Kumar et al. 1972)

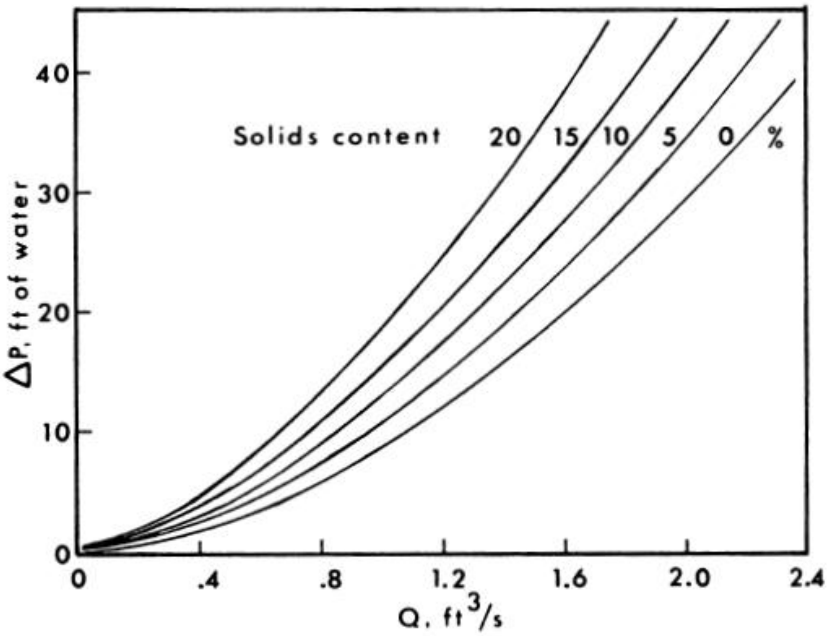


Figure 5: Predicted flow curves for 100 mm pipe (Staley et al. 1973)

The data presented above is for sludge and slurries comprised of raw animal manure. However, the sludge in a treatment pond or an anaerobic digester would be expected to have different characteristics. Masse et al. (2005) studied particle size, COD, nutrient, micro-nutrient and heavy metal distributions in raw and anaerobically digested (AD) manure from a growing-finishing pig operation. Anaerobic digestion was performed in sequencing batch reactors operated at 25°C. They found that AD reduces the TS concentration of animal slurry and changes the particle size distribution. It was observed that particles <10 µm accounted for 64% of TS in raw slurry while it reached 84% of TS in AD slurry. Marcato et al. (2008) also study the particle size distributions for raw and AD pig slurries. In AD, stirring and high temperatures facilitate microbial degradation of large particles, leaving relatively small particles made of slowly degradable material. Hence, it would be expected that the rheological properties of an AD sludge would be different to the raw manure from which it was derived.

Pollice et al. (2007) studied the physical characteristics of the sludge from a complete retention membrane reactor. Figure 6 shows the rheogram that they developed for their sludge at two different TS contents as well as the fitted curves for the Ostwald, Bingham and Herschel-Buckley models.

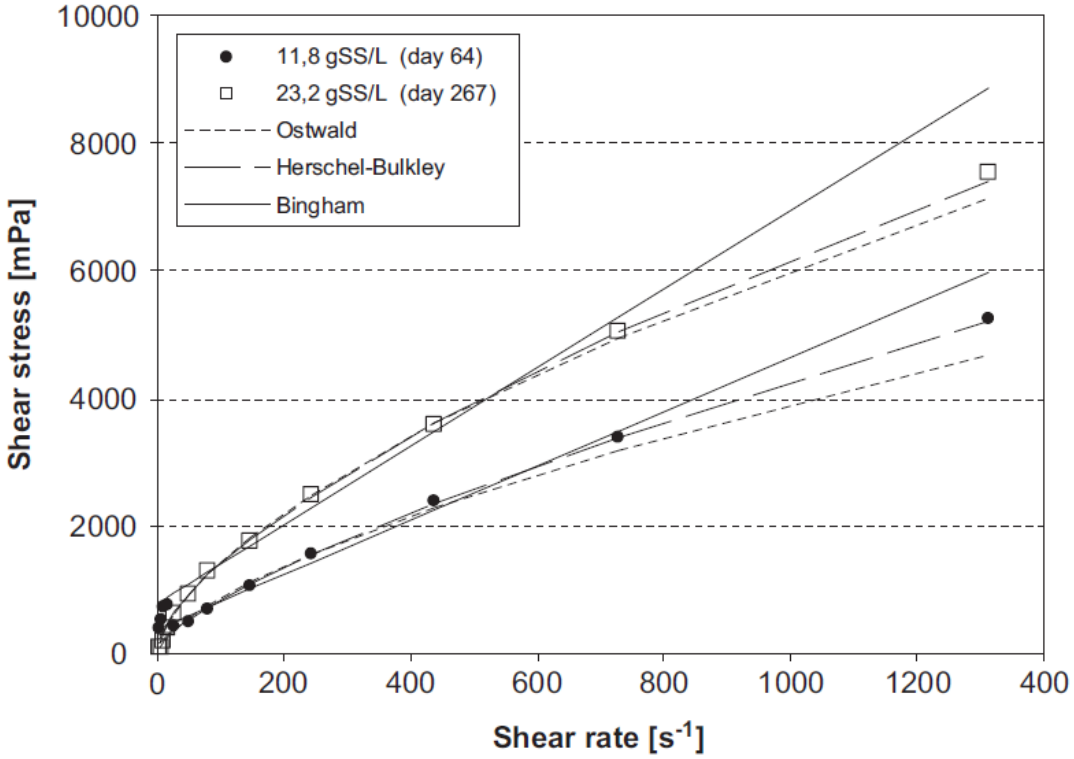


Figure 6: Rheogram of reactor sludge at two different TS contents

2.5.3 Angle of Repose of Sludge

The angle of repose or the critical angle of repose of a sludge is the steepest angle of descent or dip of the slope relative to the horizontal plane when material on the slope face is on the verge of sliding (Figure 7). This parameter only applies to sludge (stackable or spadeable solids – see Figure 2*: Handling characteristics of manure at different moisture contents*
) as effluent and slurries have a sufficiently high moisture content that they cannot sustain a solid shape. Angle of repose is an important parameter as it determines the "flowability" of sludges in the base of a treatment pond. This determines the volume of sludge that can be accessed by a suction line of a sludge pump located in one position.

Figure 7: Schematic description of angle of repose

Glancey and Hoffman (1996) provide data on the angle of repose of municipal solid wastes and poultry manures in raw and composted states. Landry et al. (2002) provides data on the angle of repose of sheep manure at different moisture contents. Unfortunately, no papers were found that reported the angle of repose of sludge in the base of anaerobic treatment ponds. However, practical experience indicates that, as the age and total solids content of the settled sludge increases, the angle of repose greatly increases. Densely settled pond sludge can stand up at a steep angle of repose.

3 Sources of Sludge and Slurries - Pond Systems

3.1 Background

Almost all conventional piggeries in Australia currently use pond-based systems to treat their effluent. Overtime, settleable solids present in the influent, or formed during the treatment process, will result in a steadily growing bottom sludge layer in the base of each pond that reduces the effective treatment volume of that pond. The loss of treatment volume will, eventually, adversely affect the overall treatment ability of the pond, causing the nutrient and solids content of the liquid (supernatant) portion to increase, more sludge to be produced, and more odours to be released from the pond's surface as organic matter degradation slows. Eventually, this sludge must be removed to ensure that the pond maintains the required hydraulic retention time (HRT) to keep performing properly. Desludging also provides an opportunity to utilise the sludge, which can be used in place of expensive inorganic phosphorus fertilisers. Desludging the ponds has always been problematic. However, the challenge has increased with the recent moves towards synthetically-lined and/or covered ponds for reducing GHG emissions and generating renewable energy for use on-farm. The feedlot industry is also looking at developing similar systems, with purpose-built covered ponds that will be loaded with manure to enhance biogas production. They will face the same challenges with these systems. Great care is needed when desludging these ponds to prevent damage to the synthetic liners and/or covers. Equipment such as excavators and agitators are unsuitable in these systems. Dewatering the sludge removed from the ponds can also be difficult, odorous and time consuming.

3.2 Pre-Treatment

In many feedlots and piggeries, a pre-treatment system (solid separator) is installed between the waste source and the first treatment pond. The aim is to reduce the TS content of the waste stream. The solid removal system can be based on settling, filtering, centrifuging or chemical flocculation. Most feedlots have a sedimentation basin that removes solids entrained in runoff by a settling process. In piggeries, there is a wider range of solid removal systems that are used. These can be settling basins, static, rotating or vibrating screens or screw presses.

These various pre-treatment systems vary in their solids removal efficiency (i.e. the proportion of incoming solids that are removed by the system) and the particle size distribution of the removed solids. These performance parameters affect the quantity and quality of sludge that subsequently forms in the treatment ponds.

3.3 Effluent Ponds

Effluent ponds are used for the effective treatment of piggery and feedlot effluent. The main advantage is their simplicity to build and operate, with minimal maintenance requirements and resilience to variable inflows. Despite their simple design, the systems contain complex ecosystems which include viruses, algae, bacteria, protozoa, insects, parasites, and fungi (Kehl et al. 2009). Through the action of microorganisms, complex organic cells are broken down into simple non-organic substances. A major goal of an effluent pond system is to provide optimum growth conditions for these organisms that promote complete decomposition of organic material and inactivation of pathogens (Gloyna 1971). The treatment processes cannot be fully controlled and are largely guided by physical and environmental constraints. These include solar radiation, temperature, wind, pH, pond geometry, organic loading and pond hydraulics.

Different types of ponds serve different purposes. The range of operating parameters distinguishes the type and performance. Ponds are distinguished largely by the dissolved oxygen (DO) of the layers within the ponds, which in turn, is dependent on the organic matter loading of the pond system.

3.4 Pond Types

The oxygen requirements of the bacteria and their relative numbers determine the classification of the pond as either anaerobic (absence of oxygen) or aerobic (measurable dissolved oxygen present) or facultative (containing a mix of anaerobic, aerobic and facultative bacteria, which can grow with or without oxygen).

3.4.1 Anaerobic Ponds

Anaerobic ponds are populated mainly with microorganisms that do not need free oxygen from the air to function (anaerobic microorganisms). Hence, they can have a role in treating effluent that has a relatively high organic matter content. They provide a relatively cheap way to stabilise the effluent. If the pond is covered, methane generated during the process can be captured and used for power generation.

Anaerobic ponds are typically 4-6 m deep. Ideally, they should be relatively narrow, with steep side batters to minimise surface area for odour release or covering, and to allow for easy desludging. As anaerobic microorganisms grow slowly, the ponds work best if there is a regular inflow of effluent in relation to pond active volume that does not have rapid and large variations in composition.

Anaerobic digestion of organic matter is a two-stage process. The first stage involves the breakdown of complex organic matter like carbohydrates, fats and proteins to mainly yield organic acids. The anaerobic and facultative microorganisms involved in this stage are known as the “acid forming bacteria”. The effluent is stabilised during the second stage. In this stage, microorganism known as “methane forming bacteria” convert these organic acids into methane and carbon dioxide gas. There is a range of groups of methane formers and each group digests only a limited number of organic acids. Consequently, complete digestion requires the presence and action of multiple different groups of methane formers. The methane formers have a narrow pH range in which they survive and function. When the system is balanced, the methane-formers break down the organic acids at the rate that they are generated. If the organic acids are not broken down as they are generated, the pond will become more acidic (and odorous). This adversely affects the second stage and can lead to the release of the odorous acidic by-products of the first stage. It is for this reason that a regular inflow of effluent helps to maintain good anaerobic pond function.

When sized appropriately, anaerobic ponds routinely remove 70% of BOD load (Metcalf & Eddy Inc. 2003). In Australian piggeries, primary anaerobic ponds are designed to reduce VS loading by around 70% (Tucker et al. 2010). Removal efficiencies of 80% to 90% have been recorded in anaerobic lagoons designed to New Zealand dairy industry guidelines (Mason 1997). Chastain (2006) suggests that anaerobic dairy lagoons remove around 56% of the VS load via settling. Pre-treatment by solid–

liquid separation would remove some of the readily settleable solids before the effluent enters the anaerobic pond and therefore reduce the percentage solids reduction achieved in the pond. Hence, the sludge characteristics of an anaerobic pond with solids removal is likely to be different from a pond with no solids removal.

3.4.1.1 Uncovered Anaerobic Ponds

The IPCC 2006 guideline defines uncovered anaerobic ponds as:

"*A type of liquid storage system designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. The water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.*" (Dong et al. 2006)

The majority of effluent treatment systems at Australian dairies and piggeries are uncovered anaerobic ponds. They provide a long retention time and are perceived as a low capital cost option. This system operates naturally from the microbial population that is already present in piggery effluent. The activity of these ponds will vary depending on ambient temperature, and may be affected by some feed additives. Uncovered anaerobic ponds can only achieve partial treatment and so materials such as phosphorus, nitrogen and ash accumulate in the bottom of the pond as a sludge layer. However, in general, anaerobic ponds are resilient, effective for reducing VS and require low maintenance.

Uncovered anaerobic ponds are usually sized using a VS loading rate method. A minimum treatment volume is determined plus an additional volume for sludge build up. The primary anaerobic pond volume can be split into two or more ponds operating in parallel to allow the effluent treatment operation to continue while one pond is being desludged.

3.4.1.2 Anaerobic Pond Design – Rational Design Standard

The most common methods for designing anaerobic treatment ponds are either the Rational Design Standard (RDS) or variations of it. This method was developed by (Barth 1985) and was based on three requirements:

- Control of lagoon odour.
- Allowance for sludge accumulation.
- Maintain a minimum treatment volume.

Climate has a large effect on the biological activity of a pond. Anaerobic activity within piggery ponds is reduced with lower average ambient temperatures. The volatile solids (VS) loading rate is adjusted using a factor (k), which varies according to piggery location. Higher average ambient temperatures in an area give a higher optimum pond loading rate. For instance, an area with a k factor of 1.0 has twice the ability to degrade organic material as a lagoon with a k factor of 0.5.

The standard VS loading rate (100 g VS/m^3/day) is multiplied by the temperature dependent k factor to calculate the minimum required active volume of a pond (Equation 1).

Not all the solids that enter the pond are degradable. Approximately 20% of the solids in fresh piggery waste are fixed (ash) and are not degradable. A certain percentage of the VS also degrades very slowly and will remain in the pond (dead cells). The rate at which solids accumulate in the bottom of the pond is called the sludge accumulation rate (SAR). This is generally measured as a volume per kg of total solids (TS) added. Few methods are available for estimating SAR accumulation in anaerobic ponds. The most widely accepted is that reported by Barth (1985) where he estimated SAR as 0.00303 m^3/kg of TS added. This figure is regarded in Queensland as being an over-estimate of SAR, with measured SAR for piggeries in southern Queensland being lower than this. The research by Anderson et al. (2000) obtained an accurate estimate of the sludge volume in an anaerobic pond after 15 years continuous use. The figure they obtained was found to be 79% lower than the sludge volume estimated using the ASAE method. Equation 2 is used to calculate the required volume for sludge.

The minimum required active volume is added to the sludge volume to give a total required pond volume (Equation 3).

The Rational Design Standard also requires the calculation of a maximum volatile solid loading rate based on a 20% odour detection rate. This is calculated from a standard VS loading rate for odour control (61 g VS/m^3/day), multiplied by the temperature dependent k factor (Equation 4).

Whichever is the larger, the volume required for odour control (Equation 4) or the volume required for active plus sludge (Equation 3) is used as the total design volume of an anaerobic pond.

Active vol. (m3) = VS loading (g/day) / (k factor x 100 (g/m^3/day)) **Equation 1**

Sludge vol. (m3) = TS loading (kg/yr) x SAR (m3/kg) x Pond life **Equation 2**

Total pond volume = Active vol. + Sludge vol. **Equation 3**

Vol. for odour control (m3) = VS loading (g/day) / 61 (g/m^3/day) x k factor **Equation 4**

For the Darling Downs in south-east Queensland, a typical VS loading rate is 85 g VS/m^3/day (100 g VS/m^3/day times a k factor of 0.85). Thus, if a Standard Pig Unit (SPU) produces 250 g VS/day (90 kg/yr), the required active volume per SPU is approximately 3 m^3. If it is assumed the SAR is 0.00303 m^3/kg of TS added and the pond is designed to last 10 years before desludging, with a TS production/SPU of 110 kg/yr, a required sludge volume would be approximately 3 m^3. This gives a total pond volume (active + sludge) of 6 m^3/SPU for a piggery on the Darling Downs with allowance for 10 years sludge accumulation. If the total volume for odour control is calculated, it equates to about 5 m^3/SPU. Because the volume required for active plus sludge is greater than the volume for odour control, this is used as the total design pond volume.

The adopted method for designing anaerobic ponds in Queensland is to calculate the required active and sludge volumes (Equations 6, 7 and 8), because these are generally greater than the volume required for odour control (Equation 9).

Large ponds tie up land and can be a source of odour problems. Due to their large surface area, these ponds generally require infrequent desludging (i.e. approximately every 10 years). Desludging can be expensive and may require a facility shut down or alternative manure handling system while desludging occurs.

3.4.1.3 Covered Anaerobic Ponds (CAP)

Covering the anaerobic pond prevents odour releases and provides an opportunity to capture biogas (methane) that can be used for energy generation. The technology employed to capture the biogas generated by anaerobic ponds is relatively simple. An impermeable cover extends across the surface of the pond with its edges buried in the embankment to prevent gas loss and, more importantly, air entry.

CAPs are designed in much the same manner as uncovered anaerobic ponds. Current recommendations for designing a CAP are to construct a steep-sided, deep pond (e.g. 6 m) with a length to width ratio of 3:1. These ponds are designed with a hydraulic residence time of 40-50 days and a variable sludge accumulation period between six months and the life of the cover. Photograph 1 shows an example of a CAP at a piggery.

Photograph 1: Covered anaerobic pond

Pond covers are constructed from 1.0-1.5 mm high quality geo-membrane cover such as low-density polyethylene (LDPE) or polypropylene (PP). High-density polyethylene (HDPE) - is also used. However, it is generally more difficult to install and there are problems associated with heat expansion.

3.4.2 Facultative Ponds

A facultative pond provides a mixture of anaerobic (oxygen starved) treatment at lower levels and aerobic (oxygen rich) treatment nearer to the surface of the pond. Facultative ponds are typically designed with a depth of up to 2 m (Metcalf & Eddy Inc. 2003).

Facultative ponds contain a complex ecology and allow for the robust removal of contaminants through settling, biodegradation and disinfection (Bryant 1995). These processes create a layer of sludge at the base of the pond. The structure of a facultative pond is guided by the presence of dissolved oxygen. Due to the turbidity of the pond, sunlight cannot penetrate through the entire water column and a distinct temperature gradient can develop (Water Corporation 2010). Such ponds can become stratified, influencing the flow conditions. The top layer of the pond is thus rich in carbon dioxide, nutrients and sunlight, promoting the growth of algae and aerobic bacteria. This is a highly aerobic environment. Levels of dissolved oxygen decrease throughout the water column, forming an anaerobic layer at the base of the pond (Tadesse et al. 2004).

A range of microbial processes in the facultative pond further breakdown the remaining organic material. The sludge layer is anaerobic and is responsible for a significant degree of decomposition that takes place (Gloyna 1971, Water Corporation 2010).

Often, at feedlots and piggeries, facultative ponds develop a purple colour. Purple sulphur bacteria (psb) have the potential to reduce pond odour by oxidising hydrogen sulphide into elemental sulphur during photosynthesis. They occur in anaerobic environments that have reduced sulphur present. They give the pond a brownish purple to pink colour, depending on the population. The conditions required to maintain a healthy population of psb is not well known. Work by Gilley et al. (2000) suggests that high levels of dietary copper fed in weaner diets may reduce the potential for psb to proliferate, whereas dietary zinc may inversely promote its growth. Other conditions that may reduce the potential for the presence of psb are high salinity level (>6 dS/m) and the presence of antimicrobials in the ponds.

Schulte and Koelsch (1998) reported the results of a detailed study of eight anaerobic lagoons and the survey of an additional 28 anaerobic lagoons in Nebraska. The results were collected in early spring and again in mid-summer. As the reported temperature range for the summer sampling is closest to Australian conditions, only the summer results will be discussed here.

Bacteriochlorophyll *a* (Bchl *a*) was used as a measure of the abundance of psb, with values between 0.043 and 1.018 mg/L obtained at the lagoon surface. Bchl *a* concentrations in purple lagoons were significantly greater than in non-purple lagoons ($P = 0.02$). Average pH values for purple and non-purple ponds were 7.4 and 7.8 respectively (statistically different at the $P = 0.005$ level). The oxidation-reduction potential (redox) at the surface was found to vary from -266 mv to -321 mv, and was less negative for purple lagoons than non-purple lagoons ($P = 0.006$).

No relationship was found between psb and volatile solids loading rate, but the purple lagoons were found to have comparatively high volumes of flush and cleaning water per animal unit. Solids, alkalinity, salinity and COD concentrations were lower in purple lagoons compared to non-purple lagoons, but were not statistically different. Ammonium concentrations were statistically lower in purple lagoons than in non-purple lagoons ($P = 0.01$). Salinity levels in excess of approximately 6 dS/m were associated with consistently low levels of Bchl *a*.

Hydrogen sulphide oxidised by psb is abundant in animal waste ponds because of sulphate-reducing bacteria, which reduce sulphate to hydrogen sulphide. The elemental sulphur formed by psb eventually returns to sulphate, completing the sulphur cycle. Anecdotal evidence suggests that the presence of purple sulphur bacteria is an indication of good lagoon function and reduced odour production. However, there are no odour emission studies to confirm this.

Unlike heavily-loaded ponds, pink ponds have the following characteristics:

- Uniform bright pink to dark purple-brown colour
- Little floating scum
- Few large bubbles – fine uniform bubbles across the pond surface
- “Musky” character to odour.

Photograph 2 shows a typical pink facultative pond.

Facultative ponds are simple and low maintenance but they can be easily overloaded and seasonality will affect performance. For effluent streams with high organic loads, facultative ponds should be used only after an anaerobic pond has provided substantial treatment and removal of settleable solids. If land area permits, an anaerobic pond followed by a facultative pond can form a suitable secondary treatment process.

Similar to anaerobic ponds, sludge distribution in facultative ponds has been found to be highly uneven and is further illustrated in Photograph 3.

Photograph 2: Typical pink facultative pond at a piggery

Photograph 3: Variable sludge distribution in ponds

3.4.3. Aerobic ponds

Aerobic ponds can be used to further polish the liquid effluent. Aerobic ponds are either shallow, with a large surface area to enhance the natural movement of oxygen into the liquid phase or are equipped with aerators to mechanically force air containing oxygen into the liquid phase. The aerobic process does not produce methane but converts organic material into carbon dioxide. Aerobic ponds can be mechanically or naturally-aerated. Photograph 4 illustrates a mechanically aerated aerobic pond.

In aerobic treatment ponds, aerobic microorganisms use dissolved oxygen to degrade the organic matter into carbon dioxide, water and cell biomass. Passive or naturally aerated ponds rely on oxygen produced by phytoplankton during photosynthesis and, to a lesser extent, diffusion of oxygen from the air into surface layers (Shilton 2005).

In naturally-aerated ponds, light penetration and photosynthetic activity may extend down only 50 to 150 mm (the 'euphotic' depth) (Sukias et al. 2001). As algal growth is restricted in ponds where the mixing depth exceeds five times the euphotic depth, aerobic processes may be restricted below a depth of 0.75 m. However, where the pond depth is <1 m, bottom-growing weeds may become established, decreasing capacity and, when decaying, adding biological load. True naturally aerobic ponds are rare in agricultural effluent treatment systems, as many so called 'aerobic' ponds have anaerobic conditions below the top 0.20 m (Sukias et al. 2001) and thus should be described as facultative.

Mechanical aerators increase the concentration of dissolved oxygen in the pond. The aerators increase oxygen diffusion at the surface whilst also providing mixing throughout the water column. The dissolved oxygen is spread throughout the pond allowing enhanced action of aerobic bacteria.

The recommended depth for aerobic ponds is therefore a compromise between efficacy and practicality, and usually ranges from 1.0 to 1.5 m.

Photograph 4: Mechanically-Aerated Aerobic Pond

Naturally-aerated aerobic ponds are suited to relatively dilute effluents. Although they could be used as a stand-alone option, the required surface area would be too large to be economical, and poor water quality would restrict light transmittance and algal photosynthesis.

3.5 Sludge Accumulation and Distribution

3.5.1 Sludge Accumulation

The depth and spatial variability of sludge in an effluent pond can vary widely depending on loading rates and the position of the inflow and outflow points. It is typically measured by probing at a number of points of the pond (e.g. 15 to 60 points per ha, (Westerman et al. 2008a). Typically, a lightweight pole or a tube open at each end is lowered into the pond until the apparent top of the sludge layer is reached and the depth is recorded. The pole or tube is then pushed further down at the same location until the bottom of the pond is reached and this depth is recorded. This is not always possible because the sludge is often so dense that refusal of the pole is reached before the base of the pond. In deeper ponds, it can be difficult to determine the interface between liquid and sludge. The probing method is time consuming, poses health and safety risks and the accuracy of the measurement itself is subjective.

More recently, infrared sensing, sonar and GPS have been used as a rapid sludge measurement tool that can be remotely controlled (Duperouzel nd., Singh et al. 2007)). The depth to sludge layer can be determined by the time lapse between the transmitted and reflected signals from the transducer (Westerman et al. 2008b). The Queensland DPI (Duperouzel nd.) found that sonar in piggery effluent ponds offers rapid sludge measurement with an accuracy comparable to the light reflectance. Singh et al. (2007) reported on the development of a GPS-enabled sonar equipment that can map sludge profiles without requiring a person in a boat. At this stage, only a few commercial contractors can provide a sonar service.

Three distinctly different zones are likely to be found within an anaerobic pond. First, an accumulation of solid inert material is found near the inflow pipe(s). The inert material - rocks, sand, excess feed etc. - accumulate near the inflow pipe(s) and drift to the bottom of the pond. This sediment is solid in nature with an easily identifiable interface between the solid and slurry layers. Second, above this zone, a moderately viscous sludge high in nutrients, bacteria, and organic matter is commonly found. This sludge layer may occur in mounds rather than in an evenly distributed layer on the bottom of the pond. This material can be handled by pumps designed for higher solids (e.g. slurry) applications. It is biologically active and the likely source of much of the anaerobic degradation occurring in a pond. Lastly, above the sludge layer is a liquid layer low in solids, moderately rich in nutrients, and easily pumped with irrigation pumps. With reference to Figure 2*: Handling characteristics of manure at different moisture contents*
, these three layers could be described as stackable, slurry and effluent respectively.

Sludge accumulates continuously in effluent treatment ponds, but mainly in the primary pond, which is usually the anaerobic pond. The Rational Design Standard (RDS) method allows for sludge accumulation at a rate of 0.00303 m^3/kg of TS (Barth 1985). This rate is incorporated into the ASABE standards (Table 2). For many years, the sludge storage capacity of anaerobic ponds in Australia has been sized using this figure.

However, this rule of thumb was queried by Hamilton (2010) who, over a nine year period, monitored sludge accumulation in two anaerobic / facultative ponds treating the wastewater from breeder piggeries. At one unit, the sludge was left largely undisturbed. At the other, solids were removed with each irrigation. At the first unit, sludge accumulated in a pattern consistent with the complex accumulation model proposed by Barth (1985) although only about half as quickly as previously thought. At the second unit, when sludge was removed with irrigations, it accumulated more quickly. It was suggested that this could be because regular removal of sludge also removes the micro-organisms responsible for breaking down the wastewater, affecting digestion of the incoming waste. In light of the results, a sludge accumulation rate of 0.0012 m^3/kg TS was proposed for ponds with undisturbed sludge assuming the storage period is longer than ten years. The sludge accumulation rate also escalates when sludge exceeds about 30% of the pond volume.

Chastain (2006) proposed a new sludge accumulation model based on basic treatment and mass balance approach. This was incorporated into the updated standards of ASABE (2011) for sludge accumulation rate (Table 2).

Table 2: Sludge accumulation rate for anaerobic ponds

	ASAE, 2004	ASABE, 2011
Type of waste	m^3 sludge per kg TS added	m^3 sludge per kg TS added
Swine	0.00303	0.00137
Poultry	0.00184 (layer), 0.00284 (pullet)	0.00202 (layer or pullet)
Dairy	0.00455	0.00455

However, research in sewage wastewater ponds has demonstrated that sludge deposition is not a linear process, as accumulation rates are influenced by pond configuration and influent loadings and tends to decrease with time due to anaerobic degradation and consolidation of sludge (Abis & Mara 2005, Picot et al. 2005). Hence, application of a simple linear per annum rate is a significant approximation. A complex accumulation model, Equation 5, has been suggested to predict the sludge accumulation in piggery treatment ponds (Hamilton 2010):

$$\boldsymbol{S} = (\boldsymbol{M_T} \times \boldsymbol{R})/\boldsymbol{k} \times \left(\mathbf{1} - \boldsymbol{e}^{-\boldsymbol{k}\boldsymbol{t}'}\right) + \boldsymbol{M_T} \times (\mathbf{1} - \boldsymbol{R}) \times \boldsymbol{t}' \qquad \textbf{Equation 5}$$

where:

S = accumulated sludge total solids (mass)
M_T = total solids loading rate (mass/time)
R = steady-state solids removal fraction (mass removed/mass loaded)
t' = time between lag time (when sludge begins to accumulate) and the critical time (when lagoon begins to show signs of failure

In a nine-year monitoring of two lagoons for pig manure, Hamilton (2010) found that sludge accumulated in the undisturbed lagoon followed a similar pattern as predicted by the above model, while Chastain (2006) proposed a relatively simply and flexible method to allow the constant sludge accumulation rate to be overcome.

MSL = [(1-FVSD) SVS MVS + STS MTS - SVS MVS + MFSSOIL] T - **Equation 6**

where:

M_{SL} = mass of sludge,
F_{VSD} = fraction of VS destroyed over the specified time period,
S_{VS} = fraction of VS that settles to the sludge layer,
MVS = mass of VS loaded per day = (VS /TS) * MTS,
S_{TS} = fraction of TS that settles to the sludge layer,
MTS = mass of TS loaded per day (manure solids + wasted feed + organic bedding),
MFS_{SOIL} = mass of soil or sand bedding added per day,
T = (δ * θ) = sludge storage period in days,
δ = number of days the lagoon is loaded per year
θ = number of years for sludge storage.

And the mass of total solids generated on an animal farm includes contributions from manure, wasted feed, and organic bedding

$$MTS = fFW\ TSM + MOB. \qquad \textbf{Equation 7}$$

where:

fFW = wasted feed factor (Table 6)
TSM = mass of TS from manure (gTSM / kgLAW-day,)
MOB = mass of organic bedding added to the manure (g / kgLAW-day).

In facultative ponds, solids settling at the bottom of the pond undergo anaerobic decomposition. In aerated ponds, sludge accumulation tends to be small due to the aeration that keeps solids suspended, and solids may thus be discharged in the outflow.

Regardless of the sludge accumulation rate, maintaining sufficient treatment volume in the pond is very important. Based on the research findings of Skerman et al. (2008), the National Environmental Guidelines for Piggeries included a recommendation that the need for desludging should be investigated if the VS reduction in the anaerobic pond falls below 50% or the VS concentration of the treated effluent exceeds 1% (Tucker et al. 2010).

Birchall (2010) examined the sludge accumulation rate in a covered anaerobic pond at Bears Lagoon piggery near Bendigo. The solids accumulation rate was determined to be 0.00094 m^2/kg TS over five years of operation. This rate is approximately one-third of the commonly used estimate by Barth and Kroes (1985) but within the range proposed by Chastain (2006) in his review of additional data from the USA. In Queensland, Skerman et al. (2008) identified a sludge accumulation rate of "less than 0.001 m3/kg TS after 22 months of operating a highly loaded pond.

3.4.2 Sludge Distribution

An understanding of the distribution of sludge across a pond would help in the design and management of a sludge removal system. However, sludge distribution in anaerobic ponds has been found to be highly uneven (Figure 8). Sludge levels are often found to be higher at the inlet, outlet and in the corners (Abis & Mara 2005). For example, in the primary pond at the municipal wastewater treatment facility at Mèze (France), Picot et al. (2005) shows that the depth of sludge reduced from more than 1 m at the inlet to less than 0.6 m at 50 m from the inlet. However, high velocity of the incoming flow could reduce the sludge depth near the inlet (Saqqar & Pescod 1995). High sludge levels in the corners are attributed to wind action, as gaseous products of anaerobic distribution force sludge to the surface, where it is blown into the corners. Patterns of sludge distribution are often attributed to pond geometry and inlet layout. For example, ponds with steep sides was found to provide favourable conditions for uniform distribution of sludge (Papadopoulos et al. 2003), and five inlets instead of one resulted in more even distribution of sludge (Nelson et al. 2004). Local climate conditions are important and sludge distributions are known to change throughout the year. There are obvious interactions between sludge distribution and pond hydrodynamics with regard to differences in channel depth and differing flow velocities throughout the pond. The processes involved are poorly understood and have not been well studied for anaerobic ponds.

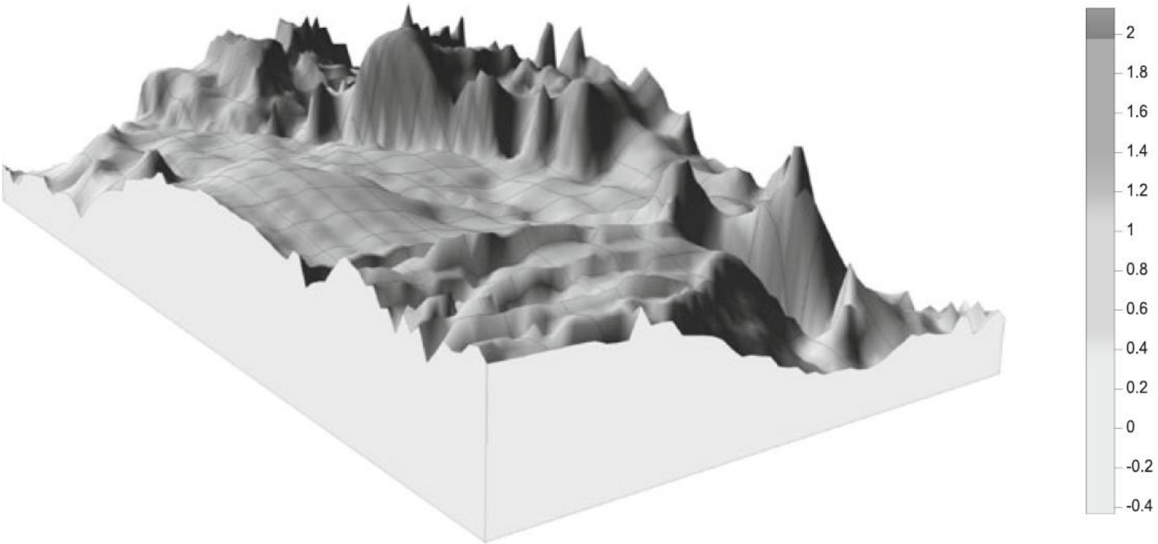


Figure 8: Sludge distribution in a primary pond (Keffala et al. 2013)

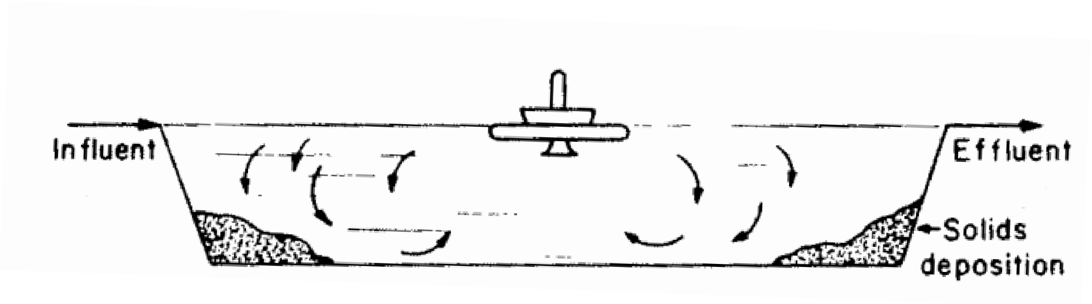


Figure 9: Sludge distribution in a facultative pond with incomplete aeration (adopted from Ramalho 1977)

In aerobic ponds, sludge distribution depends on the turbulence level on the surface (Figure 9). In municipal wastewater treatment plant, solids from the aerobic system are often collected and recycled back to the aerated system to minimise the sludge accumulation. In an aerobic pond at a piggery, however, no such recycling exists and solids concentration in the pond is a function of wastewater characteristics and detention time, usually between 80 to 200 mg/L (Ramalho 1977).

4. Pumping slurries and effluent

The design choices for the pumping of slurries and effluent is primarily dependent on the TS content of the material. Generally, effluent was a TS <2% can be pumped with conventional centrifugal pumps as it has hydraulic characteristics similar to water. For fluids with 2% to 10% TS content, pumping is still possible but special pumps (e.g. positive displacement or vacuum) are required. It is virtually impossible to pump fluids with a TS content >15%. Brambilla et al. (2013) provides a good review of the different pumps used in pumping anaerobic digester slurries.

Correct pump selection is very important because pumps are designed to suit specific pumping conditions. The following steps should be used to select the appropriate pumps (Warman International Ltd. 2000).

1. Determine the flow rate, usually established by the volume of solids to be pumped and the proposed concentration of solids. The flow rate through the pump is directly proportional to pump speed, head to speed squared and power to speed cubed (Grzina 2002). It means that if the pump speed is doubled, then the generated head would generally need to be four times higher and the power consumption eight times higher.
2. Determine the static head, the vertical height on both the intake and discharge side of the pump.
3. Determine the pump head and efficiency corrections, which is determined by the average particle size of the solids (d_{50} mm, Figure 10, Grzina (2002), the concentration of solids (% by weight) and the dry specific gravity of the solids.
4. Determine the pipe diameter, which will provide the optimum velocity to minimise friction.
5. Determine the friction head loss. For TS contents greater than 2%, friction losses are from 1½ to 4 times the friction losses for water (Guyer 2011).
6. Calculate the total dynamic head.

Pump type can then be selected from the supplier product catalogue. Brambilla et al. (2013) note that there are essentially two types of pumps sued for slurries – open-volute centrifugal pumps and positive-displacement pumps.

4.1 Centrifugal pumps

Centrifugal pumps can provide flow rates from a few litres to thousands of litres per second and can handle solid particle sizes from microscopic to sand. Their main limitation is that they cannot develop pressures higher than 7 MPa even when they are arranged in series.

Centrifugal pumps with semi-open or vortex impellers are considered more suitable for pumping slurries with a high solids content (Brambilla et al. 2013). It may be either self-contained motorized or PTO driven, although the latter is more commonly found. A minimum positive head of 610 mm shall be provided at the suction side of centrifugal type pumps and thus is desirable for all types of sludge pumps.

Some pumps are specially designed for pumping sludge from ponds, for example with an adjustable pump length (Table 3) supplied by GEA Technologies and different versions driven by a tractor (Figure 11). The major factors to consider when sizing pumping equipment include the distance from the storage to the field and the average flow rate needed for the desired application rate. The solids are moved along only when drag forces, generated by the faster water, overcome gravity forces (Grzina 2002). When this is not achieved, solids can settle and thus block the pipe. A rule of thumb, the liquid velocity for pipe sizing is that needs to be greater than 1 m/s to keep the solids suspended.

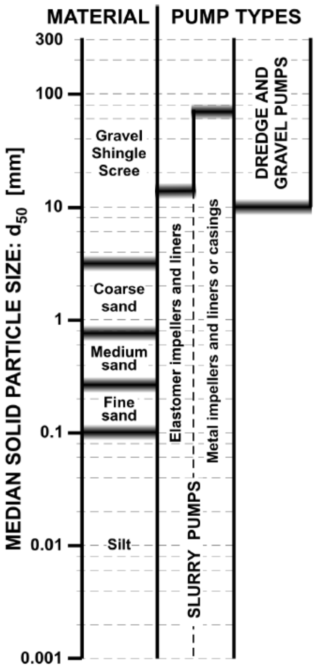
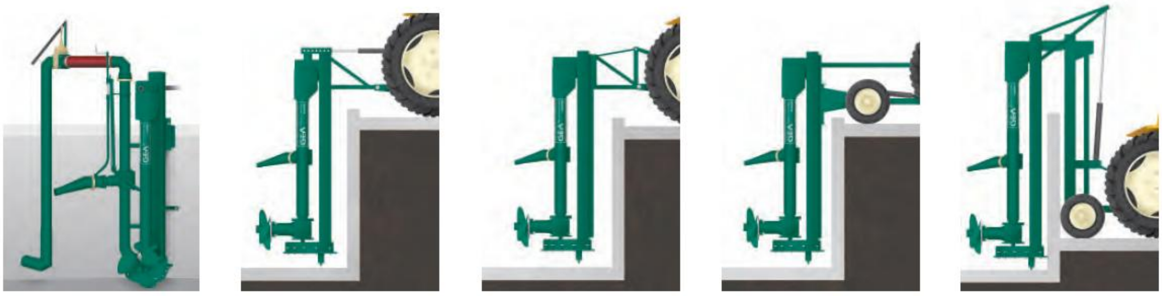


Figure 10: Pump selection guide

Table 3: Example pumps from GEA

Pump	Description	Revolutions Per Minute (RPM)	Capacity (m^3/hr)
Agi-Pompe	To agitate, chop and transfer effluent containing fibrous material and high percentage solids	540 RPM (with 120 HP min), 1000 RPM (with 160 HP min)	Up to 4878
Super Pump	To handle thick manure slurry with a low chopped straw content	540 RPM (with 90 HP min), 1000 RPM (with 180 HP min)	Up to 4878
Articulated screw propeller agitator	effectively mix sludge from the pond floor, large impeller for faster agitation without splash and less odours, optional side to side articulation	540 RPM (with 120 HP min)	



Agi-Pompe® Stationary*
Agi-Pompe® Tilting 3-point hitch*
Agi-Pompe® Sliding 3-point hitch*
Agi-Pompe® Trailer mount*
Agi-Pompe® Above ground tank*

Figure 11: Five versions of agi-pompe and super pump of GEA

4.2 *Positive displacement pumps*

Positive displacement pumps are either reciprocating (piston-and-diaphragm or piston-and-cylinder design (plunger) with inlet and outlet poppet valves) or rotary (progressing-cavity pump and rotary-vane vacuum pumps). They can generate much higher pressures than even multi-staged centrifugal pumps but their design flow rate range is limited from 50 to 1000 L/s mainly due to their large physical sizes (Grzina 2002). Rotary pumps are self-priming and deliver a constant, smooth flow regardless of pressure variations.

4.2.1 Diaphragm pumps

A diaphragm pump is a reciprocating pump also known as a membrane pump, air operated double diaphragm pump (AODD) or pneumatic diaphragm pump. It is a positive displacement pump that uses a combination of the reciprocating action of a rubber, thermoplastic or Teflon diaphragm and suitable valves either side of the diaphragm (check valve, butterfly valves, flap valves, or any other form of shut-off valves) to pump a fluid. Diaphragm pumps are self priming and are ideal for viscous liquids.

Commercial examples of diaphragm pumps used to pump municipal and mining slurries include:

GEHO PD Slurry Pumps	http://www.weirminerals.com/default.aspx
Mud Sucker	http://www.wastecorp.com/mudsucker/slurry-pump.html
Sandpiper (AODD pumps)	http://www.sandpiperpump.com/

Figure 12 shows a schematic diagram of the GEHO diaphragm pump while Figure 13 shows a schematic of a Mud Sucker pump. The essential elements are a flexible diaphragm and inlet / outlet valves. It is claimed that these pumps can deliver material with a TS content of greater than 15%.

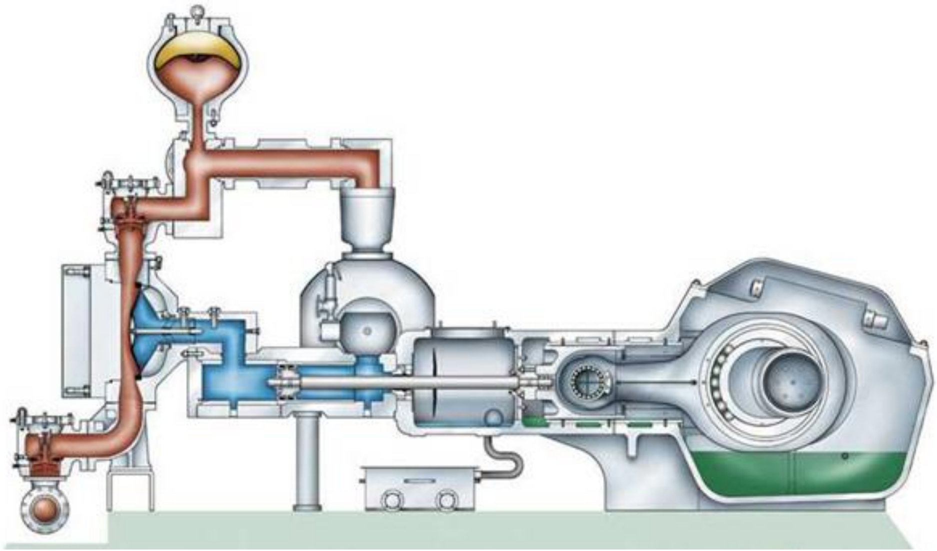


Figure 12: Schematic of GEHO-ZPM diaphragm pump

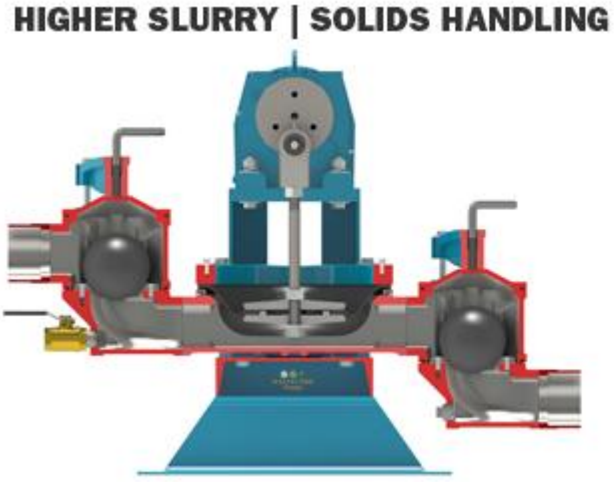


Figure 13: Schematic of Mud Sucker diaphragm pump

4.2.2 Plunger and piston pumps

Piston pumps and plunger pumps are reciprocating pumps that use a plunger or piston to move media through a cylindrical chamber.

A piston pump is a type of positive displacement pump where the high-pressure seal reciprocates with the piston (Figure 14). A plunger pump is a type of positive displacement pump where the high-pressure seal is stationary and a smooth cylindrical plunger slides through the seal (Figure 15). This makes them different from piston pumps and allows them to be used at higher pressures. This type of pump is often used to transfer municipal and industrial sewage.

Rotary piston and plunger pumps use a crank mechanism to create a reciprocating motion along an axis, which then builds pressure in a cylinder or working barrel to force gas or fluid through the pump. The pressure in the chamber actuates the valves at both the suction and discharge points. Plunger pumps are used in applications that could range from 70 to 2070 bar. Piston pumps are used in lower pressure applications. The volume of the fluid discharged is equal to the area of the plunger or piston, multiplied by its stroke length. The overall capacity of the piston pumps and plunger pumps can be calculated with the area of the piston or plunger, the stroke length, the number of pistons or plungers and the speed of the drive. The power needed from the drive is proportional to the pressure and capacity of the pump.

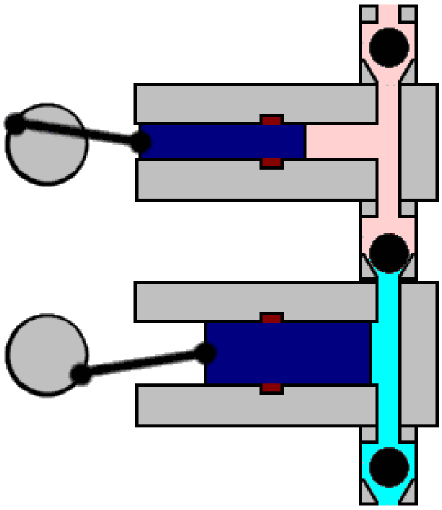


Figure 14: Schematic of piston pump

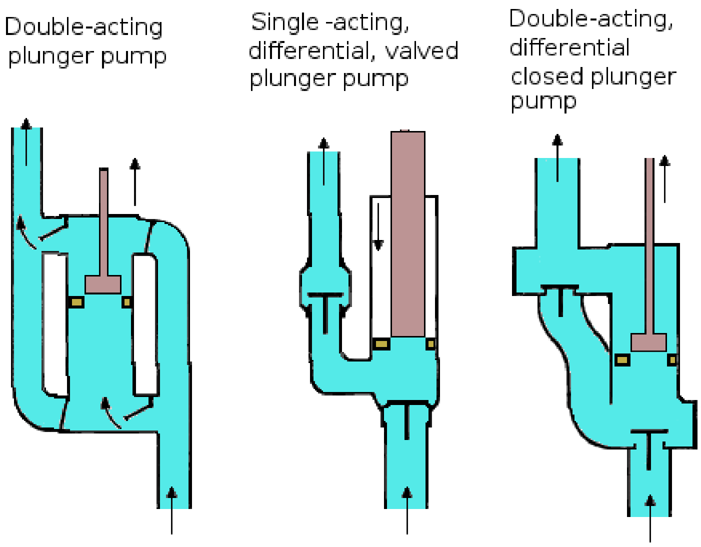


Figure 15: Schematics of plunger pumps

4.2.3 Progressing-cavity pumps

A progressing-cavity pump is a type of positive displacement rotary pump and is also known as an eccentric screw pump or cavity pump. It transfers fluid by means of the progress, through the pump, of a sequence of small, fixed shape, discrete cavities, as its rotor is turned. This leads to the volumetric flow rate being proportional to the rotation rate (bidirectionally) and to low levels of shearing being applied to the pumped fluid. Hence, these pumps have application in fluid metering and pumping of viscous or shear-sensitive materials. The cavities taper down toward their ends and overlap with their neighbours, so that, in general, no flow pulsing is caused by the arrival of cavities at the outlet, other than that caused by compression of the fluid or pump components.

The progressing-cavity pump consists of a helical rotor and a twin helix, twice the wavelength and double the diameter helical hole in a rubber stator (Figure 16). The rotor seals tightly against the rubber stator as it rotates, forming a set of fixed-size cavities in between. The cavities move when the rotor is rotated but their shape or volume does not change. The pumped material is moved inside the cavities.

These pumps are often referred to by the specific manufacturer or product names. Hence names can vary from industry to industry and even regionally; examples include:

Moineau (after the inventor, Rene Moineau)	http://gb.pcm.eu/en/
Mono pump	http://www.monopumps.com.au/

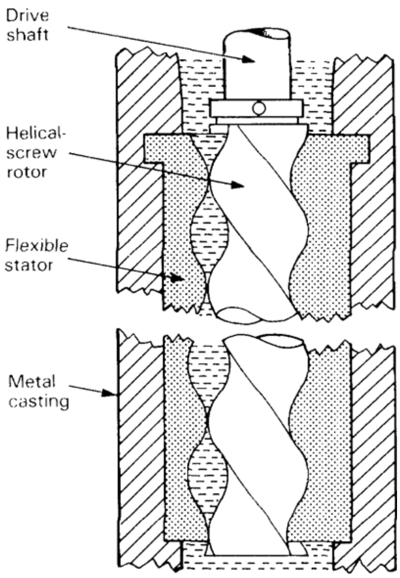


Figure 16: Schematic of progressing-cavity pump

4.2.4 Rotary vane vacuum pumps

A rotary vane pump is a positive-displacement pump that consists of vanes mounted to a rotor that rotates inside of a cavity (Figure 17). In some cases, these vanes can be variable length and/or tensioned to maintain contact with the walls as the pump rotates. Rotary vane pumps are a common type of vacuum pump, with two-stage pumps able to reach pressures well below 10-6 bar.

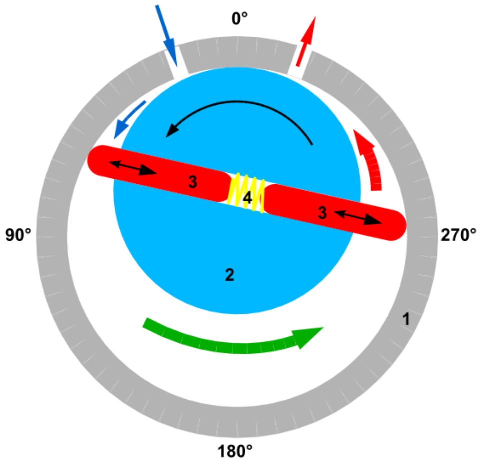


Figure 17: Schematic of rotary vane vacuum pump

Rotary vane vacuum pumps are the most common type of pump used on agricultural slurry tankers. Many vacuum pumps on slurry tankers are supplied by Battioni Pagani Pompe.

Battioni Pagani Pompe http://www.battionipaganipompe.it/bp/default.asp?sLang=EN

4.2.5 Pump type selection

The selection of a pump for a particular situation needs to take into account a number of variables specific to the site and the application. Table 4 gives some general guidelines.

Table 4: General selection characteristics for positive displacement pumps

Parameter	Reciprocating pumps	Rotary pumps
Capacity	Low	Low/Medium
Pressure (Head)	High	Low/Medium
Maximum Flow Rate	10,000+ GPM	10,000+ GPM
Maximum Pressure	100,000+ PSI	4,000 PSI
Requires Relief Valve	Yes	Yes
Flow Type	Constant	Constant
Flow Characteristic	Pulsating	Smooth
Space Considerations	Requires More Space	Requires Less Space
Initial Costs	Higher	Lower
Maintenance Costs	Higher	Lower
Energy Costs	Lower	Lower
Liquids Recommended	Viscous liquids, dirty chemicals, tacky glue and adhesives, oil, and lubricating fluids. Specialty fitted pumps can handle abrasives.	Optimum for viscous fluids. Requires clean, clear, non-abrasive fluid due to close tolerances.

Source: PDHengineer.com

5. Removal of sludge and slurries from ponds

Sludge removal and disposal/reuse incurs significant costs, both in extraction, storage, transport and eventual disposal. Equipment that is suitable and effective for removing solids from ponds has been developed in both the municipal/industrial/mining and agricultural arenas.

Equipment and techniques for cleaning solids from municipal and industrial ponds has been available for many years. Procedures using this equipment are designed to clean the pond in a short period (within a few days) on a "one-time" basis.

Choices of pond desludging techniques depend on the operation and structure of pond, sludge physical characteristics and the frequency of desludging. Desludging can be broadly categorised into three groups:

- desludging dewatered ponds (after effluent removal)
- desludging an uncovered pond containing effluent
- desludging a covered pond.

5.1 Desludging dewatered ponds

Due to the high cost of desludging, for ponds with very old or thick sludge, it is often cheaper to remove the water layer first and then excavate the sludge with conventional earthmoving equipment such as an excavator and dump trucks (Watson 1999).

Some contractors prefer at least one of the long sides of the pond to be 6 m wide to allow for machinery access during desludging. Earthen ramps with a grade of 1:10 will allow safe approach to, and departure from, the embankment. It is also beneficial to provide a gravel-topped crest to maintain good traction while machinery is working beside the pond. Such machinery can weigh in excess of 30 tonnes, and OH&S issues must be considered.

Photograph 5 shows a pump being used to dewater a piggery pond. This illustrates two problems with this approach for piggeries. Firstly, there must be a suitable place for the effluent removed from the pond to be stored or used immediately. Secondly, there must be an alternate pond available to receive incoming wastewater while the pond is being desludged. If not, the piggery must cease operation during the desludging operation. Even after dewatering, the sludge is still quite wet making removal an inefficient process (Photograph 7). If the pond is above natural ground level, it is possible to simply breach the pond embankment and let the sludge flow out as a slurry into a drying bay. The embankment is then reconstructed and normal pond operations recommence.

This issue generally does not exist for feedlot sedimentation ponds and holding ponds. As these structures only fill with water following rainfall events, there are inevitably dry periods when the basins and ponds become dry and the accumulated sludge can be removed by conventional means (Photograph 6).

Photograph 5: Dewatering an anaerobic pond prior to desludging

Photograph 6: Dried sludge in a feedlot sedimentation basin ready for removal

Photograph 7: Sludge removal from a dewatered pond with an excavator

Photograph 8: Anaerobic pond after dewatering and desludging

5.1.1 Advantages and disadvantages

The advantage of this method is that it is relatively simple and does not require specialist equipment. It is only suited to infrequent pond desluding so the pond needs to have a large sludge accumulation volume allocated during the design.

There are several disadvantages with this method.

1. The pond must go off-line during the desludging operation. A location must be found for the effluent removed during dewatering and an alternate pond for receiving fresh effluent must be provided to maintain piggery operation.
2. A large volume of sludge is produced in a short time period. This usually means that a site for storage and dewatering of the sludge is required.
3. Following the sludge removal, the base of the pond is generally cleaned (Photograph 8). This removes any biological seal that may have developed in the base of the pond. If soil conditions are conducive, this could lead to groundwater contamination when the pond is refilled.
4. This method is completely unsuitable for a plastic-lined pond as damage to the liner would be inevitable.

5.2 Desludging uncovered ponds containing effluent

It is usually more desirable to remove sludge from a pond without dewatering as this maintains the function of the pond. There are three basic methods of sludge removal from an operating, uncovered pond. They are:

1. Pumping. This uses a pump or vacuum tanker located on the bank of the pond. It may or may not include agitation of the sludge in the base of the pond.
2. Dredging. This involves the use of a system where the pump is within the pond and is mobile so that all sections of the pond can be accessed.
3. Mechanical Removal. This involves the use of a long-reach excavator or similar to remove the sludge without pumping.

5.2.1 Pumping (with or without agitation)

In this method, a pump is located on the embankment of the pond. The slurry / sludge is pumped either into a tanker for immediate disposal or to a dewatering location. The pump can either be a vacuum pump or a positive displacement pump (Photograph 9). Photograph 10 shows a tanker with a vacuum pump removing sludge directly from a pond.

One problem with this method is that the sludge in the base of the pond has usually settled into a solid mass and does not flow. A conical void usually forms around the suction end of the pipe and eventually only effluent is pumped. This is overcome by regularly moving the location of the suction inlet around the pond. For large ponds, it is sometimes difficult to reach the centre of the pond.

One solution is, before pumping the sludge from ponds, to agitate the sludge to suspend the solids with mechanical agitation being the most common method deployed (Figure 18). This converts “sludge” into “slurry” or “effluent” which is much easier to pump. Depending on the thickness, age and type of sludge, this may occur a few hours ahead of desludging and should continue during desludging. Since the accumulation of solids is generally heaviest near the inlet, agitation in the inlet area is critical for effective suspension of solids. Photograph 11 shows a pond agitator at work.

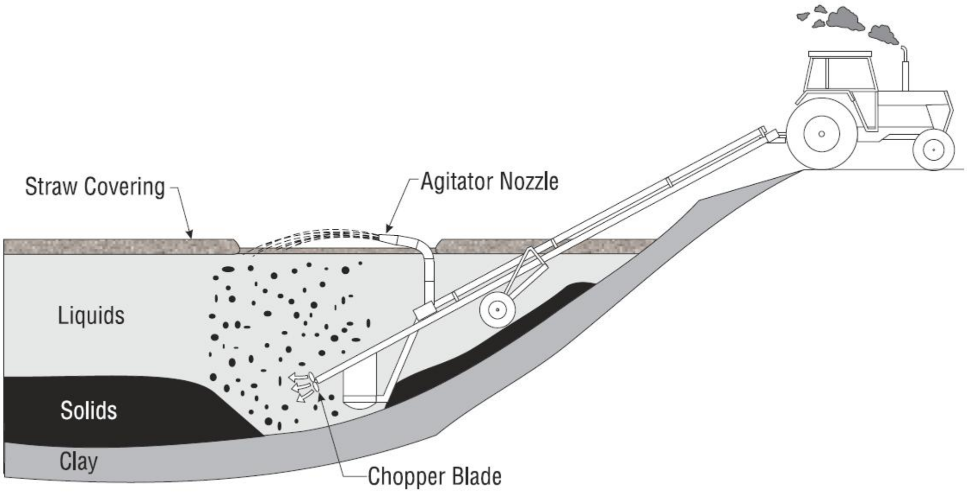


Figure 18: Agitating the manure pond (adopted from PAMI, 1997)

The effectiveness of the suspension depends on the power of the agitator and the size of the pond. High-volume pumps (15 000 to 25 000 litres/minute), specifically designed for agitation and loading, will provide the best suspension of solids. However, agitation equipment is generally effective only in suspending solids within a limited area (within about 15 m of the agitator) and for a short period of time. Therefore, more than one agitator may be needed for a large pond or one agitator needs to move around the pond so as to suspend most of the sludge.

The effluent with suspended sludge should be pumped out of the pond during the agitation to prevent the solids from settling. Caution needs to be taken that the agitator head and the pump inlet are kept a reasonable distance above the bottom of pond (e.g. 0.5 m) so that the pond lining is not damaged by the turbulence (PAMI 2000). Additionally, agitation equipment can erode earthen liners and should be used cautiously. With care, agitators can be used on plastic-lined ponds.

Pump-out of pond sludge should be designed to encourage easy setup, regular (every few years) sludge removal, and protection of liner integrity. Infrequent sludge removal will result in significant nutrient accumulation, substantial land disposal area requirements, and significant transportation cost.

Photograph 9: Sludge removal with a mono pump (no agitation)

Photograph 10: Sludge removal using a suction tanker and agitation (Source: Alan Skerman, DAFF)

Photograph 11: Pond agitator (Source: Alan Skerman, DAFF)

5.2.2 Dredging

For large ponds, sludge may be dredged and pumped at the same time using a floating dredger, similar to the process used for sand dredging (Figure 19). This is often used in municipal and mining ponds. A suction auger is used to suck the sludge out and transport it through a pipe supported by pontoons. The dredger needs to be operated from around the pond perimeter to access all sludge. Alternatively, a manual survey or ultrasonic detection may be used to find the main area of sludge before dredging. Depending on the access depth of the dredger, the water level of the pond may need to be reduced so that the lower layer of sludge can be reached. To prevent damage of pond linings, the cutter head of dredger may be modified by adding a wheel system to keep the cutter head about 100 mm above the surface of the sludge. Photograph 12 shows a pond dredge in operation.

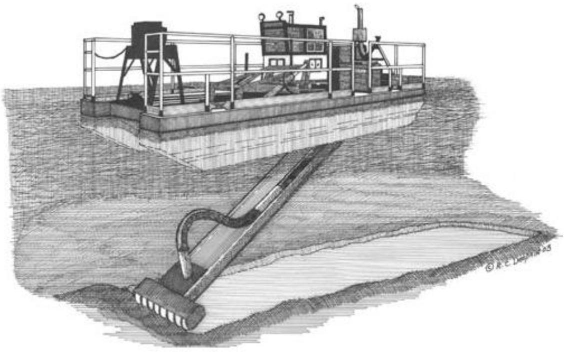


Figure 19: Sludge dredging (VanDevender 2003)

Dredging services are provided by a few Australian companies and a brief comparison among them is shown in Table 5. Sludge is often sucked out with a large amount of water (e.g. sludge:water = 1:5) and thus dewatering of the resulting slurry needs to be performed immediately afterwards.

More details can be found at the websites for some companies operating in Australia. This is not intended to be a comprehensive list of all dredging companies.

UAT SludgeRat	http://www.uat.com.au/sludgerat.html
Epsom Environmental	http://www.epsomenviro.com.au/services/lagoondredging
Apex Envirocare	http://www.apexenvirocare.com.au/products/microdredger
Dredging Solutions	http://www.dredgingsolutions.com.au/
Dredging Systems	http://www.dredgingsystems.com.au/

Photograph 12: Pond dredge in operation (Dredging Solutions)

Epsom Environmental has used Sludgemaster® for dredging covered anaerobic ponds and found that concentration of 4-6% is ideal for pumping. When TS content reaches 12%, flows start to significantly drop off. Typical flows have been found to range from 80-130 m^3/hr. The dredger is designed to not affect clay liners and synthetic liners since wheels are fitted to either side of the head.

5.2.3 Mechanical removal

It is possible to desludge uncovered ponds without dewatering using mechanical methods. One method is the use of draglines that drag a scoop bucket across the base of the pond drawing a wet slurry up onto the side bank of the pond. Another method is to use a long-reach excavator (Photograph 13) which can access most areas of the pond from the side banks.

Photograph 13: Long-reach excavator

5.2.4 Advantages and disadvantages

GHD (2008) undertook a study comparing three desluding methods for uncovered ponds. They compared a Mono pump, a SludgeRat and a long-reach excavator.

Table 6 gives a technical and economic evaluation of the three desludging options. Table 7 gives a SWOT analysis of the three methods. Each method has advantages and disadvantages so the optimum solution is dependent on site conditions.

Table 5: Comparison of three dredging services in Australia

Name	Company	Capacity (m^3/hr)	Engine	Operation	Dredge depth (m)	Pump Type	Dimension (m)	Weight (tonnes)
Sludgemaster 9000	Epsom Environmental	75	Perkins Diesel	Diesel/ Hydraulic	4.5	Direct Drive 100mm Gorman Rupp Slurry Pump	L=6.7, W=3.6, H=2.6	
Microdredger[a]	Apex Envirocare						L=6, W=2	2
Dredging Solutions	Dredging Solutions							
SludgeRat	UAT	100[b]		Remote control	3.5		L=3, W=3.8, H=1.7	1.5

[a] Information on the Microdredger, Apex Envirocare, can be found at: http://www.apexenvirocare.com.au/products/microdredger

[b] Estimated from GHD (2008) case study where it achieved 30L/s pumping rate

Table 6: Desludging cost comparison

Desludge method	Hire rates	Capacity	Hire duration	Hire cost	Transport cost	Power usage	Total cost	Desludge trial conc.	Total Solids removal	Comparison cost
	$/day	m3/hr (ave.)	Days	$	$	kWh/hr	$	TS%	Dry tonnes (ave.)	$/dry tonne
Mono pump	350	32	4	1400	1000	617	2460	10%	100	25
SludgeRat®	557	108	2	1100	1500	65	2620	8%	80	33
Kato long reach excavator	2320	50	3	7000	2000	-	9000	15%	150	60

Source: GHD (2008); SludgeRat, UAT, www.uat.com.au

Table 7: Desludging SWOT analysis (GHD 2008)

	Strength	Weakness	Opportunity	Threat
Long-reach excavator	High sludge volume removed High %TS concentration	Labour intensive Time consuming High hire costs Weight of dump trucks causes wheel ruts in sludge drying bays making it difficult for emptying	New design for excavator bucket so not to damage pond liner	Excavator could potentially fall into the pond if used by an inexperienced operator Rising fuel costs Risk of damage to pond liner
SludgeRat	High sludge volume removed Short sludge removal duration Can desludge all of the pond, not just the edges	Lowest %TS concentration Setup time is consuming Requires operator present at all times Maximum solids 9%	New design that does not require winch system, saving on set-up time Modify sludge intake to adjust variable depths	Pipe blockages Pond having variable depths causing inefficient sludge removal Rising electricity costs
Mono pump	Operate unmanned	Positioning suction pipe in pond until suitable place is found Needs crane to position footvalve lowest sludge volume removed Maintenance costs	Prevent littler from going into pond so that pump maintenance costs can be reduced Use in conjunction with permanent pipe network to reduce operational time and increase pond access	Pipe blockages May pump clear effluent for some time before being repositioned Rising electricity costs

5.3 Desludging Covered Anaerobic Ponds (CAP)

Sludge removal from covered anaerobic ponds presents specific difficulties as the cover cannot be removed during the operational phase. There are essentially three methods of sludge removal from CAPs. They are:

1. In-situ desludging. In this approach, the solids settle to the base of the CAP and are removed by pumping via a pre-installed pipeline.
2. Suspension removal. In this approach, the solids are not allowed to settle. They are kept in suspension using agitators inside the CAP. The solids are removed as part of the effluent flow out of the CAP.
3. Life-time accumulation. In this approach, solids are allowed to settle but are not removed until the operational life of the pond cover is reached and the cover is removed. In this

approach, a large sludge-accumulation volume is needed to be designed as part of the internal volume of the CAP.

5.3.1 *In-situ desludging*

Continuous or semi-continuous sludge draw-off is desirable for covered ponds (Watson 1999). This is done by laying a network of pipes at the base of the pond and sucking the sludge out through inlets on the pipes (Figure 20). Photograph 14 and Photograph 15 show the installation of sludge removal pipes in a high-rate treatment pond (Goulburn Valley Water). Photograph 16, Photograph 17 and Photograph 18 show the ends of sludge removal pipelines extending beyond the pond covers.

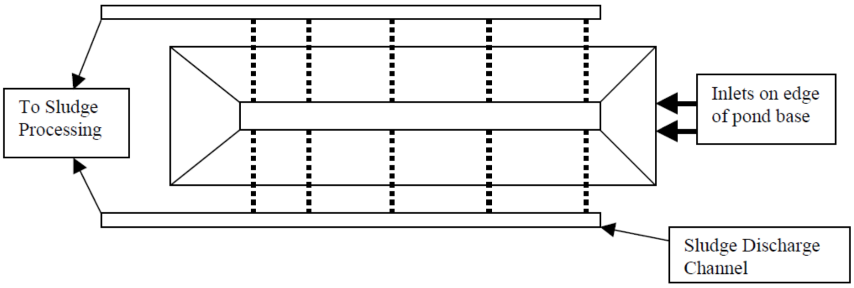


Figure 20: Desirable layout of anaerobic pond to facilitate desludging (Watson 1999)

Usually, conventional positive-displacement or vacuum pumps are used to remove sludge. Air-lift pump systems have been suggested for sludge draw-off due to their minimal blockages, ability to pump high solids concentrations and to mix sludge (Watson 1999). Compressed air is injected through the air supply line to the lower part of the sludge draw-off pipe, and as the air bubbles upwards through the pipe, the liquid can be taken together with the air flow (Figure 21). However, limitations of using air-lift pump include that the specific gravity of sludge needs to be close to 1.0 and the flow rate can be limited. More importantly, for desludging covered ponds, strategically located mechanical mixers need to be used to prevent the introduction of oxygen under the gas collection cover and the generation of a potentially explosive atmosphere (Watson 1999).

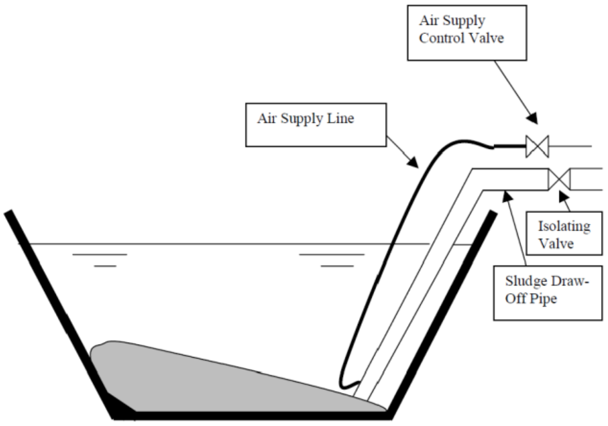


Figure 21: Airlift pump (Watson 1999)

The main problem with submerged pipes is that they are only effective for removing the sludge near the inlet holes. After a period of time, a sludge void may develop near the inlet holes and the sludge removal will become much less effective. Mechanical scrapers may be used to push the sludge closer to the pipes but this is not likely to be cost-effective for farms. A few features of pond layout have been suggested to facilitate the in-situ desludging (Watson 1999).

- using deep ponds to increase sludge flow to draw-off pipeline
- using long narrow ponds to permit draw-off from side of pond
- providing two inlets to the pond, discharging towards the sides of the pond to preferentially deposit heavy sludge components closer to draw-off point
- providing sludge discharge channels alongside the pond to receive removed sludge and discharge to the sludge processing area.

Butler and Johns (2012) report on the design and operation of a 5 m deep CAP at an abattoir on King Island. Provision was made for sludge removal via a single 160 mm OD HDPE sludge extraction pipe positioned longitudinally down the centre of the pond base.

The pipe was capped at the northern end and exited horizontally through a penetration in the liner at the southern end. The end performed a 90° bend to the vertical and terminated at ground level in an upstand with a camlock and cap fitting to allow connection to a sludge pump or truck. The upstand was embedded in a concrete slab to minimise movement during pumping. The pipe was elevated approximately 200 mm off the CAP base by a series of 160 mm OD concrete-filled weights to minimise movement of the pipe and to negate its buoyancy if filled with biogas. The weights were capped water tight with HDPE caps to prevent concrete erosion in the slightly acidic conditions in the CAP and held in place by straps welded to a HDPE wear strip.

The pipe (24 m length on the pond base) was drilled with 16 x 30 mm diameter holes for sludge entry. The holes were on alternate sides of the pipe and positioned to avoid the weights. The hole spacings increased as the distance to the sludge discharge point reduced to avoid rat-holing as much as possible.

The sludge in the CAP increased to a depth of about 2 m after three months of operation and to 2.7 m in the next three months. After six months, a sludge truck withdrew 10 m^3 of black sludge through the sludge pipework over about 15 minutes. There was little indication of rat holing (breakthrough of liquid) during the pumping since analysis of sludge sampled at even intervals during the withdrawal process showed little decrease in TS with 2.7, 2.4, 2.4 and 2.2%TS in sequential samples. The extracted sludge was analysed. The sludge averaged about 70% VS, 4400 mg/L TDS and 50 000 mg/kg of TKN.

The sludge analysis data indicates that the material that was removed should be described as "effluent" (see Section 2.3) rather than "sludge" due to the low TS content. Also, the high VS content of the sludge would suggest that there was considerable methane-generation potential still left in the removed material.

This data illustrates a general issue with sludge removal from a covered pond. If sludge removal is frequent (every few months), the sludge is likely to be relatively low TS and be fluid so that it can easily be pumped. However, the sludge would not be completely digested thus losing methane generation potential.

Photograph 14: Installation of sludge removal pipe system

Photograph 15: Installation of sludge removal pipe system

Photograph 16: Sludge extraction pipelines (deflated pond cover)

Photograph 17: Pump suction pipe inserted into in-situ desludging pipe

Photograph 18: Sludge (black) and effluent (white) removal pipes

5.3.2 *Suspension removal*

RCM (http://www.rcmdigesters.com/) have developed the covered pond digesters to generate methane from flushed manure while reducing the sludge accumulation. This is achieved by connecting two ponds in series. The primary pond is for biological treatment of manure and biogas generation and the secondary pond is as a solids drying bay (Figure 22). By agitating the solids in the primary pond, less sludge would deposit at the bottom and would flow to the secondary pond and settle out. Desludging the primary pond is necessary every 8 to 15 years, by which time the pond cover has reached its life time. This means that the pond volume includes a treatment volume and a sludge accumulation volume.

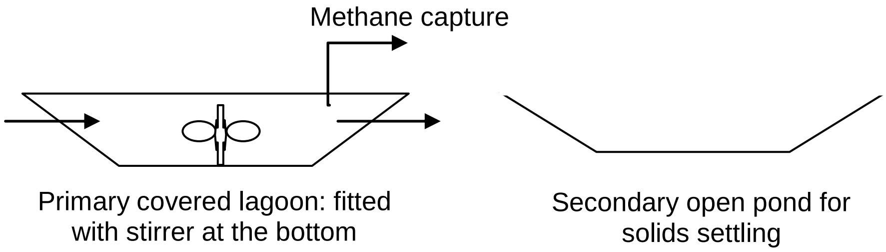


Figure 22: Schematic illustration of RCM's covered lagoon digester

Source: http://www.rcmdigesters.com/rcm-technology/covered-lagoon/

5.3.3 *Life-time accumulation*

An extension of the RCM concept is to provide an even larger, sludge accumulation volume without including internal pond agitators. The effluent exiting from the CAP would not have a large TS content and, hence, would not require sludge settling before disposal. In this case, the larger pond excavation cost would need to be offset by reduced costs of sludge agitation and the construction of a secondary pond.

As far as is known, no CAP has been designed with this concept in Australia.

5.3.4 *Advantages and disadvantages*

The choice of desludging method requires an economic and practical trade-off between:

1. cost of larger pond construction
2. completeness of methane generation
3. functionality of sludge removal pipeline
4. frequency of sludge removal.

6. Dewatering of sludge and slurry

6.1 Solid-liquid separation of sludge and slurry

Depending on the final utilisation method for the sludge or slurry, it may be desirable to dewater the removed sludge or slurry. This is particularly applicable if the final utilisation site is some distance from the source. There are several methods of dewatering (solid separation) for sludge and slurries. They include:

- settling basins (sedimentation and/or evaporation)
- screens (runoff, vibrating, rotating)
- centrifuges
- belt presses
- static filtration
- screw presses (pressurised filtration)
- DAF or similar.

Hjorth et al. (2010) provides a detailed review of these methods as applied to animal slurries. An example of the use of these types of dewatering systems is the Z-Filter (http://www.z-filter.com/index.html). Appendix C provides details of the Z-Filter system that was tested at the Westpork Piggery in March 2012. This testing was not part of this project and no details of its performance are included in this report.

However, most of these options are not suitable for dewatering sludge and slurries because:

- Removal efficiency is not sufficiently high to achieve a “dry” sludge.
- Capital, operating and maintenance costs are high.
- Capacity is too low for a large volume of sludge removed in a short period.
- High technical skills are required.

In reality, most sludge and slurries removed from ponds is dewatered using free drainage and/or evaporation in bays or tubes. The methods include:

1. Long-term bulk storage
2. Short-term drying bays
3. Sedimentation and Evaporation Pond Systems (SEPS)
4. Geotextile tubes

6.2 Long-term bulk storage

The most common method of sludge dewatering is simply to place the sludge in a large bunded area. To reduce the footprint of the sludge storage area, the depth of sludge storage can be significant (>2 m). Photograph 19 and Photograph 20 show typical long-term, large-volume sludge dewatering storages.

The major problem with this method is that it takes a long time (many months or years) for the sludge to dry. Typically, a dry crust forms on the surface of the storage area, thus reducing the evaporation rate from the sludge. Very little free drainage occurs from this heavily settled sludge. If storage time is not an issue, this is a viable solution to dewatering sludge. To minimise the risk of groundwater contamination, the beds of the drying bays should be compacted in accordance with Skerman et al. (2005).

6.3 Short-term drying bays

Sludge and slurries can be dewatered more quickly by placement in specific drying bays. These bays are shallow (<0.4-0.8 m of sludge) and are designed to drain as much as possible. To minimise the risk of groundwater contamination, the beds of the drying bays should be compacted in accordance with Skerman et al. (2005).

GHD (2008) evaluated three variations on shallow sludge drying bays. The basic design was a clay-lined bay with a depth of 0.8 m similar to Photograph 21. The first variation had a sand base with slotted drainage pipes to enhance drainage from the base of the drying bay. The last variation was a bay lined with shade cloth that extended up on all sides. There was a 75 mm sand base with 50 mm drainage pipes in the sand. Table 8 gives the estimated construction and operating costs of each drying bay. GHD (2008) concluded that, although the sand and shade cloth bays achieved a marginally better drying rate, the results were not significantly different to the standard clay-lined drying bay.

Table 8: Estimated construction and operating cost of drying bays

Drying bays	Area (m^2)	Volume (m^3)	Total construction cost ($)	Comparative construction cost ($/$m^3$)	Total operating cost ($)	Comparative operating cost ($/$m^3$)
Clay	750	600	15,000	25	315	7
Sand	840	670	26,000	38	6600	8
Shade cloth	810	650	16,000	25	6800	10

Source: GHD (2008)

Photograph 19: Long-term sludge drying bay

Photograph 20: Surface crusting of long-term drying bay

Photograph 21: Narrow drying bay

6.4 Sedimentation and evaporation pond systems (SEPS)

The Sedimentation and Evaporation Pond System (SEPS) is a low-capital effluent management system based primarily on shallow pond sedimentation of effluent solids and annual evaporation of the liquid to allow retrieval of the solids (Payne et al. 2008). The original concept was developed to overcome the difficult problem of removing sludge from large, deep conventional anaerobic ponds and to access manure solids annually for use as organic fertiliser. The SEPS consist of two or three parallel earthen channels that are long, narrow, shallow and trafficable. They are typically 7 m wide and 0.8 m deep and are laid out along the contour (Photograph 22 and Photograph 23). The shallow depth allows for rapid drying although a crust forms on the surface. This crust can be disrupted by rolling with tractor tyres or a wheeled device as in Photograph 25. Dried solids can then be removed by excavators (Photograph 22) or front-end loaders (Photograph 24). Kruger et al. (2008) provides design information for SEPS. To minimise the risk of groundwater contamination, the beds of the SEPS bays should be compacted in accordance with Skerman et al. (2005).

Although these bays were originally designed as part of a waste treatment system, they are completely suited to operate as a sludge dewatering system. Depending on the TS content of the influent sludge, the relative capacity of the SEPS bay and/or local rainfall and evaporation conditions, it may be necessary to have a system at the outflow of the SEPS to retain excess drained effluent.

The main difference between short-term drying bays and SEPS is that short-term drying bays are generally smaller and are batch loaded. SEPS can be continuously loaded over an extended period (e.g. six months). The specific needs of the situation would determine whether batch-loading of several individual bays would be preferred over continuous loading of a large SEPS bay.

Research has been done on odour emissions from SEPS (Hayes et al. 2007, Payne et al. 2008) and by Skerman et al. (2013). Skerman et al. (2013) noted that the maximum odour emissions from the Queensland SEPS were in the range recorded for conventional anaerobic ponds. These results suggest that the overall odour emissions from SEPS are likely to be lower than for conventional ponds due to the significantly smaller surface area of the active and drying SEPS channels and similar or lower odour emission rates per unit area.

Photograph 22: SEPS bays

Photograph 23: Dried SEPS bay

Photograph 24: Solids removal from dried SEPS bay

Photograph 25: Tyres used to break the surface crust to enhance solids drying in a SEPS

6.5 Geotextile tubes

Solids can be removed from sludge and slurries by filtration through a geotextile membrane. They have been widely used for sewage sludge (Fowler et al. 1996), but they have also been trialled with animal manures and pond sludge (e.g.Worley et al. (2008)). Baker et al. (2002) tested the removal efficiency of geotextile filtration on dairy and pig manure and pond sludge. Removal efficiency for pond sludge was about 88% of TS. The removal efficiency for dairy manure was about 47% for TS while for pig manure, it was about 70% for TS. Cantrell et al. (2008) also assessed the performance of geotextiles for dewatering pond sludge and animal manure. They achieved similar results to Baker et al. (2002). Chemical coagulants and flocculants can be added to the influent to enhance solid and nutrient removal and to hasten the rate of liquid drainage.

There is a range of commercial geotextile products available for the dewatering of sludge and slurries. In all cases, the slurry is pumped into a geotextile tube and dewatering occurs by drainage and some minor evaporation (Photograph 26). Examples include:

Dredging Solutions	http://dredgingsolutions.com.au/DEWATERING.aspx
Apex Envirocare	http://www.apexenvirocare.com.au/products/geopro-desludging-tubes
UAT Geobags	http://www.uat.com.au/geobags.html
Geosynthetics ProTube	http://www.globalsynthetics.com.au/files/data_sheets/introduction_protube.pdf
Geotube	http://www.tencate.com/amer/geosynthetics/solutions/dewatering_technology/default.aspx

Advantages over short-term drying bays or SEPS include:

1. The tubes are suited to constrained sites.
2. The tubes can be used in sites where the topography does not allow the construction of drying bays or SEPS.
3. The tubes can be used in environmentally sensitive sites, e.g. in public view or close to receptors.
4. Dewatering is usually more rapid than with drying bays.

Disadvantages over short-term drying bays or SEPS include:

1. A prepared pad (concrete or compacted material) is required to site the geotextile on.
2. Provision must be made for the containment and collection of the drained effluent.
3. Costs are higher than open drying bays, particularly if coagulants or flocculants are used.

Most piggeries and feedlots are not located in environmentally sensitive areas and usually have large areas of land available near to the effluent source. Hence, in most situations, dewatering of removed sludge and slurries can be done more economically using drying bays or SEPS rather than geotextile tubes.

Photograph 26: Dewatering sludge using geotextile tubes (Dredging Solutions)

7. Methodology

7.1 Introduction

Samples were taken and analysed at piggeries and feedlots across Australia to determine some baseline data on sludge and slurry characteristics.

Sludge samples were collected from five piggery sites (Piggery A – Piggery E) and six feedlot sites (Feedlot A – Feedlot F). At Piggery A, a field experiment was conducted to determine the pipe pressure loss from different lengths of suction pipe accessing sludge removal pipes in the bed of a covered anaerobic pond. Sludge samples were taken during this pump test and were analysed for particle sizes and rheology characteristics.

7.2 Sample sites and sampling methods

At all sites, disturbed samples were taken rather than trying to take undisturbed samples in the bed of a pond. Disturbed samples do not represent the sludge was in its natural state before sampling. However, in this case, in-situ conditions are less relevant as all sludge would be agitated during removal and handling.

At the piggery sites, the pump was started and run for 5 minutes to clear the pipe. After 5 minutes, a sample was taken every 60 second over about an 8 minute period. The sub-samples were combined to form a composite 2 L sample for analysis. At all piggery sites (except Piggery C), the composite sample was placed in a snap-lock plastic bag, labelled according to the location and type of sample, sealed and placed in a second snap-lock bag for safety. The sample was placed sealed in an insulated cooler box and immediately covered with ice. Samples were delivered to the laboratory within two days of sampling.

At Piggery C, samples of sludge were collected with a sample bottle attached to the bottom of an aluminium pole. The sampling bottle was lowered about 0.5 m below the surface of the drying bay where the sludge layer was encountered.

At feedlot sites, sludge samples were collected in the same method as Piggery C. The samples were transported from the site in strong waterproof sample bags and stored at 4°C in a foam esky with freezer packs. The sludge was transferred to stronger containers and posted to the laboratory the next day. Three replicates were collected and analysed for each feedlot site.

7.2.1 Piggery A

Piggery A is a finisher (grow-out) enterprise located in southern Australia with a capacity of about 22 000 pigs. The area has a dry, winter-dominant rainfall pattern with an average 395 mm per year. The piggery has conventional sheds with slatted floors. The raw wastewater is screened over a run-down screen prior to entry into a CAP.

The sludge is pumped with a Mono pump from the bottom of the CAP to clay-lined drying bays (Photograph 27). The riser main from the CAP is shown Photograph 28. All samples at this site were collected during the pipe friction loss experiment (see Section 7.3).

Photograph 27: Piggery A drying bay

Photograph 28: Piggery A slurry pipeline riser adjacent to drying bays

7.2.2 Piggery B

Piggery B is a farrow-to-finish enterprise located in southern New South Wales with a capacity of about 22 000 pigs. The area has a winter dominant rainfall pattern with an average 698 mm per year. The piggery has conventional sheds with slatted floors. The raw wastewater is pumped straight to a CAP with no solids separation.

The CAP has a polyethylene pipe through the embankment of the pond. Sludge was pumped through the pipe to the SEPS.

7.2.3 Piggery C

Piggery C is a breeder unit located in southern Australia with a capacity of about 12 000 pigs. The area has a winter dominant rainfall pattern with an average 707 mm per year. The piggery has conventional sheds with slatted floors. The raw wastewater is pumped directly to a series of clay-lined anaerobic ponds with no solids separation.

The clay-lined drying bay at Piggery C (Photograph 29) was 2 m deep and contained the sludge from three anaerobic ponds that were dewatered two months prior to sampling. The sludge was removed using an excavator and transported to the sample site via truck. Samples of sludge were obtained from the clay-lined drying bay about 0.5 m below the surface.

Photograph 29: Piggery C sampling site

7.2.4 Piggery D

Piggery D is a 1300 pig gilt acclimation unit located in southern Queensland. The area has a summer-dominant rainfall pattern with an average rainfall of 616 mm per year. The piggery has tunnel-ventilated conventional sheds with slatted floors and pull-plug effluent collection. The raw wastewater flows via gravity to an HDPE-lined anaerobic pond with no solids separation. Sludge samples were collected using the same method as in Piggery C. Sampling site of Piggery D is shown in Photograph 30.

Photograph 30: Piggery D sampling site

7.2.5 Piggery E

Piggery E is a grower-finisher unit located in southern Queensland with a capacity of about 600 pigs. The area has a summer-dominant rainfall pattern with an average rainfall of 900 mm per year. The piggery has conventional sheds with partly slatted floors. The raw wastewater flows via gravity to an anaerobic pond with no solids separation.

Sampling site of Piggery E is shown in Photograph 31. Sludge samples were collected using the same method as in Piggery C.

Photograph 31: Piggery E sampling site

7.2.6 Feedlot A

Feedlot A is located in northern New South Wales with a capacity of about 40 000 head. The area has a winter-dominant rainfall pattern with an average rainfall of 831 mm per year. The runoff is directed via a sedimentation basin to a holding pond.

Sediment sludge samples were taken at the sedimentation basin weir outlet to the holding pond (Photograph 32). Sludge samples were collected using the same method as in Piggery C (Photograph 33).

Photograph 32: Feedlot A sampling site – sedimentation basin

Photograph 33: Feedlot A sampling site (sampling method at weir)

7.2.7 Feedlot B

Feedlot B is located in southern Queensland with a capacity of about 50 000 head. The area has a summer-dominant rainfall pattern with an average rainfall of 662 mm per year. The runoff is directed via a sedimentation basin to a holding pond. Sludge samples were taken from close to where the drainage channel entered into the sedimentation basin (Photograph 34). Sludge samples were collected using the same method as in Piggery C.

Photograph 34: Feedlot B sampling site

7.2.8 Feedlot C

Feedlot C is located in central Queensland with a capacity of about 4000 head. The area has a summer-dominant rainfall pattern with an average rainfall of 789 mm per year. The runoff is directed via a sedimentation basin to the holding pond.

Sludge samples were taken from the main sediment basin. The sampling point was on the opposite side of the pond weir. At Feedlot C, the same procedure was carried out as per Feedlots A and B.

7.2.9 Feedlot D

Feedlot D is located in southern Queensland with a capacity of about 2700 head. The area has a summer-dominant rainfall pattern with an average rainfall of 932 mm per year. The runoff is directed via a sedimentation terrace to the holding pond.

Sludge samples were collected from the effluent holding pond immediately below the sedimentation basin (Photograph 35). The same procedure was carried out as per Feedlots A, B & C.

Photograph 35: Feedlot D sampling site

7.2.10 Feedlot E

Feedlot E is located in southern Queensland with a capacity of about 9000 head. The area has a summer-dominant rainfall pattern with an average rainfall of 646 mm per year. The runoff is directed to an anaerobic sedimentation pond (5 m deep) and then to the secondary holding pond.

Both samples were taken using the same method described for the other feedlot samples. Two sludge samples were obtained from different locations within the same sediment basin. It is understood that this pond has not been desludged in many years. Sample SB/1 was collected from the northern end of the east bank of the pond close to a spillway for the feedlot runoff (Photograph 36).

Photograph 36: Feedlot E sampling site, SB/1

Sample SB/2 was taken from the southern end of the east bank close to another spillway (Photograph 37). This area of the pond was noted to be heavily crusted over and no longer functioning.

Photograph 37: Feedlot E sampling site, SB/2

7.2.11 Feedlot F

Feedlot F is located in southern New South Wales with a capacity of about 17 000 head. The area has a winter-dominant rainfall pattern with an average rainfall of 582 mm per year. The runoff is directed via a sedimentation basin to a holding pond.

Sludge samples were taken from different sedimentation basins, SP/1 and SP/2. Sample site SP/1 (Photograph 38) was close to the sedimentation weir on the southern side of the feedlot and this basin collected the runoff from a smaller section of the feedlot than SP/2. The SP/1 sample location was much drier than SP/2 and the sample was collected as per the other feedlot samples. The sample was taken after the surface-crust was broken by a front-end loader.

Photograph 38: Feedlot F sampling site, SP/1

Sample SP/2 was collected from the sedimentation basin at the northern end of the feedlot. The sample was collected near the weir and this location had more standing water than SP/1, Photograph 39. The sample was retrieved by the same method described for SP/1 but no surface crust braking was required.

Photograph 39: Feedlot F sampling site, SB/2

7.3 Pipe friction loss experiment – Piggery A

The high solids content of sludge is expected to make pumping difficult because pipe friction losses are greatly increased (see Section 2.5). The sludge settling process is time-dependant, producing a thicker sludge after longer settling periods before extraction. Consequently, if sludge is extracted too infrequently, the high solids content may make it very difficult to pump. This effect also has great practical significance for pump selection and/or pond management, but has not been previously quantified for piggery sludge.

Hence, an experiment was conducted at Piggery A to determine the friction loss in the suction pipe that removes sludge from the CAP under different TS contents in the sludge. The experiment included in-field assessment and laboratory experiments. The laboratory experiments were conducted to validate the field results, with the aim of assessing the practicality of pumping sludge at a particular solids concentration.

The design and operation of the CAP is described by Birchall (2010). The CAP was installed in 2004 and was not desludged at all until some efforts in 2010. The liquid depth of the pond is 7.48 m but by 2010, sludge had accumulated to within 2 m of the surface. A perforated sludge removal pipeline does not appear to have been installed in the base of the pond. Access to the sludge is achieved via “emergency gas vents”. In 2010, Birchall (2010) extracted sludge at increasing depths in the CAP. Table 9 shows the VS:TS ratio for the sludge removed at different depths. Except for the deepest layers, the VS:TS ratio is about 0.60 indicating that the sludge is well degraded. The TS content of the sludge at 2 m was about 2%. This increased to about 4% at 3 m and over 10% at 5 m.

Table 9: VS:TS data for sludge removed from different depths within a CAP

Depth (m)	2.0	2.5	3.0	3.5	4.0	4.5	5.0
VS:TS	0.60	0.61	0.61	0.63	0.59	0.56	0.45

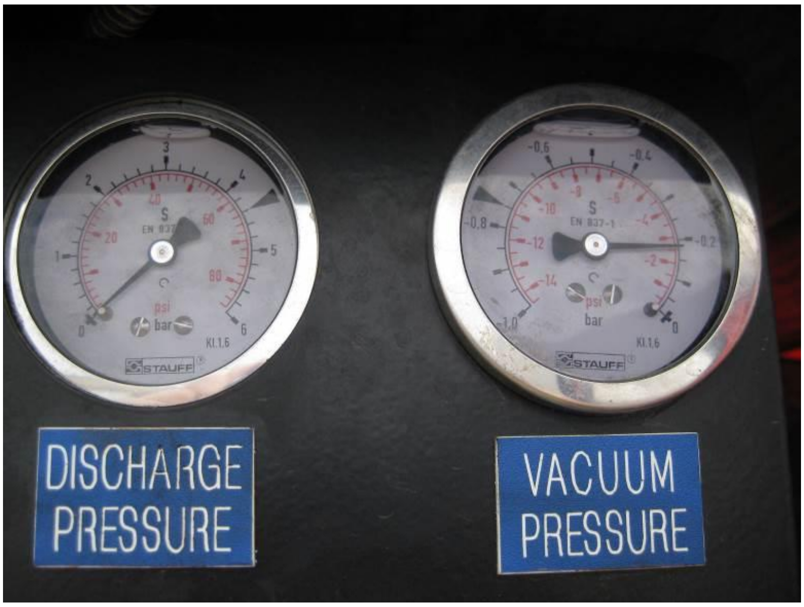
The CAP has a 500 mm nominal diameter HDPE pipe installed down the internal batter to facilitate extraction of sludge as shown in Photograph 40. A 110 mm (outside diameter, OD) polythene pipe with inside diameter (ID) of 96 mm was inserted into the HDPE pipe as the suction pipe as shown in Photograph 17 and Photograph 40. The suction hose was marked at 1 m intervals so that the length of pipe inside the HDPE pipe could be recorded to allow the suction head to be calculated. Six suction heads were evaluated which resulted in a range of TS contents in the accessed sludge.

Photograph 40: Suction pipe inserted into CAP

The pump was a vacuum pump mounted on a trailer. The pump was fitted with analogue pressure gauges as shown in Photograph 41. The analogue pressure gauge readings were compared with the electronic transducer.

A instrumented section was constructed from 100 mm poly hose to house a flow meter and pressure transducer. The manifold pipe was coupled between the pump suction and the suction pipe installed down the HDPE pipe into the CAP.

A Siemens Magflo meter was installed in the discharge pipe to measure the flow rate (Photograph 42, Photograph 43). An electronic pressure transducer was installed in the instrumented section of the discharge pipe to measure suction pressure. The pressure transducer was connected to an electronic display. Flow rate and pressure measurements were recorded each minute during pumping for each incremental increase in depth of suction hose in the pond. Photograph 44 shows the typical consistency of the sludge removed from the CAP during the experiment.



Photograph 41: Analogue pressure gauges

The suction pipe was marked at 6.0, 6.5, 7.0, 7.25 and 7.5 m from the access pipe into the CAP. With an internal batter of 1V:2.5H, this translates to vertical depths of 2.2, 2.4, 2.6, 2.7, 2.8 m. At suction insertions of 6.0 m and 6.5 m, sub-samples of sludge were collected each minute over a four-minute period. The sub-samples were mixed in a 10 L bucket and then a composite sample collected for analysis.

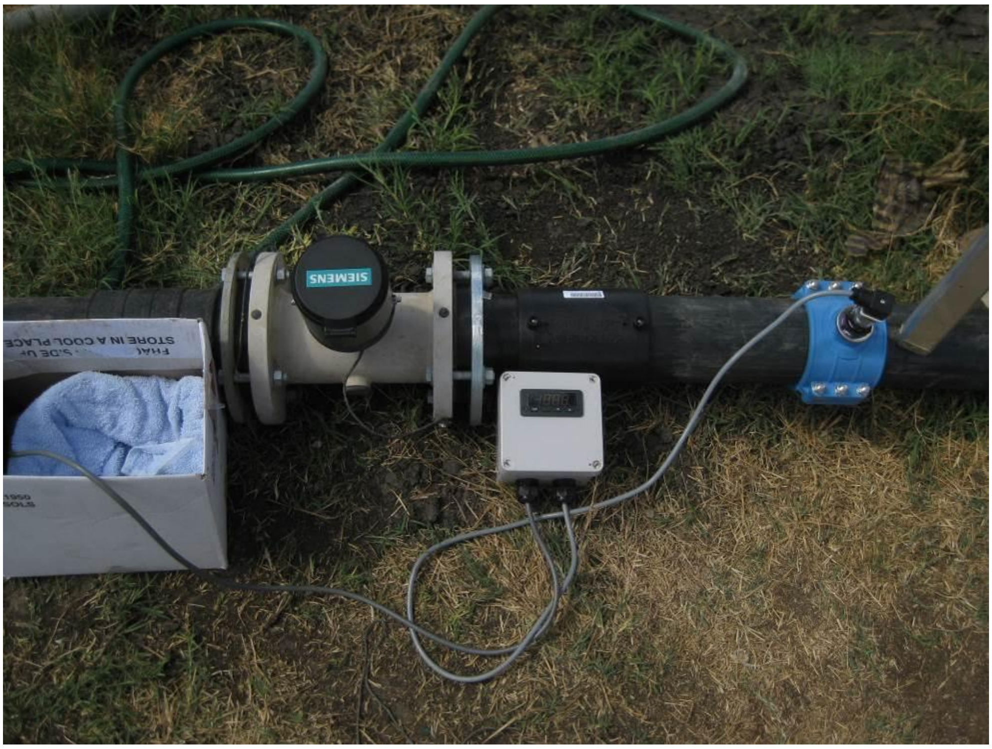
At suction insertion lengths of 7.0, 7.25 and 7.5 m, samples were collected every minute over an eight-minute period rather than four minutes. This was due to the flow rate significantly decreasing when the suction pipe was inserted beyond 6.5 m. Hence, it was decided to sample for longer periods of time to collect more representative samples. The sub-samples were mixed in a 10 L bucket and then a composite sample collected for analysis.

Five samples were collected from the site for further analysis. Table 10 gives the Sample ID labels used in later sections of the report and the respective sampling depths.

Table 10: Sample identification for sludge pumping test

Sample ID	Pipe Insertion Length (m)	Sampling Depth below pond cover (m)
1090/1A	6.0	2.2
1090/2A	6.5	2.4
1090/3A	7.0	2.6
1090/4A	7.25	2.7
1090/5A	7.5	2.8

Photograph 42: Vacuum pump and pipework



Photograph 43: Magflo flow meter (left) and in-line pressure transducer and electronic readout (right)

Photograph 44: Sludge removed from CAP during pump priming

7.4 Sludge characterisation methodology

Sludge is characterised by considerable colour, odour, high concentrations of both inorganic and organic nutrients and a high moisture content. These characteristics presented a real challenge in accessing a commercial laboratory willing and able to undertake the required testing to analyse wet sludges (without drying first). Discussions were held with commercial wastewater and geotechnical testing laboratories (e.g. SGS Australia Pty Ltd and Chadwicks TT); and research laboratories (RMIT university, University of Queensland) to determine if any would accept sludge samples.

The University of Queensland Advanced Water Management Centre (UQ AWMC) in Brisbane was best able to characterise each sample in its raw form. UQ AWMC undertook the analysis of all samples collected for this project.

Appendix A describes the testing methodologies used by UQ AWMC for this project.

8. Results and discussion

8.1 Sludge characterisation

8.1.1 Total solids and volatile solids

Table 11 shows the average results of the replicates for TS and VS of the piggery sludge. The TS ranged from 3.2 to 16.4%. Total solids values of piggery sludge samples are generally lower than those collected by DAFF (unpublished), with a range of 6.9 – 17.1% reported for a number of sludge samples taken from piggeries in south-east Queensland. This could be due to the sampling method DAFF used, where some of the liquid effluent overlying the sludge may have mixed with the sludge during the sampling process.

VS:TS ratios of the piggery sludge range from 0.55 to 0.67. This ratio gives an indication of the breakdown of VS that has occurred in the sludge Assuming that the VS-to-TS ratio of the raw manure entering the pond was 0.85 and that the majority of the FS component of the manure stayed in the sludge, the amount of VS degraded can be calculated. For VS:TS ratios of 0.55 and 0.67, 78% and 64% of the VS has degraded, respectively. This indicates that the sludge is well degraded with only the highly-indigestible lignin and similar components left.

Table 11: Piggery sludge analysis results (VS and TS)

Site	Sample ID	TS (%)	VS(%)	VS:TS
A	1090/1A	3.6	2.2	0.62
	1090/1A (screened)	3.2	2.0	0.62
	1090/2A	6.6	3.9	0.59
	1090/3A	9.2	5.6	0.61
	1090/3A (screened)	10.4	6.3	0.61
	1090/4A	9.6	5.5	0.57
	1090/5A	9.4	5.5	0.58
	1090/5A (screened)	7.1	4.1	0.59
B	2421/EP/1	6.5	4.3	0.67
	2421/EP/2	7.0	4.4	0.62
C	2021/SP/1	10.3	5.7	0.56
	2021/SP/2	8.4	4.7	0.55
D	69/GA/P1	12.9	7.6	0.59
E	232/P1	16.4	6.0	0.36

Table 12 shows the average of the replicates for TS and VS of the feedlot sludge. The TS ranged from 15.3 to 44.9%. These TS concentrations are significantly higher than the piggery sludge samples. This is because the feedlot samples were generally collected from sedimentation basin systems that are allowed to dewater following runoff events and did not generally have a liquid proportion overlaying the sludge layer. VS-to-TS ratios of the feedlot sludge ranged from 0.19 to 0.58. As with the piggery sludge, this ratio gives an indication of the breakdown of VS that has occurred in the manure However, unlike piggery, feedlot sludge could also contain a proportion of soil. This soil could have either originated from the feedlot pen surface prior to runoff or from the base of the sedimentation basin during sampling Any VS:TS ratios of less than 0.50 would likely contain large quantities of soil.

Unlike piggery manure that is excreted in a shed, collected in a pit and regularly flushed from the pit, feedlot manure is deposited on a pad. Over time, the VS in the manure breaks down and is released to the atmosphere as CH_4 or CO_2. Davis et al. (2010) regularly measured the VS content of the manure on the pen surface to study the breakdown. Pen manure samples were obtained directly after pen cleaning, prior to harvest and in between. The loss of VS from the pen surface was then calculated. The following was concluded from the pen manure decomposition stage of the study.

- After 20 days, a reduction of between 60 and 70% in VS in the pad manure compared to fresh manure was measured. Fresh faeces typically is about 80% VS. The greatest rate of VS decomposition occurs in the first 10-20 days.
- After 35 days, there was a 70% reduction in VS in the pad manure compared to fresh manure.
- After 80-100 days, there was a reduction of 75% in VS in the pad manure compared to fresh manure.

This indicates that a large proportion of the VS will be degraded before being transported from the feedlot pen surface before entering the sedimentation / pond system. Hence VS:TS ratios will inherently be lower for feedlot manure than piggery sludge.

Table 12: Feedlot sludge analysis results (VS and TS)

Site	Sample ID	TS (%)	VS(%)	VS:TS
A	14/SP/1	17.4	9.2	0.53
	14/SP/2	17.2	8.9	0.52
	14/SP/3	18.1	9.4	0.52
B	84/SB/1	39.7	10.4	0.26
C	87/SB/1	16.6	8.6	0.52
D	132/EP/1	15.3	6.6	0.43
E	205/SP/1	22.2	12.8	0.58
	205/SP/2	22.6	12.5	0.55
F	1070/SP/1	44.9	8.5	0.19
	1070/SP/2	30.7	7.1	0.23

8.1.2 Bulk density

Table 13 shows the bulk density results for the piggery samples. These ranged from 1007 to 1103 kg/m³, with an average of 1023 kg/m³. As anticipated, the sludge samples have a bulk density only slightly higher than water.

Table 13: Piggery sludge analysis - bulk density

Site	**Sample ID**	**Remoulded bulk density (kg/m³)**
A	1090/1A	1007
	1090/1A (screened)	Not Measured
	1090/2A	1007
	1090/3A	1009
	1090/3A (screened)	Not Measured
	1090/4A	1004
	1090/5A	Not Measured
	1090/5A (screened)	Not Measured
B	2421/EP/1	1010
	2421/EP/2	1010
C	2021/SP/1	1023
	2021/SP/2	1011
D	69/GA/P1	1050
E	232/P1	1103

Table 14 shows the bulk density results for the feedlot samples. These ranged from 1020 to 1294 kg/m³, with an average of 1116 kg/m³. The bulk densities of the feedlot samples are considerably higher than the piggery samples with an average difference of 93 kg/m³. This is due to the high TS content of the feedlot samples.

Table 14: Feedlot sludge analysis - bulk density

Site	**Sample ID**	**Remoulded bulk density (kg/m³)**
A	14/SP/1	1020
	14/SP/2	1036
	14/SP/3	1056
B	84/SB/1	1259
C	87/SB/1	1064
D	132/EP/1	1070
E	205/SP/1	1069
	205/SP/2	1110
F	1070/SP/1	1294
	1070/SP/2	1184

8.1.3 Particle size analysis

At Piggery A, five samples of sludge (1090/1A – 1090/5A) were collected at vertical depths of 2.2 – 2.8 m approximately, measured downwards from the sludge access pipe (see Section 7.3). The particle size distribution (PSD) analysis for the samples showed that the proportion of particles <63 μm decreases with pond depth. The use of 63 μm as a benchmark is only a guide to work from and has no specific significance. Fine sand is measured as being above 63 μm on the international PSD scale so comparisons could be made with other sludges or slurries if required. TS recorded for four of five samples analysed for this parameter increased with pond depth (Table 11).

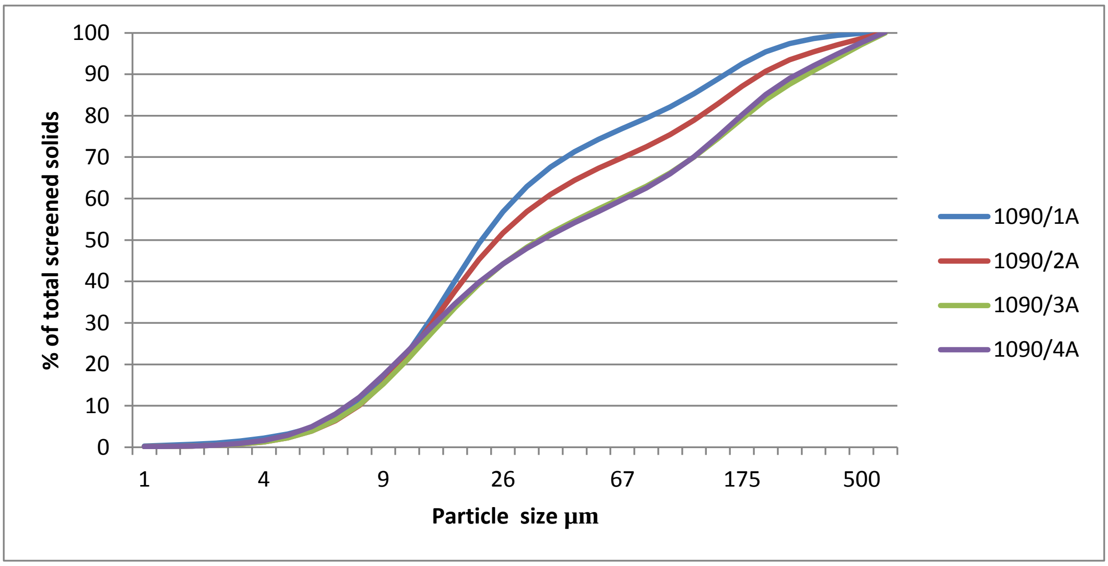


Figure 23: PSD for sludge samples taken from Piggery A covered anaerobic pond

Figure 23 shows the PSD as a percentage of screened solids for the five Piggery A samples. All samples had a similar bulk density (Table 13), but TS for Samples 1A and 2A are considerably lower than for 3A and 4A (Table 11). The higher TS is accounted for by the lower depth from which Samples 3A and 4A were collected, which was further into the compacted solids layer. Further to this, the higher settling velocity of the larger solids would mean that they would potentially end up deeper in the layer.

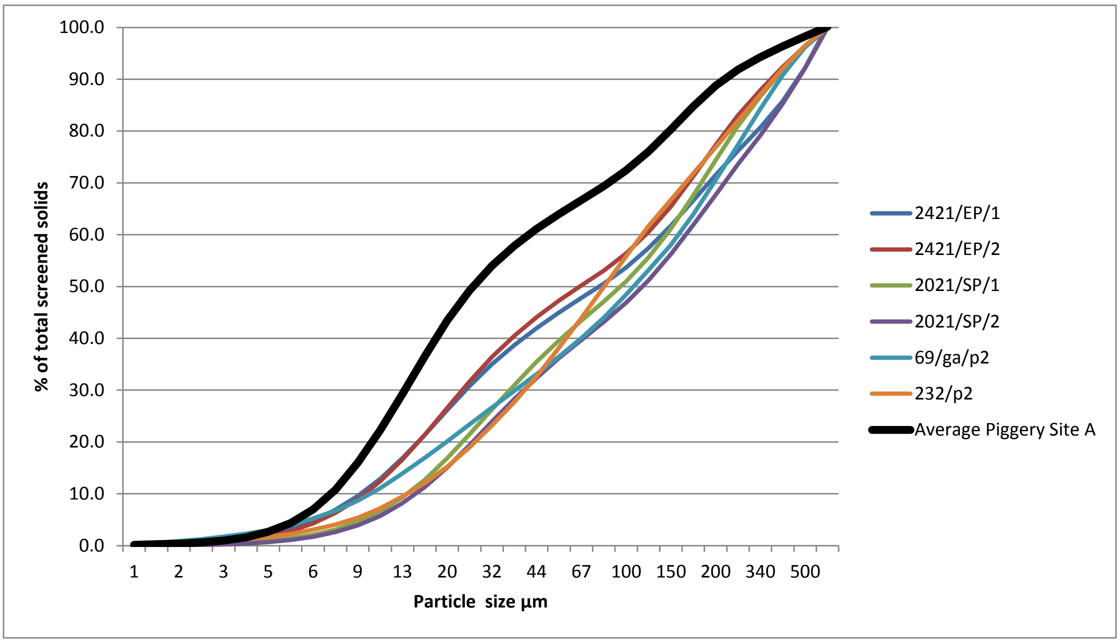


Figure 24: PSD for samples taken from other piggeries compared with the average results from Piggery A

Figure 24 shows that the samples taken from the other piggery sites have a higher concentration of particles >63 µm than the average for Piggery A. The difference in the particle size profile of Piggery A and the other ponds could be attributed to the sampling method. All Piggery A samples were pumped, while all of the other samples were 'grab' samples dragged from the sediment layers of the ponds. When pumping slurries, some of the heavier solids can be left behind in the sediment layer due to 'slippage'. The lighter or smaller solids are more likely to be sucked up than the heavier ones. The forces acting on these solids are dependent on the pumping power and shear rates applied. These forces are not applicable in grab sampling as all material is dragged. This could also account for the higher bulk densities found in the other piggery samples than those from Piggery A (Table 13). The PSD for the other piggery samples are quite similar demonstrating that uniformity exists among pond sludge from different piggeries.

The PSD results from all the feedlot samples was graphed against the average for Piggery A (Figure 25). This shows that, like the piggery samples, the concentrations of particles >63 µm are higher with the exception of sample 1070/SP/2 from Feedlot F. The rest of the samples have a similar PSD, indicating some uniformity. However, the bulk densities recorded show that some samples contain a higher concentration of soil particles (Table 14), and this is also indicated by the VS/TS ratios for these samples (Table 12). Feedlot sedimentation basins probably contain more soil particles than piggery basins, as mentioned previously.

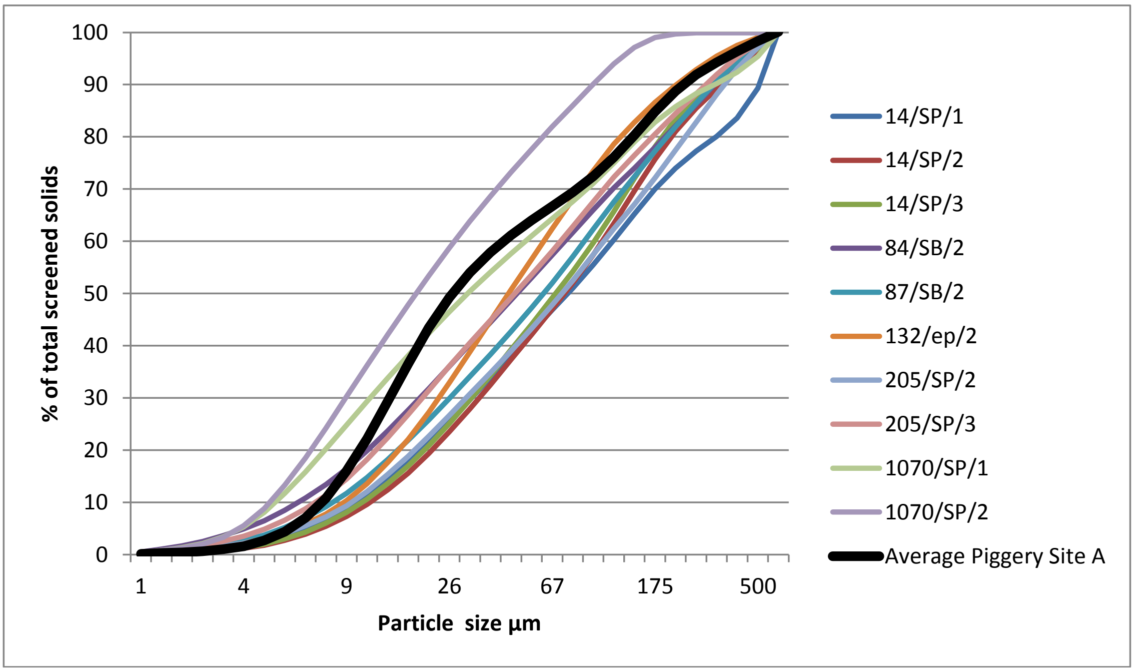


Figure 25: PSD for samples taken from other feedlot sedimentation basins compared with the average results from piggery site A

When the comparison between the results shown in Figure 26 is made to the corresponding TS content, some assumption can be made of the percentage of particle sizes >63 µm. The increase is not linear but it is notable (Table 15).

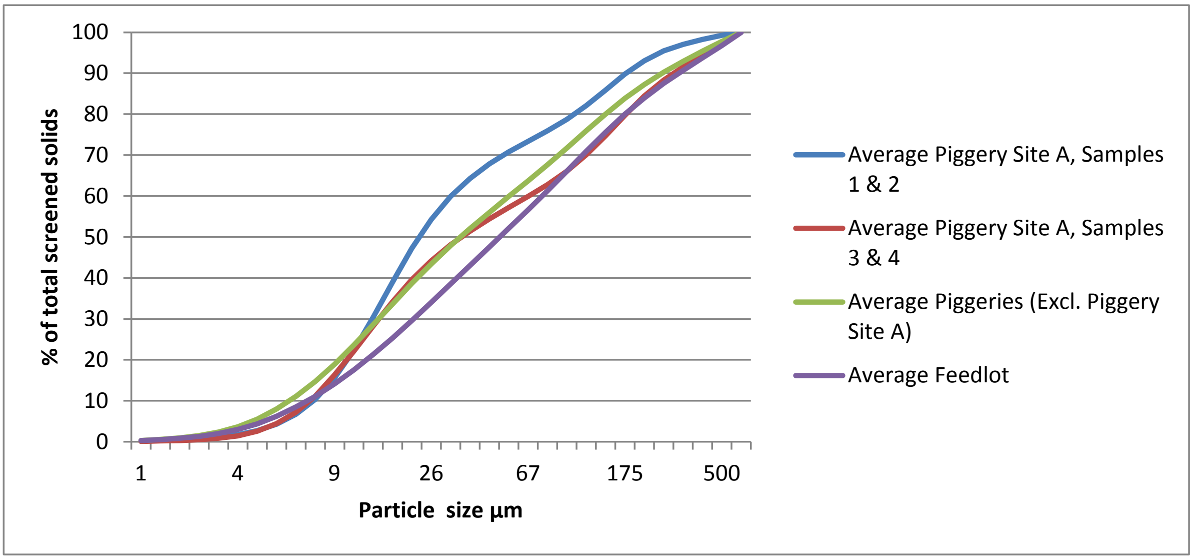


Figure 26: Comparison of average samples taken from Piggery A (2), other piggeries (1) and feedlots (1)

Table 15: Comparison of TS and particle sizes in averaged samples from piggeries and feedlots

	% TS	% Particles >63 μm
Average Piggery A - 1A & 2A	3.4	27
Average Piggery A - 3A & 4A	7.9	41
Average piggery (minus Piggery A)	10.3	37
Average feedlot	24.5	46

8.1.4 Rheological analysis and pipe friction loss

Table 16 shows the pressure, flow rate, velocity, calculated shear rate and shear stress, Reynolds number and flow regime measurements taken at five different stages during the Piggery A pipe pressure-loss experiment. Each stage corresponds to a different length of suction pipe inserted into the CAP (the lengths were 6, 6.5, 7, 7.25, 7.5 m respectively). These pipe lengths took into account the batter incline of the covered pond so the actual pond depths (head) ranged from 2.2 – 2.8 m vertically below entrance pipe to the pond.

Table 16: Flow rates, shear and flow regime during pumping of sludge from Piggery A

Sample	Average Pressure (bar)	Average Flow Rate (L/sec)	Average Pipeline Velocity (m/s)	Pipeflow Shear Rate (8V/D)	Wall Shear Stress (tau)	Reynold's Number	Flow Regime
1090/1A	1.90	16.08	2.2	185	9.39	4205	Turbulent
1090/2A	1.92	13.84	1.9	159	9.50	3078	Transitional
1090/3A	1.84	4.52	0.6	52	9.08	344	Laminar
1090/4A	1.96	4.73	0.7	54	9.70	353	Laminar
1090/5A	2.09	4.39	0.6	51	10.46	281	Laminar

These results demonstrate the problems that can occur when pumping non-soluble and settling solids along with liquids. There is a critical velocity at which flow in a pipeline transitions from turbulent to laminar. Eshtiaghi et al. (2012) investigated the laminar / turbulent transition in a sludge pipeline. Using rheological data collected on sewage sludge and several different models to calculated Reynold's Number, they calculated the critical velocity for their sludge at 3.2%, 4.7% and 6.6% TS. For the model they preferred, the respective critical velocities were 0.85, 1.59 and 2.94 m/s.

Turbulent flow, at velocities of between 2 to 5 m/s, is usually required to move sludge of the consistencies found throughout the Piggery A experiment. This was achieved at the beginning of the pumping (Sample 1090/1A) but could only be maintained for four minutes for Samples 1A and 2A (Figure 15). The TS content of this material was only 3.2% (see Table 11) indicating that it was "effluent" as per the definition in Section 2.3. This material should be able to be pumped fairly easily.

However, the flow regime quickly turned to laminar with the flow rate dropping off quickly after the depth was increased by between 10 to 20 cm. At this stage, the pumped material had a TS content of about 7-10% (see Table 11) indicating that it would be difficult to pump. Figure 15 shows that the flow of sludge continued for eight minutes but at a risk of solids settling in the pipe due to the very low velocities achieved. Interestingly, the VS:TS ratio for the first samples was 0.62 (see Table 11) while the average VS:TS ratio of the deeper sludge was 0.59, which is only marginally more degraded. This would suggest that the sludge was reasonably well digested for all sludge that was pumped. However, the deeper material had settled more resulting in a higher TS content. These data are consistent with the findings of Birchall (2010) at the same site.

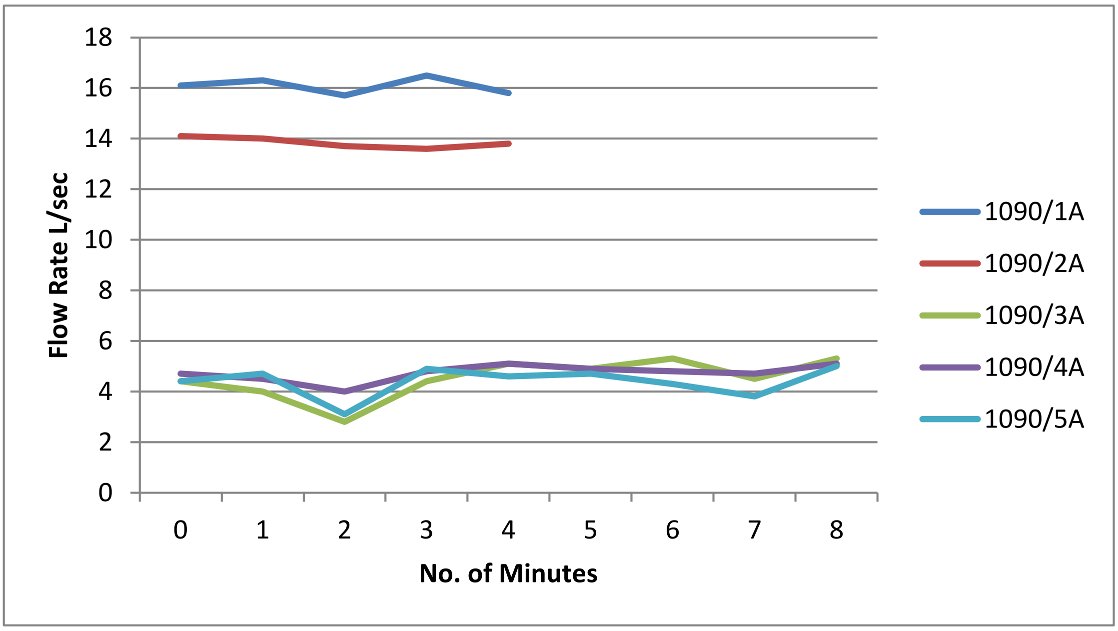


Figure 27: Flow rate and number of minutes of flow during pumping and sampling at Piggery A

The experiment concluded at an insertion length of 7.25 m because the pump was reaching its potential (the flow rates started to plateau) and the consistency of the samples started to look very similar. It appeared that more supernatant was being drawn from above the sludge profile (rabbit-holing), thus reducing the TS content. It is possible that there was settling of solids within the pipe, causing a blockage, and this reduced the concentration of solids in the final sample.

8.1.5 Viscosity and shear stress

Figure 28 shows the viscosity of three of the five samples taken from Piggery A, calculated using Stokes' Law of frictional drag of particles in water. The sample with the lowest TS, 1090/1A, also had the lowest viscosity while the sample with the highest TS, 1090/3AT, had the greatest viscosity. Figure 28 also demonstrates, as expected, that viscosity is lower at 25°C than at 15°C. A higher sludge viscosity would require more pumping power so the timing and TS content are important. The viscosity of all three samples declined when the shear rate increased. Pumps operate with a constant shear rate but in non-Newtonian fluids, the shear rate is variable and this creates problems when the rate fluctuates. Variable viscosities caused by temperature and TS content can cause the pumped material to move from one flow regime to another. This was demonstrated during the trial when the flow regime moved from turbulent to laminar with a very small change in depth but a big increase in TS.

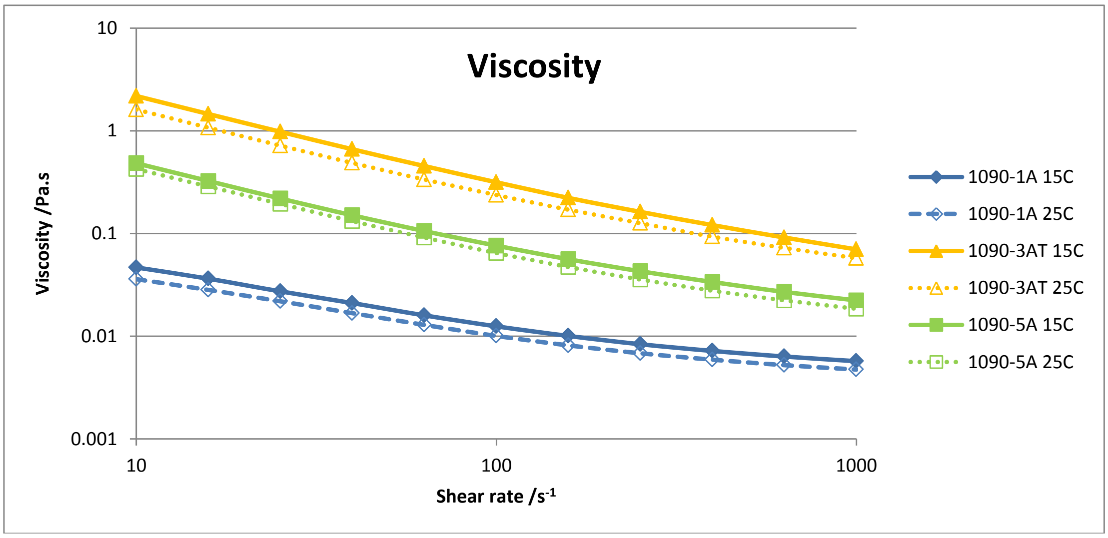


Figure 28: Viscosity of three samples from Piggery A at two different temperatures

Figure 29 shows a rheogram for sludge samples from Piggery A at three different solids contents (3.2%, 7.1%, 10.4%) and two fluid temperatures (15°C and 25°C). It shows that the stress on the pipework during the pumping of sludge at Piggery A increased with higher TS content and at a lower temperature. The stress also increased with a higher shear rate. Sample 3AT at 15°C showed a yield stress about 10 times that of Sample 5A where the increase in TS content was three-fold.

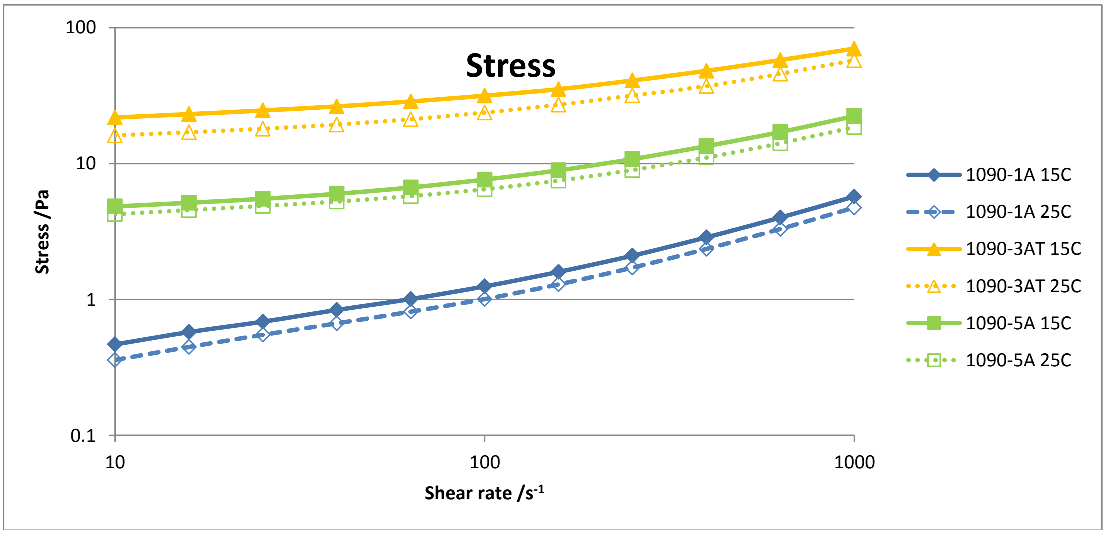
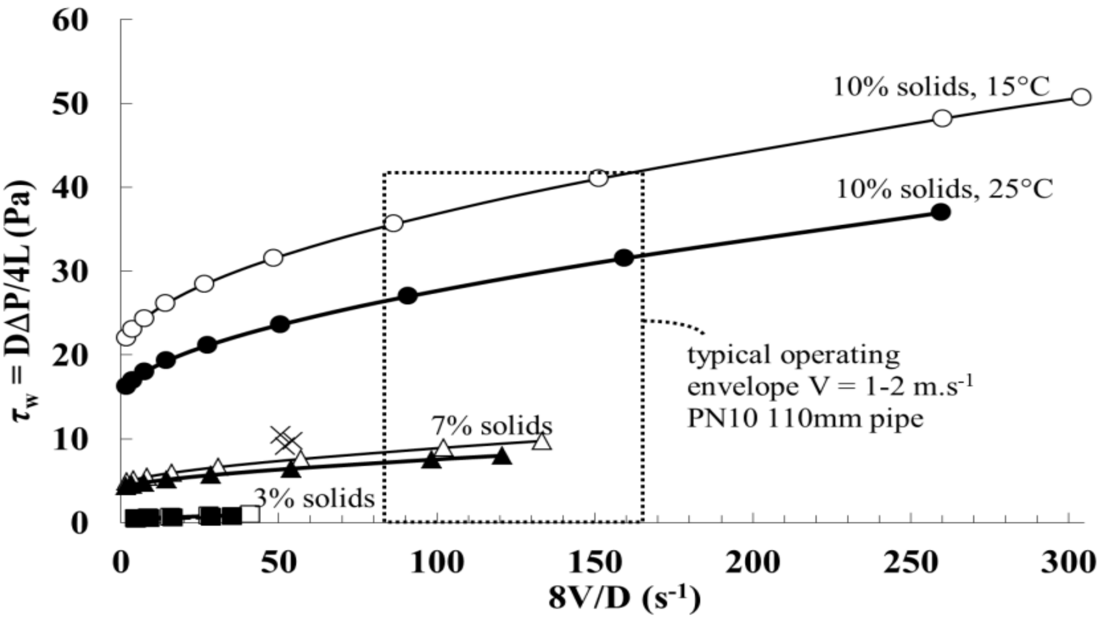


Figure 29: Rheogram of samples from Piggery A

Figure 30 (Tait 2013) shows that, as expected, a higher solids content leads to higher pipe pressure losses (that is, a higher pipe wall shear stress for a corresponding pipe flow shear rate). There was remarkable agreement between the on-site pressure loss measurements (x) and the ARES measurements (diamonds) for the same sample tested at lab-scale, giving confidence in the data collected because the on-site measurements were considered to be most direct/reliable.



Legend: on-site measurements, X
Lab-based measurements of solids concentrations, 3.2% (■,□), 7.1% (▲,△) and 10.4% (●,○)
Lab test temperatures, 15°C (□,○,△) and 25°C (■,▲,●)

Figure 30: Pipe flow wall shear stress (τw) vs. shear rate (8V/D) showing onsite measurements and lab-based measurements for sludge

To size a pump, a pipe flow velocity (V, units of m/s) is arbitrarily selected (say at 1-2 m/s) and the corresponding pipe flow shear rate is calculated = 8 V/D for a known pipe internal diameter (D, units of meters). The corresponding T_w value is then read off Figure 30 for a specific solids concentration and the pipe pressure loss estimated = $T_w \times 4/D$, Figure 31, (with units of kPa/m of pipe length). The practicality of pumping sludge at a particular solids concentration can then be assessed.

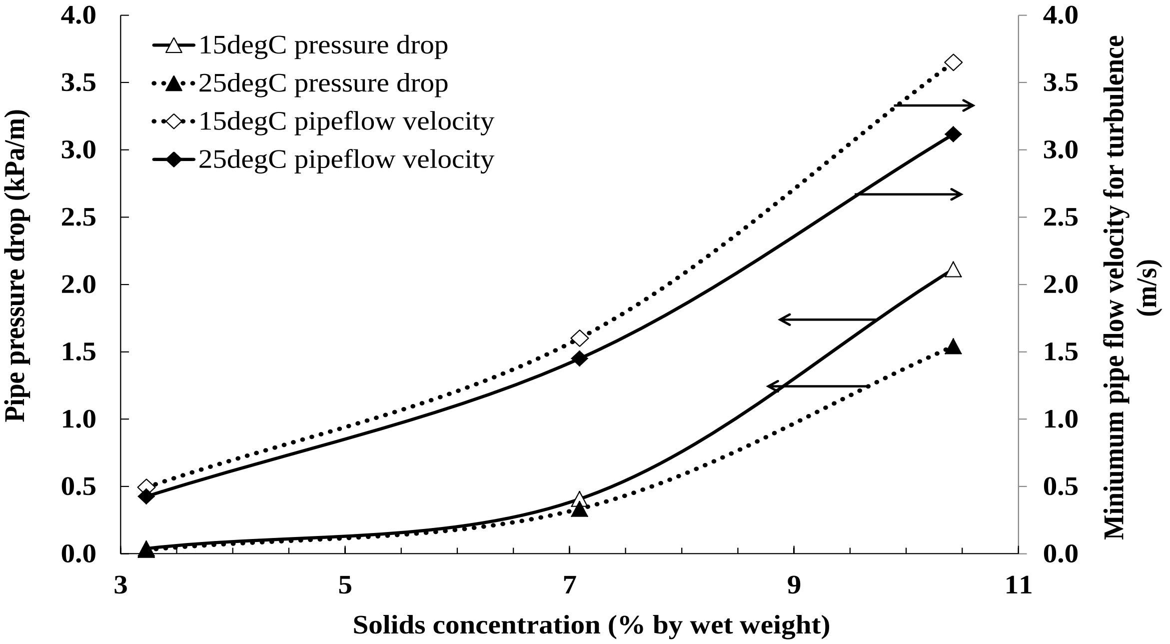


Figure 31: Pipe flow pressure drop for trial at piggery site A

Note that the Figure 30 datasets are only valid for ID 96 mm (PN 10 110 mm OD pipe). As an example, the on-site measurements were at a flow velocity of 0.6 m/s with pipe length L = 430 m (so 8V/D = 8 × 0.6/0.096 = 50 s^{-1}, read off T_w = 10 Pa, and ΔP = 10 × 4 × 430/0.096 = 179,000 Pa = 1.79 bar).

9. *Conclusions and recommendations*

Sludge accumulates in various waste management ponds at piggeries and cattle feedlots. Eventually, this sludge needs to be removed and handled. Many existing piggery ponds are reaching the point where sludge removal is becoming a pressing issue. Another issue has arisen recently with the use of covered treatment ponds to generate biogas. Sludge removal from covered ponds presents special difficulties.

Sludge is a mixture of water and solid materials (total solids (TS)). The TS component can be inorganic material (any materials such as debris, sand or rocks plus the ash component of organic wastes), slowly digestible organic material or dead microbial cell mass. The ratio of water to solids (TS content) can vary considerably. As the TS content increases, the sludge's characteristics and handling requirements change. The particle size and particle size distribution (PSD) can vary from very fine colloidal material to larger particles. Some particles can be cohesive (i.e. they tend to stick together) while other particles such as sand are non-cohesive. Rheology is the study of the flow of matter. This is an important feature in the design of sludge removal systems.

The term – sludge – is widely used for a range of materials. However, the handling and management options for "sludge" is heavily dependent on the TS content of the material. In this report, the following terms have been defined.

1. Effluent. This is material with a TS content of <5%.Effluent is a material that can be pumped and behaves like other Newtonian fluids, e.g. water.
2. Slurry. This is material with a TS content of 5-15%. These materials are "thick" but can flow. They behave in a non-Newtonian manner and require specialised pumping equipment.
3. Sludge. This is material with a TS content >15%. Essentially, this material is too thick to pump and must be handled with bulk mechanical methods.

The actual properties of sludges derived from different sources vary, even at the same TS content. Hence, the TS contents stated above are a general guideline for use in this report rather than a fixed rule. Care needs to be taken when reviewing other work as the definition of sludge used in the literature is highly variable.

The physical characteristics of the sludge or slurry is importantly in determining the appropriate pumping and handling methods. Particle size distribution (PSD) and bulk density are important but the rheological properties have the greatest influence. Several studies have been conducted into the rheological properties of raw and digested manure in sludge or slurry forms. Most researchers find that viscosity (i.e. resistance to pumping) increases with increasing total solids content and decreases with temperature. Effluent with a TS content <2% can be pumped with centrifugal pumps. Slurries with a TS content of about 5-10% TS can be pumped with various types of positive displacement pumps. Sludge with a TS content greater than 15% is virtually impossible to pump.

When desludging ponds, there are three techniques depending on the operation and structure of pond, sludge physical characteristics and the frequency of desludging. Desludging can be broadly categorised into three groups:

- desludging dewatered ponds (after effluent removal)
- desludging an uncovered pond containing effluent
- desludging a covered pond.

Due to the high cost of desludging, for ponds with very old or thick sludge, it is often cheaper to remove the water layer first (i.e. dewater the pond) and then excavate the sludge with conventional earthmoving equipment such as an excavator and dump trucks.

However, it is usually more desirable to remove sludge from a pond without dewatering as this maintains the function of the pond. There are three basic methods of sludge removal from an operating, uncovered pond. They are:

1. Pumping. This uses a pump or vacuum tanker located on the bank of the pond. It may or may not include agitation of the sludge in the base of the pond.
2. Dredging. This involves the use of a system where the pump is within the pond and is mobile so that all sections of the pond can be accessed.
3. Mechanical Removal. This involves the use of a long-reach excavator or similar to remove the sludge without pumping.

Sludge removal from covered anaerobic ponds presents specific difficulties as the cover cannot be removed during the operational phase. There are essentially three methods of sludge removal from CAPs. They are:

1. In-situ desludging. In this approach, the solids settle to the base of the CAP and are removed by pumping via a pre-installed pipeline.
2. Suspension removal. In this approach, the solids are not allowed to settle. They are kept in suspension using agitators inside the CAP. The solids are removed as part of the effluent flow out of the CAP.
3. Life-time accumulation. In this approach, solids are allowed to settle but are not removed until the operational life of the pond cover is reached and the cover is removed. In this approach, a large sludge-accumulation volume is needed to be designed as part of the internal volume of the CAP.

Depending on the final utilisation method for the sludge or slurry, it may be desirable to dewater the removed sludge or slurry. This is particularly applicable if the final utilisation site is some distance from the source. There are several methods of dewatering (solid separation) for sludge and slurries. However, most of the available options are not suitable for dewatering sludge and slurries because:

- Removal efficiency is not sufficiently high to achieve a “dry” sludge.
- Capital, operating and maintenance costs are high.
- Capacity is too low for a large volume of sludge removed in a short period.
- High technical skills are required.

In reality, most sludge and slurries removed from ponds is dewatered using free drainage and/or evaporation in bays or tubes. The choice of dewatering method is site-specific. The methods include:

1. Long-term bulk storage.
2. Short-term drying bays.
3. Sedimentation and Evaporation Pond Systems (SEPS).
4. Geotextile tubes.

Samples of pond sludge were taken and analysed at several piggery and feedlot sites across Australia. The sludge was accumulated from different sources, had different ages and consequently had different rheological properties. Additionally, a sludge pumping test was undertaken measuring the pipe friction losses for the digested sludge in a covered anaerobic pond at different total solids contents.

The TS contents ranged from 3 to 16% TS. Bulk density ranged from 1020 to 1294 kg/m^3 indicating that the majority of the sample was water. Particle size distribution varied due to a range of source and age issues. In the pipe friction loss experiment, sludge with a TS content of about 3% had a low friction loss and could be easily pumped. However, as the TS content increased to 10%, the friction loss increased rapidly and the material was very difficult to pump. The VS:TS ratio of all sludge in this experiment was about 0.6 indicating that the material was well digested. This experiment would suggest that frequent removal of recently settled sludge (<3%TS) from the covered pond would be preferred over infrequent removal of densely settled sludge (>10%TS).

Further work is required in understanding the optimal sludge removal frequency from covered anaerobic ponds coupled with the correct design of the sludge removal pipeline system and correct selection of pump type.

10. References

Abis, K & Mara, D 2005, 'Research on waste stabilization ponds in the United Kingdom: Sludge accumulation in pilot-scale primary facultative ponds', *Environmental technology*, vol. 26, no. 4, pp. 449-458.

Achkari-Begdouri, A & Goodrich, PR 1992, 'Rheological properties of Moroccan dairy cattle manure', *Bioresource technology*, vol. 40, no. 2, pp. 149-156.

Anderson, J et al. 2000, 'Physical and chemical properties of undisturbed stratified sludge in swine waste anaerobic lagoons', in *Proceedings of the 8th International Symposium on Animal, Agricultural and Food Processing Wastes, Des Moines, Iowa*, pp. 171-178.

APHA 1989, *Fixed and volatile solids ignited at 550°C*, 17th Edn, vol APHA 2540E, Standard Methods for the Examination of Water and Waste water, American Public Health Association New York, USA.

ASTM 2008, *D 2974-07a - Standard test method for moisture, ash, and organic matter of peat and other organic soils*, PA 19428-2959, ASTM International, West Conshohocken.

Baker, KB et al. 2002, 'Treatment of lagoon sludge and liquid animal manure utilizing geotextile filtration', Clemson University.

Barth, CL 1985, 'The rational design standard for anaerobic livestock waste lagoons', in *Proceedings of the 5th International Symposium on Agricultural Wastes*, St Joseph, MI, USA, American Society of Agricultural Engineers, pp. 638-647.

Barth, CL & Kroes, J 1985, 'Livestock waste lagoon sludge characterisation', in *Agricultural Waste Utilization and Management. Proceedings of the 5th International Symposium on Agricultural Waste*, 16-17 December, Chicago, IL, ASABE.

Baudez, J et al. 2012, 'The impact of temperature on the rheological behaviour of anaerobic digested sludge', *Chemical Engineering Journal*.

Biggs, C & Lant, P 2000, 'Activated sludge flocculation: on-line determination of floc size and the effect of shear', *Water Research*, vol. 34, no. 9, pp. 2542-2550.

Birchall, S 2010, *Biogas production by covered lagoons - Performance data from Bears Lagoon Piggery*, RIRDC Publication No. 10/023, Rural Industries Research and Development Corporation, Canberra, < https://rirdc.infoservices.com.au/items/10-023 >.

Brambilla, M et al. 2013, 'Rheological properties of manure/biomass mixtures and pumping strategies to improve ingestate formulation: A review', *Transations of the ASABE* vol. 56, no. 5, pp. 1905-1920.

Bryant, CW 1995, 'A simple method for analysis of the performance of aerated wastewater lagoons', *Water Science and Technology*, vol. 31, no. 12, pp. 211-218.

Butler, B & Johns, M 2012, *Demonstration of covered anaerobic pond technology*, Final Report Project P.PIP.0290 2011, Meat & Livestock Australia Ltd, North Sydney.

Campbell, G & Shiozawa, S 1992, 'Prediction of hydraulic properties of soils using particle-size distribution and bulk density data', in *Proc. Int. Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils. University of California, Riverside*, pp. 317-328.

Cantrell, K et al. 2008, 'Geotextile filtration performance for lagoon sludges and liquid animal manures dewatering', *Transactions of the ASABE*, vol. 51, no. 3, pp. 1067-1076.

Charles, J 2000, *Solid separation using a vibrating sieve*, Pig Research and Development Corporation Group Demonstration Project, Report No. 1667, Charles IFE Pty Ltd.

Chastain, JP 2006, 'Estimation of sludge accumulation in lagoons. Paper no. 064114', in *ASABE Annual International Meeting*, 9-12 July Portland, Oregon, ASABE.

Chen, Y 1982, *Engineering properties of beef cattle manure*, ASAE, Paper No. 824085, American Society of Agricultural Engineers, St. Joseph, MI.

Chen, Y 1986, 'Rheological properties of sieved beef-cattle manure slurry: rheological model and effects of temperature and solids concentration', *Agricultural Wastes*, vol. 15, no. 1, pp. 17-33.

Chen, Y & Hashimoto, A 1976, 'Pipeline transport of livestock waste slurries', *Transactions of the ASAE*, vol. 19.

Chen, Y & Shetler, E 1983, 'Temperature effect on rheological properties of cattle manure slurry', *Journal of Testing and Evaluation*, vol. 11, no. 6, pp. 5.

Davis, RJ et al. 2010, *Quantification of feedlot manure output for BEEF-BAL model upgrade*, RIRDC Project No. PRJ-004377, Rural Industries Research and Development Corporation, Canberra.

Dong, H et al. 2006, *Chapter 10: Emissions from Livestock and Manure Management*, vol 4: Agriculture, Forestry and Other Land Use, IPCC Guidelines for National Greenhouse Gas Inventories, IGES, Japan.

Duperouzel, D nd., '*Making waves in anaerobic pond treatment systems - Wasteline #13*', viewed 21/3/2007, < www.dpi.qld.gov.au/cps/rde/xchg/dpi/hs.xsl/30_1809_ENA_HTML.htm, >.

El-Mashad, HM et al. 2004a, 'Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure', *Bioresource Technology*, vol. 95, no. 2, pp. 191-201.

El-Mashad, HM et al. 2004b, 'Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure', *Bioresource technology*, vol. 95, no. 2, pp. 191-201.

Eshtiaghi, N et al. 2012, 'The laminar/turbulent transition in a sludge pipeline', *Water Science and Technology*, vol. 65, no. 4, pp. 697-702.

Fowler, J et al. 1996, 'Dewatering sewage sludge with geotextile tubes', in *Proceedings of the 49th Canadian Geotechnical Conference*, pp. 23-25.

GHD 2008, *In-situ desludging of anaerobic lagoons and sludge drying*, APL Project Final Report, Australian Pork Ltd, Canberra, ACT.

Gilley, J et al. 2000, 'Copper and zinc in swine diets affect phototrophic anaerobic lagoons', in *Animal, agricultural and food processing wastes. Proceedings of the Eighth International Symposium, Des Moines, Iowa, USA, 9-11 October, 2000.*, American Society of Agricultural Engineers, pp. 656-663.

Glancey, J & Hoffman, S 1996, 'Physical properties of solid waste materials', *Applied engineering in agriculture*, vol. 12, no. 4, pp. 441-446.

Gloyna, EF 1971, *Waste stabilization ponds*, World Health Organization Geneva.

Grzina, A, Roudnev, A, Burgess, K, 2002, *Slurry pumping manual*, Warman International Ltd.

Guyer, J 2011, *Introduction to Sludge Handling, Treatment and Disposal*, Continuing Education and Development, Inc.

Hamilton, D 2010, 'Sludge accumulation in two anaerobic/facultative lagoons treating swine manure from breeding farms in Oklahoma', *Transactions of ASABE*, vol. 53, no. 2, pp. 529-536.

Hao, X et al. 2005, 'Influence of Canola and Sunflower Diet Amendments on Cattle Feedlot Manure', *Journal of Environmental Quality*, vol. 34, no. 4, pp. 1439-1445.

Hasar, H et al. 2004, 'Rheological properties of activated sludge in a sMBR', *Biochemical Engineering Journal*, vol. 20, no. 1, pp. 1-6.

Hayes, S et al. 2007, *Odour emissions from sedimentation and evaporative ponds*, APL Final Report Project No. 2139, December 2007, Australian Pork Ltd, Canberra, ACT.

Hjorth, M et al. 2010, 'Solid–liquid separation of animal slurry in theory and practice. A review', *Agronomy for sustainable development*, vol. 30, no. 1, pp. 153-180.

Hollmann, M et al. 2008, 'Evaluation of solids, nitrogen, and phosphorus excretion models for lactating dairy cows', *Journal of Dairy Science*, vol. 91, no. 3, pp. 1245-1257.

Keffala, C et al. 2013, 'A review of the sustainable value and disposal techniques, wastewater stabilisation ponds sludge characteristics and accumulation', *Environmental monitoring and assessment*, vol. 185, no. 1, pp. 45-58.

Kehl, O et al. 2009, 'Analysis of design approaches for stabilization ponds under different boundary conditions—A comparison', *Ecological Engineering*, vol. 35, no. 8, pp. 1117-1128.

Kruger, I et al. 2008, *Sedimentation and evaporation pond systems*, National Environmental Guidelines Workshop May 2008, Australian Pork Limited,.

Kumar, M et al. 1972, 'Flow properties of animal slurries', *Transactions of the ASAE*, vol. 15, no. 4, pp. 718-722.

Landry, H et al. 2004, 'Physical and rheological properties of manure products', *Applied Engineering in Agriculture*, vol. 20, no. 3, pp. 277-288.

Landry, H et al. 2002, 'Physical and flow properties of solid and semi-solid manure as related to the design of handling and land application equipment', in *Poster presented at the 2002 Banff Pork Seminar–Leading the Way. Banff, AB. Advances in Pork Production (2002)*, vol. 13.

Lawler, DF et al. 1986, 'Anaerobic digestion: effects on particle size and dewaterability', *Journal (Water Pollution Control Federation)*, pp. 1107-1117.

Marcato, CE et al. 2008, 'Particle size and metal distributions in anaerobically digested pig slurry', *Bioresource Technology*, vol. 99, no. 7, pp. 2340-2348.

Mason, IG 1997, 'Performance of a facultative waste stabilization pond treating dairy shed wastewater', *Transactions of the ASAE* vol. 40, no. 1, pp. 211-218.

Masse, L et al. 2005, 'Size distribution and composition of particles in raw and anaerobically digested swine manure', *Transations of the ASAE*, vol. 48, no. 5, pp. 1943.

McCave, I & Syvitski, J 1991, 'Principles and methods of geological particle size analysis', *Principles, methods, and application of particle size analysis*, pp. 3-21.

McGinn, SM et al. 2002, 'Effect of diet on odorant emissions from cattle manure', *Canadian Journal of Animal Science*, vol. 82, no. 3, pp. 435-444.

Metcalf & Eddy Inc. 2003, *Wastewater engineering: Treatment & reuse*, McGraw-Hill, New York.

Neis, U & Tiehm, A 1997, 'Particle size analysis in primary and secondary waste water effluents', *Water science and technology*, vol. 36, no. 4, pp. 151-158.

Nelson, KL et al. 2004, 'Sludge accumulation, characteristics, and pathogen inactivation in four primary waste stabilization ponds in central Mexico', *Water Research*, vol. 38, no. 1, pp. 111-127.

Pain, B et al. 1978, 'Factors affecting the performances of four slurry separating machines', *Journal of Agricultural Engineering Research*, vol. 23, no. 3, pp. 231-242.

PAMI 1997, *A Guide to Pipeline Manure Injection Systems*, Research Update No. 729, Prairie Agricultural Machinery Institute, Humboldt, SK.

PAMI 2000, *The Pork Producer's Guide to Managing Swine Manure in Saskatchewan - A Practical Guide for Farmers and Applicators*, Prairie Agricultural Machinery Institute, Humboldt, SK.

Papadopoulos, A et al. 2003, 'Sludge accumulation pattern in an anaerobic pond under Mediterranean climatic conditions', *Water research*, vol. 37, no. 3, pp. 634-644.

Payne, H et al. 2008, *Solids separation in sedimentation and evaporation pond systems (SEPS). Final report to Australian Pork Ltd - APL Project 2130*, Dept. of Agriculture and Food Western Australia, Perth.

Payne, R 1984, *Physical, chemical and microbiological characteristics of pig excreta*, Western Australian Department of Agriculture, South Perth.

Payne, RW 1986, 'Characteristics of faeces from institutional and comemrical piggeries', *Agricultural Wastes*, vol. 16, pp. 1-11.

Peters, J et al. 2003, *Recommended Methods of Manure Analysis (A3769)*, UW Extension, University of Wisconsin.

Picot, B et al. 2005, 'Wastewater stabilisation ponds: sludge accumulation, technical and financial study on desludging and sludge disposal case studies in France', *Water Science & Technology*, vol. 51, no. 12, pp. 227-234.

Pind, PF et al. 2003, 'Dynamics of the anaerobic process: Effects of volatile fatty acids', *Biotechnology and Bioengineering*, vol. 82, no. 7, pp. 791-801.

Pollice, A et al. 2007, 'Physical characteristics of the sludge in a complete retention membrane bioreactor', *Water research*, vol. 41, no. 8, pp. 1832-1840.

Ramalho, R 1977, *Introduction to wastewater treatment processes*, Academic Press.

Rickert, DA & Hunter, JV 1967, 'Rapid fractionation and materials balance of solids fractions in wastewater and wastewater effluent', *Journal (Water Pollution Control Federation)*, vol. 39, no. 9, pp. 1475-1486.

Saqqar, MM & Pescod, M 1995, 'Modelling sludge accumulation in anaerobic wastewater stabilization ponds', *Water Science and Technology*, vol. 31, no. 12, pp. 185-190.

Schulte, D & Koelsch, R 1998, 'Improving Odor Control in Swine Lagoons by Better Understanding and Management of Purple Sulfur Bacteria', *University of Nebraska, Lincoln, Nebraska, USA*.

Seyssiecq, I et al. 2003, 'State-of-the-art: rheological characterisation of wastewater treatment sludge', *Biochemical Engineering Journal*, vol. 16, no. 1, pp. 41-56.

Shilton, A (ed.) 2005, *Pond treatment technology*, Integrated environmental technology series, IWA Publishing, London, UK.

Singh, K et al. 2007, 'Sludge measurement using global positioning system (GPS) enabled sonar', in *Proceedings of the International Symposium on Air Quality and Waste Management for Agriculture*, ASABE.

Skerman, A et al. 2013, *Queensland sedimentation and evaporation pond system (SEPS) trial*, Final Report prepared for Australian Pork Ltd, APL Project No. 2009/2248.

Skerman, A et al. 2008, *Improved piggery effluent management systems incorporating highly loaded primary ponds*, Final report to Australian Pork Limited (APL), Project 2108, Department of Primary Industries and Fisheries (DPI&F), Toowoomba, Qld.

Skerman, A et al. 2005, *Clay lining and compaction of effluent ponds*, DPI&F Note, Note No: 8841, February 2005, Department of Primary Industries and Fisheries.

Staley, L et al. 1973, 'Flow properties of dairy waste slurries', *Canadian Agricultural Engineering*, vol. 15, no. 2, pp. 4.

Standards Australia 1992, *Methods of testing soils for engineering purposes: Soil moisture content tests - Determination of the moisture content of a soil - Oven drying method (standard method)*, (AS 1289.2.1.1), Standards Australia, Sydney, NSW.

Sukias, JPS et al. 2001, 'Algal abundance, organic matter, and physico-chemical characteristics of dairy farm facultative ponds: implications for treatment performance', *New Zealand journal of agricultural research*, vol. 44, pp. 279-296.

Tadesse, I et al. 2004, 'Seasonal and diurnal variations of temperature, pH and dissolved oxygen in advanced integrated wastewater pond system< sup>®</sup> treating tannery effluent', *Water Research*, vol. 38, no. 3, pp. 645-654.

Tait, S, Birchall, S, O'Keefe, M, 2013, 'Sizing Pumps for Desludging of Covered Piggery Ponds', Paper submitted to the *Australasian Pig Science Association (ASPA)* Melbourne.

Tucker, RW et al. 2010, *National environmental guidelines for piggeries - Second Edition*, APL Project 1832, Australian Pork Ltd, Deakin.

VanDevender, K 2003, *Liquid Manure Solids Management. Division of agriculture research and extension*, FSA1041, University of Arkansas, Arkansas, viewed 23 September <http://www.uaex.edu/Other_Areas/publications/PDF/FSA-1041.pdf >.

Vedrenne, F et al. 2008, 'The effect of incubation conditions on the laboratory measurement of the methane producing capacity of livestock measurement wastes', *Bioresource Technology*, vol. 99, pp. 146-155.

Warman International Ltd. 2000, *Warman Slurry pumping handbook (Australasian Version)*, February 2000, Warman International Ltd, viewed 23 September 2009, < www.pumpfundamentals.com/slurry/Warman_slurry_pumping.pdf >.

Water Corporation 2010, *Waste Stabilisation Pond Science: Implications for Design and Management*, Water Corporation, Leediville, Perth, viewed.

Watson, M 1999, *Continuous anaerobic pond desludging*, PRENV.003, Meat & Livestock Australia Ltd.

Westerman, P et al. 2008a, *Sludge survey methods of anaerobic lagoons*, Northern Carolina State University, Published by North Carolina Cooperative Extension, Raleigh, NC.

Westerman, P et al. 2008b, *Carbon credits for methane collection and combustion*, North Carolina State University and North Carolina A&T State University, Published by North Carolina Cooperative Extension.

Worley, J et al. 2008, 'Use of geotextile tubes with chemical amendments to dewater dairy lagoon solids', *Bioresource technology*, vol. 99, no. 10, pp. 4451-4459.

11. Appendix A – Definition and determination of sludge physical properties

General comments

Sludge derived from manure constitutes urinary excretions as well as the fraction of the diet consumed by an animal that is not digested and excreted as faecal material. Manure is urine plus faeces. Manure is composed of dry matter, which contains macro and micro nutrients, and water. The dry matter is the TS, which is composed of organic matter (measured as either VS or chemical oxygen demand (COD), and FS (ash).

In manure, a significant proportion of the organic matter can be in the form of volatile fatty acids (VFAs). Total VFA is usually the sum of acetic, propionic, butyric, isobutyric, isovaleric, valeric and caproic acids. As the name suggests, these acids are volatile – particularly the short chain acids such as acetic and propionic - and can disperse into the atmosphere after the faeces is excreted from the animal. The volatilisation rate of VFAs is dependent on pH, temperature and other factors.

Hao et al. (2005) examined the effect of diet on the characteristics of feedlot manure including the VFA content. The manure was taken from the pen floor after 113 days on feed and included wood chips which accounted for about 60% of the dry matter. They found that acetic acid accounted for 75 to 82% of VFA while propionic acid accounted for 12 to 18% of VFA. Together, these two acids made up 93 to 96% of VFA in the feedlot manure samples. McGinn et al. (2002) investigated the effect of three barley-based diets on manure composition in a feedlot. They did not measure the VFA content of the manure but did measure VFA emissions from the manure using a collection chamber. The dominating VFA compounds were acetic (30 to 34% of total VFA), propionic (19 to 30%) and butyric (29 to 30%), followed by valeric (4 to 6%), isovaleric (2 to 3%), isobutyric (2%) and caproic (<1%). The percent of each VFA compound was consistent across all treatments. In the McGinn et al. (2002) study, the proportion of VFA made up of acetic and propionic in the emissions from manure is much smaller than in the acetic and propionic content within manure (Hao et al. 2005). This may be due to different VFA profiles within the manure or it may suggest that VFAs volatilise at a different ratio to their content in manure. This may have implications when drying manure samples.

The content of VFAs in manure samples is an important consideration when determining moisture content and VS content of the manure. As is explained in following sections, the moisture content of a sample is determined by heating the sample thus driving the moisture out of the sample. It is well known, but rarely quantified, that VFAs also leave the sample during drying.

For example, Pind et al. (2003) undertook a study of the anaerobic digestion of a cattle manure slurry. They measured the TS and VS of the manure using standard procedures (i.e. drying at 105°C) to be 76.6 g/L and 60.2 g/L respectively (VS:TS = 78.6%). They assume that 80% of the VFAs in the sample are lost during drying but do not provide a reference for this assumption. After applying this correction, they state that the corrected TS and VS are 83.6 g/L and 67.2 g/L respectively (VS:TS = 80.4%). Reanalysing their data, it appears that VFAs constitute 13% of all VS and that VS was underestimated by 10% using standard laboratory drying procedures.

Another example is Vedrenne et al. (2008) who noted that, during TS determination, the volatilisation of a part of the organic fraction was suspected during drying of the manure at 105°C, leading to an underestimation of the TS and VS concentrations. They undertook an analysis of the total organic carbon in wet and dried (at 105°C) manure slurries and showed a loss of organic carbon after drying at 105°C (Figure 32). Analysis of carbon on wet slurry indicated a carbon content equal to 31 g L^{-1} while the carbon content of the same slurry, on the same basis but after drying, fell to 23.6 g L^{-1}. The organic fraction responsible for this loss was the VFA fraction in the manure. According to this observation and in order to avoid analytical errors, Vedrenne et al. (2008) developed a methodology to quantify exactly the TS and VS content. VFA were determined for all slurries before (on raw slurry) and after drying (after 2 h extraction of dried slurry with water). The difference between the two values was considered to correspond to the VFA lost during drying. As shown in Figure 32, the carbon mass balance confirmed their hypothesis and showed that the VFA fraction was the main loss during drying. Applying this methodology to all their samples, Figure 33 shows VFA volatilisations during drying and the respective VS underestimations for the 13 slurries studied. Contrary to Pind et al. (2003) who applied a fixed 80% correcting factor of VFA lost during drying, the proportion of VFA volatilisation was variable and represented from 0% to 88% of total VFA. Vedrenne et al. (2008) found no correlation between slurry characteristics (pH, TS, VFA contents) and VFA losses. The VS underestimations resulting from the VFA losses could reach 25%. This work clearly demonstrates that VS can be underestimated due to VFA loss during the initial drying of the manure sample but provides no guidance on an appropriate correction method.

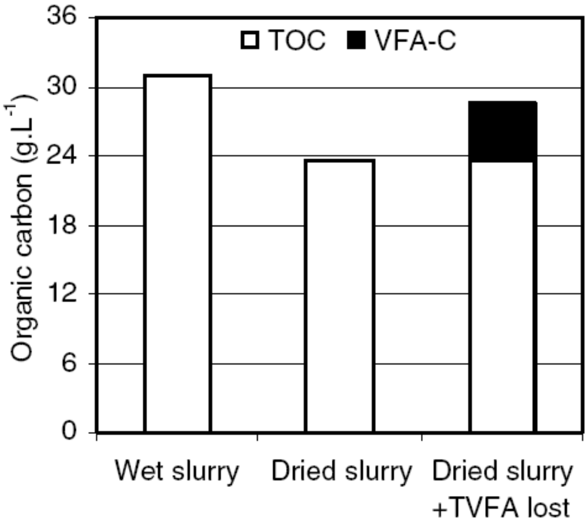


Figure 32: Loss of VFAs during manure drying at 105°C (Vedrenne et al. 2008)

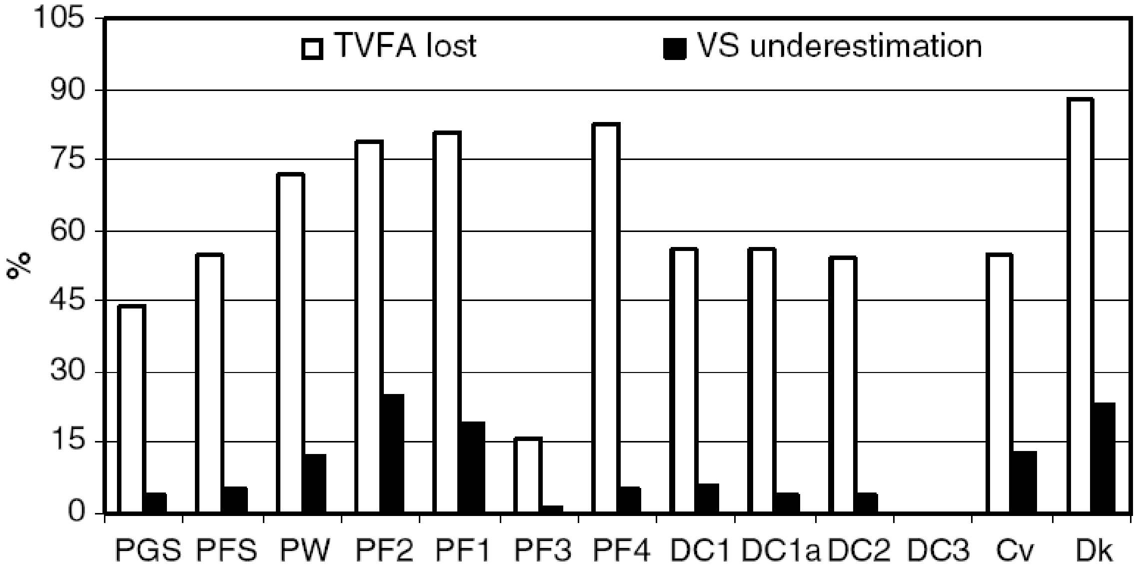


Figure 33: VS underestimation due to drying (Vedrenne et al. 2008)

11.1.1 Total solids (dry matter)

Dry Matter (DM) or TS is that matter remaining after water is completely evaporated from the sample (Peters et al. 2003). For soils, this is a relatively straightforward process. Most standards specify drying at 105°C for either 24 hours or until the weight of the dried sample is constant, e.g. Standards Australia (1992).

However, for samples containing a large percentage of organic or volatile material, it is likely that some of the volatile organics will be lost during the drying process. Certainly, anyone who has actually dried manure samples would know that more compounds than just water are driven from the samples. Peters et al. (2003) reports the outcome of a program that conducted a manure sample exchange between 14 state university laboratories in the USA. They found that drying temperatures ranged from 50°C to 110°C and documented drying times ranged from 16 to 24 hours. Clearly, there is a lack of standard methodology used for manure samples. It is probably that the lower drying temperatures used by some laboratories is an attempt to minimise the loss of volatile organics during the drying process.

The whole issue of the effect of drying temperature on TS and VS determination is exemplified when Hollman et al (2008) stated that "*to our knowledge, no data exist in the scientific literature comparing DM excretion estimates to total solids estimates*". On the face of it, this statement seems nonsensical as most authors assume (as is done in this report) that DM (dry matter) is equivalent to TS. However, Hollman et al (2008) goes on to say that DM is typically determined by agricultural scientists by drying at 60°C while TS are determined by engineers by drying at 105°C and that these two methods do not necessarily produce the same result with more variability in results dried at 60°C.

UQ AWMC TS Method

TS was determined by the Standard Methods for the Examination of Water and Wastewater.

A crucible was weighed immediately prior to use and the weight recorded. A well-mixed sample of material was placed in the porcelain crucible and the sample and crucible weight recorded. The crucible was placed in an oven and the sample dried at 103 to 105°C for 1 hour. The crucible was removed from the oven and placed in a desiccator to cool. The weight of the cooled sample and crucible was weighed. The crucible was placed in the oven again and the procedure repeated until a constant weight was obtained or until the weight loss was less than 4% of previous weight. The crucibles, desiccator and balance used to determine TS are shown in Photograph 45.

Photograph 45: Crucibles, desiccator and balance

The TS or moisture content of wastewater sample can be expressed as:

$$\%\,TS\ (wet\,basis) = \frac{Mass(solids)}{Mass(solids + water)}$$

Equation A- 1

$$Moisture\ content\ (\%\,wet\,basis) = \frac{Mass\,water}{Mass(water + solids)}$$

Equation A- 2

$$Moisture\ content\ (\%\,dry\,basis) = \frac{Mass\,water}{Mass\,solids}$$

Equation A- 3

$$Solids\ concentration\ \ (mg/L) = \frac{Mass\,solids}{Volume(water + solids)}$$

Equation A- 4

$$Total\ solids = Fixed\ \ solids + Volatile\ \ solids$$

Equation A- 5

$$Total\ solids = Dissolved\ solids + Suspended\ solids + Settleable\ solids$$ Equation A- 6

Throughout the literature, various units are used to quantify the solids content of a wastewater. Table 17 provides a conversion of %TS to a % wet basis (w.b.), % dry basis (d.b.) and a concentration of total solids in mg/L. Throughout this report, all total solids data are reported on a % total solids basis and described as TS content.

Table 17: Conversions of %TS to moisture content on a wet basis, dry basis and concentration

% TS	% Wet basis	% Dry basis	TS Concentration (mg/L)
0.5	99.5	19900	5000
1	99	9900	10000
5	95	1900	50000
10	90	900	100000
25	75	300	250000
50	50	100	500000
75	25	30	750000

These conversions assume solutions with a high TS concentration (>10%) the densities are 1 kg/L.

1. Volatile solids

The method to measure VS in the laboratory is to burn (ash) dried manure samples at high temperature. Examples are 550 °C (APHA 1989) or 440°C or 750°C (ASTM 2008). The VS portion of the sample is burnt off and only the ash remains. The VS are determined by mass balance. However, as previously noted, the VS determined using this process may be an under-estimate of the total VS due to the loss of VFAs during the initial drying process. This will be discussed in the following section.

UQ AWMC VS Method

The VS of the sludge was determined by the Standard Methods for the Examination of Water and Wastewater.

After the determination of total solids, the weighed crucible plus solids was placed in a muffle furnace at 550°C for 15 to 20 minutes. The crucible plus ash was allowed to cool to room temperature in the desiccator. The crucible plus ash was weighed and the weight recorded. The crucible plus ash was placed in the oven again and the procedure repeated until a constant weight is obtained or until the weight loss is less than 4% of previous weight. Three replicates of each sample were analysed.

11.1.2 Bulk density

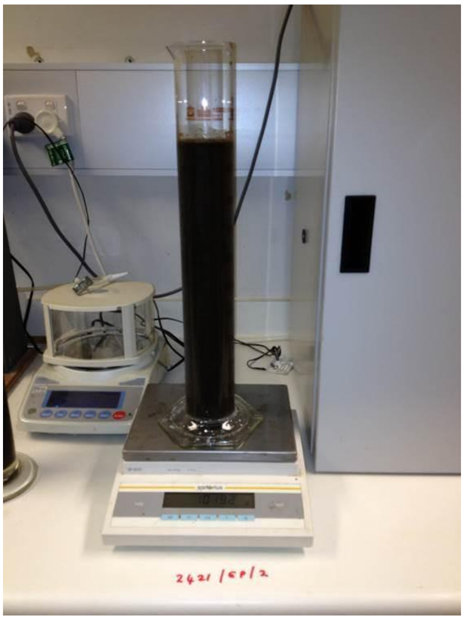
The physical properties associated with the mass of a material are important from a handling perspective. A force imparts acceleration to a mass. Weight, as a particular form of force, imparts gravitational acceleration to a mass. For comparison of various materials, it is usual to express their mass relative to a unit volume. This physical property is called bulk density (ρ) and is usually expressed as kg/m^3.

Hence, density of sludge is the weight of the material per unit volume. Density is not an intrinsic property of sludge; it can change depending on how the material is handled.
Sludge consists of greater than 95% water and therefore has a density similar but slightly higher than that of water.

UQ AWMC Bulk Density Method

The density of the sludge samples was determined by the following method. A 1 L precision bore volumetric flask was weighed and the weight recorded. The flask was filled with sludge to the 1 L mark. The flask was tapped slightly so that all air bubbles were expirated. The flask with sludge was weighed and the weight recorded. The apparatus used is shown in Photograph 46.

The density was calculated as the mass of 1 L of sludge divided by 0.001 m^3 (1 L). The density was expressed as kg/m^3. Three replicates of each sample were analysed.



Photograph 46: Bulk density measurement apparatus

11.1.3 Particle size analysis

Particle-size distributions (PSDs) are fundamental physical properties of sludge and slurries and are typically presented as the percentage of the total dry weight of sludge occupied by a given size fraction. This property is commonly used for characterisation and influences sludge dewaterability and pumping (Campbell & Shiozawa 1992).

There is no standard method for determining the size distribution of particles in wastewater. Similarly, there is no single method covering the full range of 1 μm to 2000 μm been found (Rickert & Hunter, 1967; cited in Payne, 1984). Methods for determining the larger (i.e. > 50 μm) particles include wet/dry sieving, sedimentation, centrifugation, filtration or a combination of these methods.

Smaller particles require methods such as microfiltration, electrical interference, scanning electron microscope and ultracentrifugation.

Changes that occur during the digestion process influence the fundamental characteristics of sludge, e.g. the particle size (Lawler et al. 1986). Particle size analysis has traditionally been determined by sieving (for larger particles) and sedimentation (finer particles). The sieve defines a particle diameter as the length of the side of a square hole through which the particle can just pass. Finer particles are usually determined by classical sedimentation methods such as hydrometer or pipette. Sieving and sedimentation is time consuming especially for the determination of the particles having a size less than 2 mm.

Various new methods have recently been developed for particle size analysis. For example, laser diffraction, (LD), image analysis, ultrasound (McCave & Syvitski 1991). These new methods generally have the advantage of covering a wide range of particle sizes, and rapidly analysing small samples.

Laser diffraction is finding increasing popularity as a method of particle size analysis for wastewater samples (Biggs & Lant 2000, Neis & Tiehm 1997), soil and sludge.

The laser diffraction method (LDM) is based on measuring the scattered laser beam on measured sludge particles. A particle diameter obtained by the LDM is equivalent to that of a sphere giving the same diffraction as the particles. The scattered laser light is registered on detectors. The angle at which the beam is scattered is inversely proportional to the sludge particle size.

UQ AWMC PSD Method

PSD for the sludge samples were determined using a laser analyser Malvern Mastersizer/E as shown in Photograph 47. The equipment uses the technique of laser diffraction to measure the size of particles. It does this by measuring the intensity of light scattered as a laser beam passes through a dispersed particulate sample. This data is then analysed to calculate the size of the particles that created the scattering pattern. The measurement range of the apparatus is 0.1 – 600 µm.

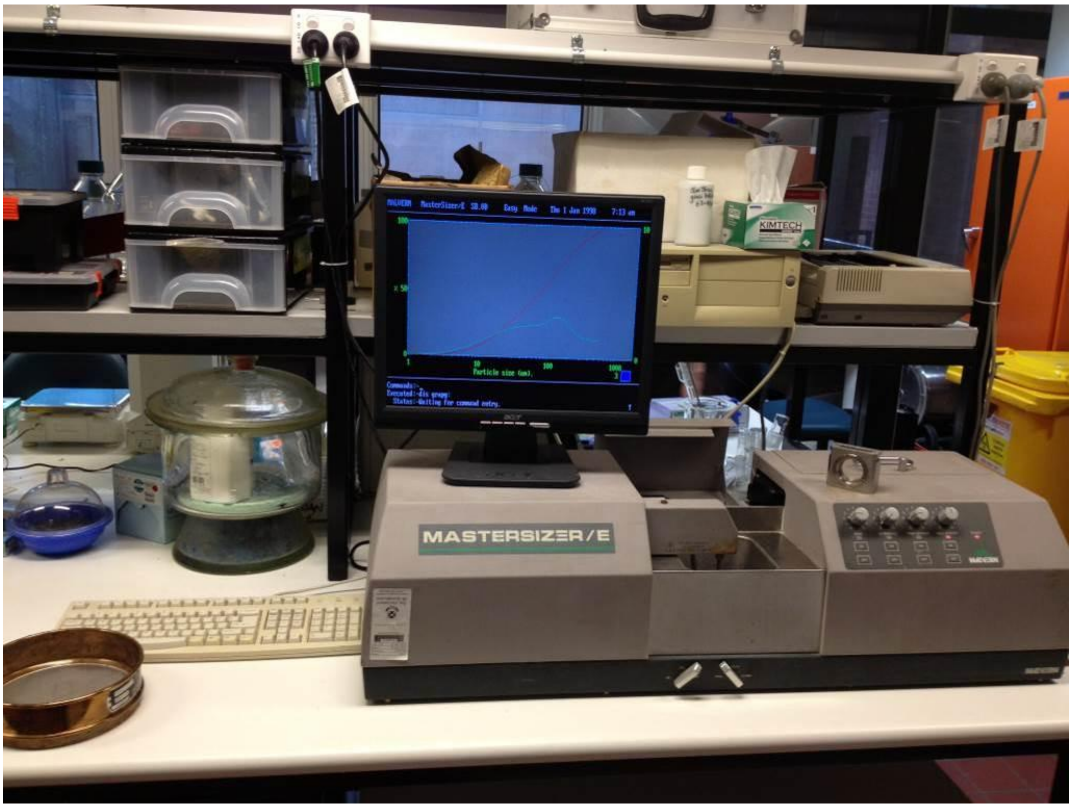
The laser analyser is equipped with

- a magnetic star stirrer; to prevent sedimentation of particles in the sample cell, by circulating the sample in the measuring system and facilitating flow through the measuring cell. The speed of rotation of the stirrer ranges from 0 to 4000 rpm and can be regulated in increments of 50 rpm.
- an ultrasonic probe; with a maximum power of 35 W and a frequency of 40 kHz.

For the determination of PSD, the Mastersizer apparatus uses two sources of light: red (wavelength 633 nm) and blue (wavelength 466 nm).

Each sludge sample was prepared by diluting in tap water. The diluted solution was immediately screened through a standard sieve with aperture size of 500 µm to remove coarse solids that were outside the measurement range of the laser analyser (Photograph 48). The solution that passed through the sieve was also used to wash off any adhering small particles on the solids that were retained on the sieve. This ensured that all the particles that would pass a 500 µm size would be analysed.

A 20 mL sub-sample of material that passed the 500 µm sieve was placed in the laser analyser sample cell. The sample was stirred continuously while the sizing took place. Three replicates of each sample were analysed.



Photograph 47: PSD analyser – Malvern Mastersizer/E

Photograph 48: Retained sludge on 500 µm sieve

11.1.4 Rheological properties

The rheological characteristics of sludge are very important because they are one of only few truly basic parameters describing the physical nature of sludge. Rheological properties are important as far as the handling and processing systems are concerned.

Rheology can be described as the deformation of a body under the influence of stress. For fluids, a flow curve or rheogram is used to describe rheological properties. These properties are of importance in handling and processing of semi-solids e.g. feeding, pumping and stirring.

Flow characteristics, in particular viscosity related effects, vary from very water-like (ideal fluids - Newtonian) to strongly non-Newtonian, as the solids content increases in concentration and complexity, and as the flow conditions move from turbulent to laminar.

Rheograms are constructed by plotting shear stress (**τ**) as a function of the shear rate (γ). For Newtonian fluids, the dynamic viscosity maintains a constant value meaning a linear relationship between shear stress (**τ**) as a function of the shear rate (γ) as shown in Figure 34. Under ordinary conditions, water is a Newtonian fluid.

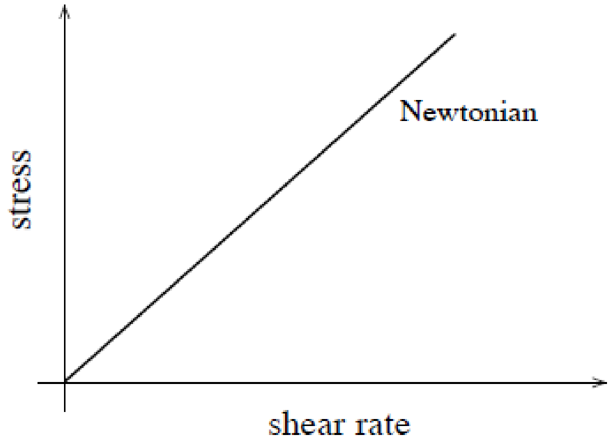


Figure 34: Rheogram of Newtonian fluid

More complex, structured fluids can be non-linear in shear. These are called non-Newtonian fluids. In general, non-Newtonian fluids exhibit a non-linear relationship between the shear rate and the shear stress, and their viscosity cannot be described by a single number, but possibly by a curve or a set of curves. Figure 35 illustrates relationships between shear rate and shear stress for non-Newtonian fluids.

Sludge varies from a Newtonian fluid, where shear is proportional to the velocity gradient, to a plastic fluid, where a threshold shear must be reached before the sludge starts to move. Most sludges are pseudo-plastic. A number of models have been developed to describe the non-Newtonian fluid parameters as in Figure 35. These include Bingham, Ostwald, Casson, Herschel-Buckley and others (Chen 1986, Pollice et al. 2007, Seyssiecq et al. 2003).

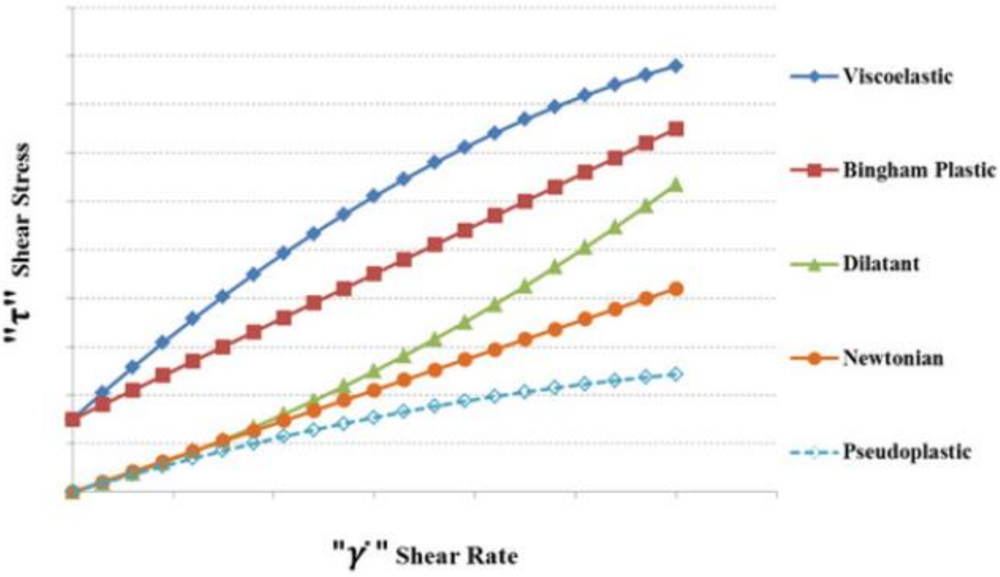


Figure 35: Qualitative rheogram of non-Newtonian fluids

(taken from Brambilla et al. (2013))

11.1.5 Shear stress

Sludges do not behave like Newtonian fluids. Sludges have an additional parameter, namely a yield stress (τ_o). Yield stress (τ_o) is defined as the force a fluid must be exposed to in order to start flowing. It reflects the resistance of the fluid structure to deformation or breakdown. Sludges behave similar to a jelly when stationary and like a fluid when moving. If a shear stress below the yield stress (τ_o) is applied to it, it flexes like a jelly and when the stress is removed it returns to its original shape.

Yield stress is important to consider when handling sludges, since the yield stress is affecting the physio-chemical characteristics of the fluid and impede flow even at relative low stresses.

11.1.6 Viscosity

Any movement of a fluid is resisted by external and/or internal friction. Fluid motion is resisted both by internal molecular friction and external, boundary friction. When a shear force is applied at a boundary of a fluid, the latter begins to move in the direction of the force, developing shear stress between adjoining layers. This property of the fluid is called viscosity. If the velocity gradient dv/dy (also known as Shear rate) between any adjacent fluid layers is constant, the fluid is called Newtonian.

The constant of proportionality between the shear stress (τ) as a function of the shear rate (γ) is called the Dynamic Viscosity, η.

The non-Newtonian nature of sludge means that its measured viscosity, varies with shear rate due to the shear-dependent deformation of the solids.

UQ AWMC Method

The solids content of the samples was measured by wet and dry weights and flow characteristics were determined with a concentric cylinder rheometer (Advanced Rheometric Expansion System, ARES) operated in steady-shear mode at 15 and 25˚C

The ARES is capable of characterising a diverse variety of materials including polymer melts, solids and reactive materials, as well as a broad spectrum of medium to high viscosity fluids. Measurements can be made over a wide range of temperatures using a forced convection oven. The forced convection oven is an air convection oven with dual-element heaters and counter-rotating airflow for optimum temperature stability. The temperature range is -150 to 600°C with heating rates up to 60°C/min.

Prior to testing of flow characteristics, coarse solids in the samples were removed with a 500 µm standard sieve. This produced results for shear rate, shear stress and viscosity.

Appendix B –Tait et al. 2013 Paper

Sizing Pumps for Desludging of Covered Piggery Ponds

S. Tait [1], S. Birchall[2] and Michael O'Keefe [3]

[1] The University of Queensland, St Lucia, QLD, 4072, Australia. [2] AgSystems Design/Dairy Australia NRM Coordinator – Murray Dairy. [3] FSA Consulting, Wangaratta, VIC.

Covered anaerobic piggery ponds (CAPs) are commonly desludged from pipes through the pond banks and extending into the pond base. Sludge solids settle in a dense bed at the base of the pond to a very high solids concentration by progressive thickening (up to 14% solids content at 5m depth, Birchall, 2010). This high solids content is expected to make pumping difficult because pipe pressure losses are greatly increased by a thicker sludge consistency. The sludge settling process is time-dependant with a thicker sludge resulting after longer settling periods before extraction. Consequently, if sludge is extracted too infrequently, the high solids content may make it impossible to pump. This effect also has great practical significance for pump selection, but has not been previously quantified for piggery sludge.

Sludge was extracted from a Victorian piggery CAP from a depth of about 4-4.5m. While extracting, pipe pressure losses and flow velocity were measured for a 430m length of PN10 110mm (96mm ID) pipe. Samples of the sludge were collected for lab analysis. The solids content of the samples was measured by wet and dry weights and flow characteristics were determined with a concentric cylinder rheometer (Rheometrics Advanced Rheometric Expansion System, RARES) operated in steady-shear mode at 15 and 25˚C. Prior to testing of flow characteristics, coarse solids in the samples were removed with a 500µm standard sieve. For one sample the solids content was artificially up-concentrated with a centrifuge. The lab measurements were fitted with a Herschel-Bulkley rheology model and the corresponding approaches described by Skelland (1967) used to express the data (field pumping and lab) on a common/general basis.

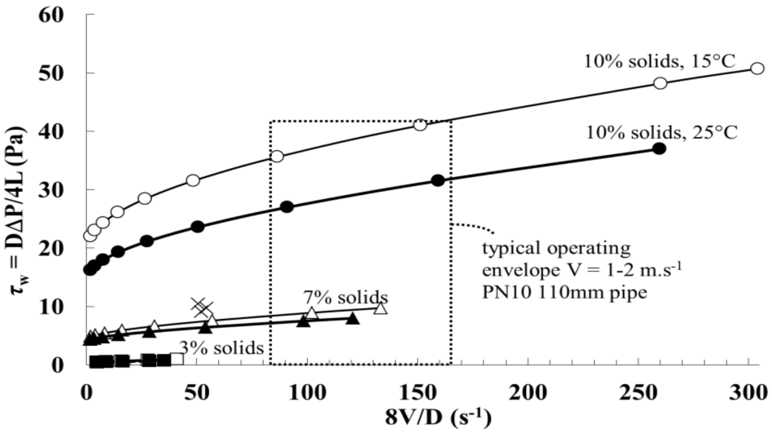


Figure 1. *Pipeflow wall shear stress (τ_w) vs. shear rate (*8V/D*) showing onsite measurements (x) and lab-based measurements for sludge with 3.2% (squares), 7.1% (triangles) and 10.4% (circles) solids concentrations and test temperatures of 15 (open symbols) and 25˚C (closed symbols).*

Figure 1 clearly shows that a higher solids content leads to higher pipe pressure losses (that is, a higher pipe wall shear stress for a corresponding pipe flow shear rate). There was remarkable agreement between the onsite pressure loss measurements (x) and the RARES measurements (diamonds) for the same sample tested at lab-scale, giving confidence in the data collected because the onsite measurements were considered to be most direct/reliable. To size a pump, a pipe flow velocity (V, units of m/s) is arbitrarily selected (say at 1-2 m/s) and the corresponding pipe flow shear rate is calculated =8V/D for a known pipe internal diameter (D, units of meters). The corresponding τ_w value is then read off Figure 1 for a specific solids concentration and the pipe pressure loss estimated = τ_w x 4/D (with units of Pascals per meter of pipe length). The practicality of pumping sludge at a particular solids concentration can then be assessed. Note that the Figure 1 datasets are valid for ID 96mm (PN 10 110mm OD pipe) or smaller. As an example, the onsite measurements were at a flow velocity of 0.6m/s with pipe length L = 430m (so 8V/D = 8x0.6/0.096 = 50 s^{-1}, read off τ_w = 10 Pa, and ΔP = 10x4x430/0.096 = 179,000 Pa = 1.79 bar).

BIRCHALL, S. (2010). “Biogas Production by Covered Lagoons”, (RIRDC Publication No. 10/023: Canberra).

SKELLAND, A.H.P. (1967). “Non-Newtonian Flow and Heat Transfer”, (Wiley: New York).

Supported in part by Australian Pork Ltd (Project #2012/1029) and a Pork CRC Fellowship. The covered lagoon sludge samples were from the Don KRC/piggery site A piggery.
Submitted to Australasian Pig Science Association conference 2013

Appendix C – Z-Filter Westpork Trial