Improved Conditioning for Biosolids Dewatering in Wastewater Treatment Plants

by

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A thesis submitted to fulfilment
of the requirements for the degree of
Master of Engineering (by Research)

UNIVERSITY OF TECHNOLOGY, SYDNEY

University of Technology, Sydney

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July, 2015

CERTIFICATE OF ORIGINAL AUTHORSHIP

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ACKNOWLEDGEMENT

I would like to express my special appreciation and thanks to my principal supervisor Dr. Tien Vinh Nguyen and my co – supervisor Professor Saravanamuthu Vigneswaran. I would like to thank them for encouraging my research and for allowing me to grow as a research scientist. Their advice on both research as well as on my career have been priceless. Without their supervision and constant help this thesis would not have been possible.

I would also like to thank all academic staffs of The Centre for Technology in Water and Wastewater (CTWW) for their valuable advices, comments, suggestions as well as encouragement during my study. A special thank to Mohammed Jorhir, laboratory manager, for his useful helps and advice for my research. I also want to thank Dr Nga Pham, Dr S. Jeong, Thuy Chung Nguyen for their helpful guidance of laboratory skills. Thanks to all my colleagues of CTWW for their support and encouragement.

In addition, I would like to thank Professor Long Nghiem and all colleagues in School of Civil Mining and Environmental Engineering, University of Wollongong, for assisting with Modified Centrifugal Index (MCI) tests and also to MAU (Microstructural Analysis Unit), Faculty of Science, University of Technology, Sydney for their technical support.

My special thanks to Sydney Water Corporation for their supports of both finance and knowledge for my research. My great appreciation for Dr. S. Murthy, Innovations Chief for the District of Columbia Water and Sewer Authority (DC Water) and Prof. M. Higgins from Buckell University, US, who have significant experience in the research

area, by virtue of their helpful consultancy for my study. Also, a grateful thank to UTS International Research Scholarship (UTS IRS) for tuition fee support for my study of Master Degree.

The last but not least, I would like to send my special thanks to family and all of my friends. They were always supporting and encouraging me with their best wishes.

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NOMENCLATURE

G = Velocity gradient (s^{-1})

g = Times gravity

R^2 = Correlation coefficient

LIST OF ABBREVIATIONS

ADS	Anaerobically Digested Sludge
AEDS	Aerobically Digested Sludge
BOD	Biochemical Oxygen Demand
CST	Capillary Suction Time
DS	Dry Solids
MCI	Modified Centrifugal Index
OPD	Optimal Polymer Demand
PD	Polymer Demand
rpm	revolution per minute
sCOD	Soluble Chemical Oxygen Demand
sP	Soluble Protein
sPS	Soluble Polysaccharides
SS	Suspended Solids
VS	Volatile Solids
WAS	Waste Activated Sludge
WWTP	Wastewater Treatment Plant
ZP	Zeta Potential

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ABSTRACT

The aims of this study were to (i) characterize different sludge types, which were anaerobically digested sludge (ADS), aerobically digested sludge (AEDS) and waste activated sludge (WAS) obtained from 3 Wastewater Treatment Plant (WWTP) of Sydney Water, Australia, for the purpose of determining feasible correlations of sludge properties with polymer demand (PD) for sludge conditioning and dewatering, and (ii) apply a new method, namely “Modified Centrifugal Index” test, in evaluating the dewaterability of these sludges after dewatering as well as determining optimal polymer demand (OPD). Besides polymer conditioning, the study also (iii) investigated several conditioning methods using other chemicals such as dual conditioning (Cationic/Anionic polymers and Iron/cationic polymer conditionings) and Fenton oxidation for improving/maintaining sludge dewaterability while reducing the chemical cost of sludge treatment.

It is believed that a comprehensive understanding of the sludge characteristics is essential for optimizing the dewatering process. The study results of sludge characteristics show that ADS required the highest polymer demand for conditioning compared to the other sludge types studied. On the contrary, WAS required the least amount of polymer. The study also proved that there were good correlations between soluble biopolymers (mainly protein and polysaccharides) and OPD, which highlights the major role of soluble biopolymers in deciding polymer demand for sludge conditioning. Besides, these relationships could provide helpful information on suitable polymer types and dosages for an effective sludge conditioning.

Although CST is the most common parameter to evaluate the solid – liquid separation ability, it is often not a reliable indicator. In this study, a modified laboratory – scale centrifuge apparatus was employed. The experimental results show that Modified centrifugal index (MCI) test can be successfully used to evaluate the dewaterability of different sludge types with and without conditioning by estimating the maximum solids cake achievable by the centrifuge. After conditioning and centrifuge, solids contents were increased from 16% to almost 30% for ADS and from 19% to 23% for WAS. These values were similar to the results observed in real WWTPs. This demonstrates that MCI measurement is good to estimate the final cake concentration as well as simulate the real centrifuge process. This method can also help to determine optimal polymer demand (OPD) required for sludge conditioning.

Based on both CST and MCI tests, lower polymer doses than currently used ones were found to be suitable for sludge conditioning of these 3 WWTPs. This could lead to an implication of reducing a significant amount of expensive cationic polymers for sludge conditioning at these plants.

Conditioning methods using other chemicals (besides cationic polymers) which are also promising solutions for replacing expensive conditioners in the WWTPs were demonstrated to improve sludge dewaterability in term of CST. However, full – scale trials or MCI test are needed in the future study to confirm this finding.

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CHAPTER 1

INTRODUCTION

1.1. Background

In recent decades, the quantities of sludge produced are staggering due to the rapid growth of industrialization and population, causing much of fear in the modern society (Sanin et al. 2011). As a result, various efforts have been made to search for sustainable solutions to tackle this problem. Sludge treatment and disposal were used to be considered merely as a component of water and wastewater treatment and there seemed to be not sufficient attention paid on this thought–to–be–unimportant subject. However, as a consequence of increasingly stricter regulations on sludge disposal along with significant developments of technology, this subject has been becoming no longer a part but an independent field of study (Gurjar 2001).

The biosolids treatment, transport and disposal are costly major components of Wastewater Treatment Plants (WWTPs) that account for more than half of treatment cost of the whole WWTPs (Davis & Hall 1997, Spellman 1997, Wei et al. 2003). This fact leads to a need of minimizing these costs by reducing biosolids generated. There have been two solutions for sludge minimization:

- Option 1: Optimization of sludge treatment process, especially conditioning and dewatering
- Option 2: Reduction of excess sludge production during wastewater treatment either by reducing provision of oxygen in aerobic processes (Yoon et al. 2004) or increasing sludge age in MBR (Laera et al. 2009)

Option 2 seems to be quite promising since it results in an immediate savings in sludge disposal and scaled down downstream processes (Paul & Liu 2012). However, additional studies, especially full–scale trials, are necessary to identify an optimal condition where wastewater treatment efficiency and sludge generation rate are balanced. Although option 1 is widely used in the WWTPs, there is a challenge in predicting dewatering performance and thus reducing the chemical cost.

Two major difficulties have been attributed to this problem. Firstly, sewage sludge possesses highly complex and unpredictable nature. In fact, there are numerous factors having impacts on dewatering characteristics of sludge (Karr & Keinath 1978, Mowla et al. 2013), which makes it even more complicated and difficult in controlling as well as predicting dewatering performance. As a result, an inclusive profile of sludge properties is necessary to elucidate factors which are of greatest concern for both sludge conditioning and dewatering. Secondly, there seems to be no reliable indicator for dewatering efficiency yet, especially for centrifuge dewatering. Thus, a good dewaterability indicator should have ability to simulate the real dewatering process as well as predict the maximum cake solids content achievable by that process.

It has been known that conditioning treatment is necessary for most of sludge types with the aim of enhancing water removal rate of dewatering processes. The amount of water residue in the biosolids is directly proportional to the subsequent cost of transportation and any further treatments. However, the conditioning for biosolids dewatering in many WWTPs has not been optimized yet and the dewatered cake produced still has high water content. As a result, it is important to optimize the conditioning and dewatering processes to minimize the water content, or in other words to maximize the cake solid content, and reduce the quantities of biosolids produced. These ultimately lead to reducing costs for biosolids handling and transport as well as undesirable impacts of biosolids to environment (Feng et al. 2009).

Although cationic polymers are primarily used for sludge conditioning, they are still considered as expensive chemicals. Therefore, reducing these agents by using either combinations of cationic polymers with cheaper conditioners or alternative conditioners such as oxidation agents could be promising solutions for minimizing the chemical cost of sludge treatment while maintaining or even improving sludge dewaterability.

1.2. Research objectives

Based on the above mentioned research gaps, the present study was carried out with 5 main objectives:

- Obtaining comprehensive knowledge on characteristics of different sewage sludge types collected from different WWTPs of Sydney Water Corporation;
- Determining relationships of sludge properties with sludge dewaterability and polymer demand for conditioning in order to identify the most influencing factors of sludge dewatering and conditioning;
- Determining optimal conditioning regimes (polymer types, optimal polymer demand (OPD) and mixing intensity) that lead to the best dewatering performance of each sludge type studied;
- Developing a new method of estimating the ultimate cake solids content achievable by centrifuge dewatering, namely Modified Centrifugal Index (MCI);
- Assessing efficiency of different chemical conditioning methods by performing conditioning experiments with different conditioning agents (cationic and anionic polymers, iron and hydrogen peroxide).

1.3. Scope of the study

The study was performed on feeding sludges (unconditioned ones) and by–products (dewatered cake and centrate/filtrate) of dewatering processes at 3 WWTPs of Sydney Water Corporation which were St Marys, Quakers Hill and Wollongong WWTPs. The selection of these WWTPs was based on (i) different sludge types and (ii) opportunities to improve dewatering at these WWTPs where dewatering has been a problem.

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CHAPTER 2

LITERATURE REVIEW

2.1. Sewage sludge

2.1.1. Classifications, sources and quantities

Sewage sludge is an inevitable by–product of wastewater treatment. However, recently, the quantities of sludge produced are dramatically rising due to increasingly stringent wastewater treatment standards and the expansions of sewerage connections. According to the 2013 survey, the total sewage sludge generation of Australia was about 1.3 million wet tonnes of biosolids which was 200,000 tonnes more than that produced in 2010 (Australian & New Zealand Biosolids Partnership 2013). This led to significant costs of sludge handling and transports as well as undesirable impacts of biosolids on the environment.

Sewage sludge quantities as well as characteristics depend not only on types and levels of wastewater treatments but also on the quality of the influent and effluent (Sanin et al. 2011, Gurjar 2001). A previous study of Xie et al. (2005) showed that the amount of sludge produced is a function of residual phosphorus concentration in wastewater (Figure 2–1). It means when reducing phosphorus content in water to near zero, the sludge solids content is greatly increased. The dependence of sludge characteristics on various factors leads to a complex nature of sewage sludge (Colin et al. 1988) that becomes increasingly troublesome to all sludge treatment technologies.

Figure 2–2 shows a typical wastewater treatment system and sludge generation from different treatment processes. These processes can be categorized into primary treatment, secondary treatment and tertiary treatment. Different typical types of sludge generated from these sources are classified (Sanin et al. 2011) as:

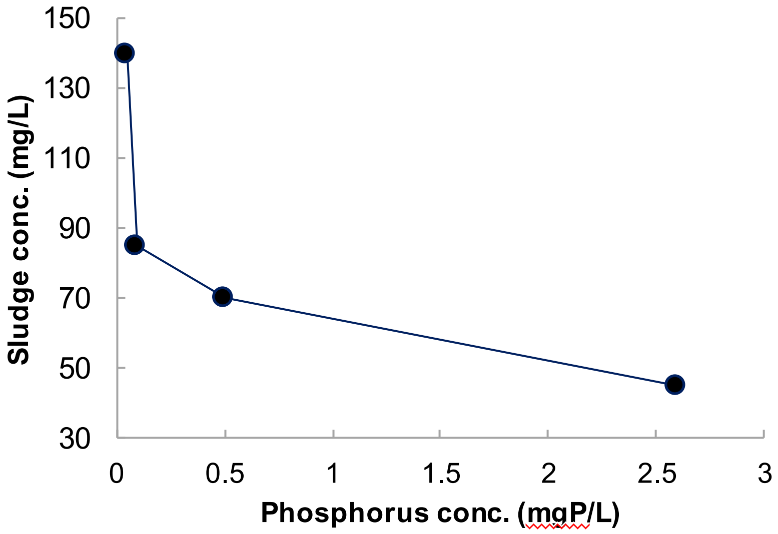


Figure 2–1 Relationship of sludge solids concentration with residual phosphorus concentration (Xie et al. 2005)

- **Primary sludge**: is produced from the settling process
- **Biological sludge**: is produced from the biological treatment of wastewater, made of a mixture of microorganisms. Part of it is recirculated to the reactor while the excess biological sludge is sent for dewatering
- **Mixed sludge**: is a blend of primary and biological sludges
- **Digested sludge**: is produced from a biological stabilizing stage called digestion which is carried out on biological or mixed sludge
- **Physico–chemical sludge**: is produced from physico–chemical treatment (coagulation and/or flocculation) of wastewater. Aluminum sulphate (alum), the most widely used flocculant in water treatment, produces waste alum sludge.
- **Tertiary sludge**: is produced from tertiary treatment of wastewater such as removal of phosphate and specific compounds (pesticides, metals, detergents, etc.)

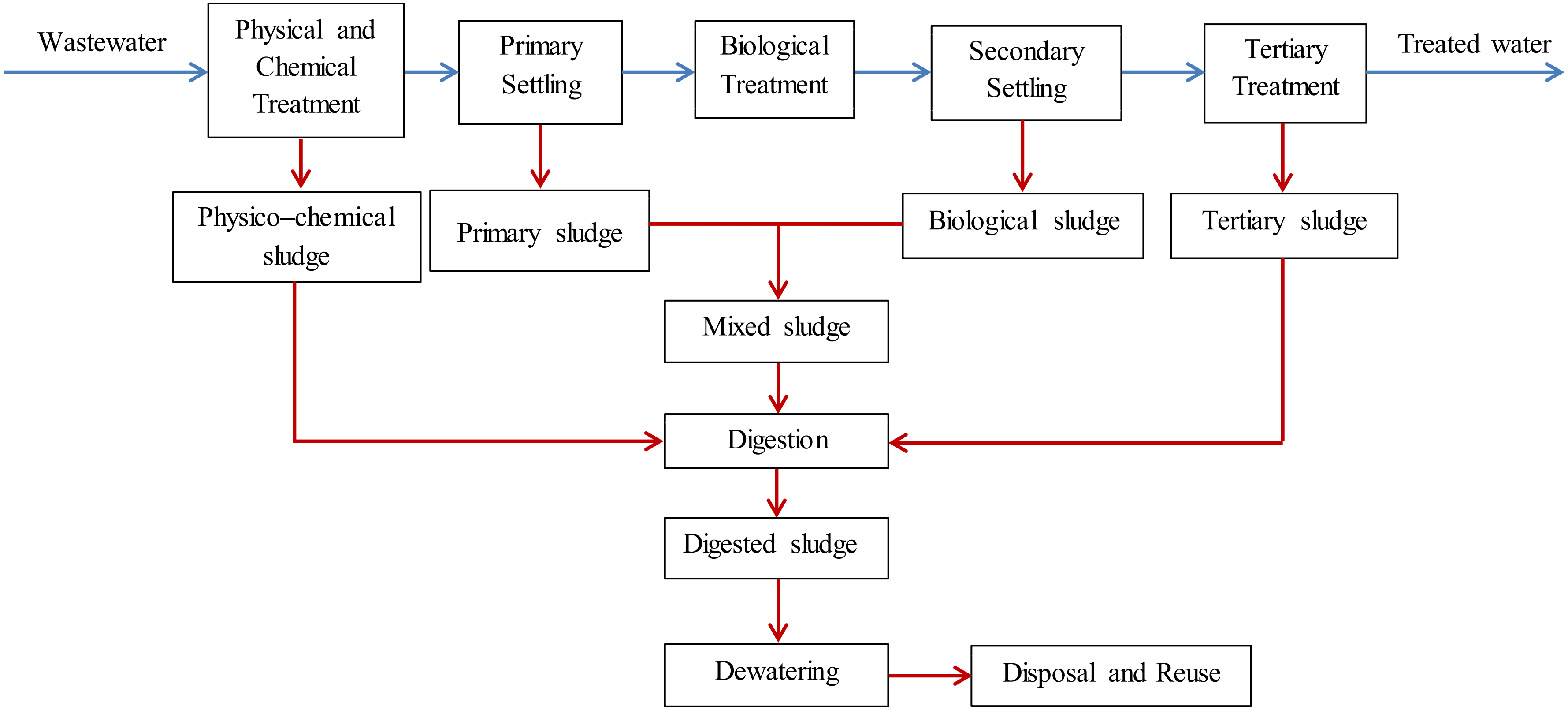


Figure 2–2 A typical wastewater treatment process and sludge generation

Each kind of sludge has specific properties and their treatment processes basically depend on their characteristics. This highlights the need for characterizing these sludges in order to better understand the factors that affect efficiency of sludge treatment.

2.1.2. Sludge characteristics

Sewage sludge generally possesses a highly complex nature with wide variations in their physical, chemical and biological characteristics (Colin et al. 1988). This attributes to their unpredictable behaviour which is one of the most difficult and elusive challenges for sludge treatment systems of WWTPs. Besides, it is relatively difficult to quantify most of characteristic parameters (Sanin et al. 2011). However, a comprehensive understanding of these properties is essentially important to identify the most influencing parameters and evaluate their effects on treatment processes.

Table 2–1 Sludge characteristic parameters

Physical characteristics	Chemical characteristics	Biological characteristics
- Color and odor - Specific gravity - Settleability - Drainability - Floc/Particle size & shape - Water distribution - **Filterability & Dewaterability** - Rheology - Floc structure & porosity - Floc density - Thermal conductivity - Fuel value or thermal content - Compressibility - Viscosity	- pH - Alkalinity - Solids concentration - Surface charge & hydrophobicity - Nutrients & fertilizer value - Heavy metal & toxic organics - Digestibility - Fat content	- Microbial community - Surface polymers/ Extracellular Polymeric Substances (EPS) - Sludge stability

Sources: Sanin et al. (2011), Gurjar (2001)

In sludge treatment systems, after being pre–treated by thickening, digestion and conditioning, sludge is often dewatered before any further processing occurs such as incineration, composting and landfill (Water Pollution Control Federation 1985). This will result in reduced sludge volume and, consequently, the reduced cost of transportation (Feng et al. 2009). Sludge dewatering is still a major challenge particularly in designing sludge treatment systems due to the highly complex nature of sewage sludge. Many factors influence dewatering characteristics of sludge (as briefly summarized in Table 2–1); however, there seems to be still a lack of consensus on which ones are the greatest concern for sludge dewatering. This makes it even more complicated and difficult in assessing dewatering performance correctly. Many attempts to identify a proper indicator to truly reflect the efficiency of dewatering process have been carried out by establishing relationships between these influencing factors and sludge dewatering properties (Peng et al. 2011, Jin et al. 2004).

The terms ‘filterability’ and ‘dewaterability’ have been used frequently to describe the ability to dewater of sludge (Sanin et al. 2011) and there seem to be no clear distinction in the use of these two parameters. Sludge filterability and dewaterability are often mentioned together and sometimes interchangeable, which possibly results in confusion and misunderstanding. Bürger et al. (2001) defined filtration as a mechanical method which is commonly applied for solid–liquid separation while Mowla et al. (2013) stated that improving sludge cake filterability is one of different ways to enhance biosludge dewaterability. These could imply that filterability should have been used for measuring the efficiency of filtration process only instead of the whole dewatering effectiveness.

Table 2–2 Characterization of common wastewater sludges and their dewaterability

Sludge types	Characteristics
Raw primary sludge	Gray–brown; bad odor; does not drain well on drying beds, but can be dewatered mechanically; high concentration of pathogenic organisms
Anaerobic primary digested sludge	Black; musty; produces gas; dewaters well on drying beds
Filter humus	Brown; fluffy
Waste activated sludge	Yellow–brown; fluffy; little odor; difficult to dewater; very biologically active
Mixed digested sludge (Primary + Waste activated sludge)	Black – brown; produces gas; musty; not as easy to dewater as digested primary sludge
Aerobic digested sludge	Yellow–brown; sometimes difficult to dewater; biologically active
Waste alum sludge	Gray–yellow; odourless; very difficult to dewater

Source: Sanin et al. (2011)

Dewaterability indicates for the final water content or the maximum solid content achievable of sludge cakes since reducing sludge volume is the ultimate target of dewatering. Nonetheless, in many previous studies, sludge filterability has been used to primarily decide the output of dewatering process (Scholz 2005, Yukseler et al. 2007, Sawalha & Scholz 2010). Hence, traditionally used dewatering indexes are developed for assessing filterability of sludge mainly (Vesilind 2000). This may cause significant errors and inaccuracies in evaluating the efficiency of dewatering.

2.2. Sewage sludge treatment

It was reported that the costs of sludge treatment, transport and disposal can take up 50 – 60% total cost of wastewater treatment in the WWTPs (Wei et al. 2003). Therefore, it is necessary to minimize the sludge produced as much as possible. Increase in cake solids content from 2% to 30% can help reduce more than 90% volume of sludge (Figure 2–3). This may lead to a significant saving of transportation cost.

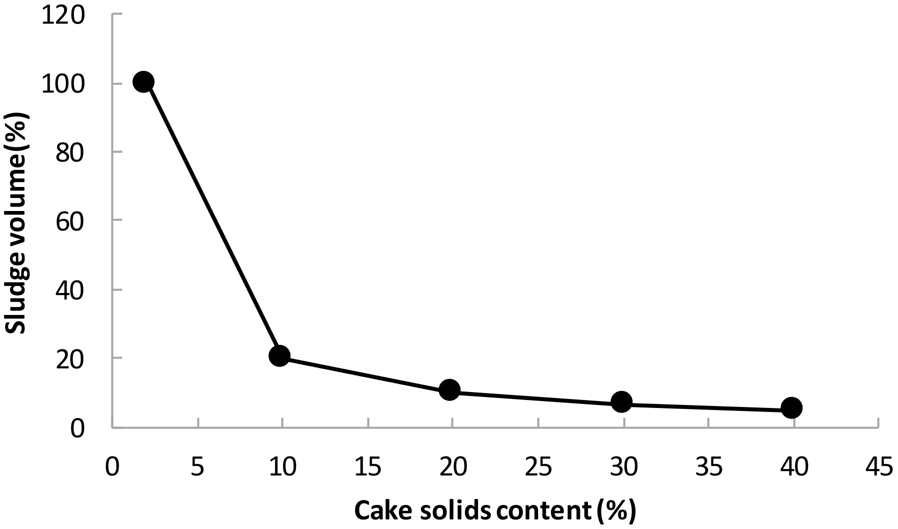


Figure 2–3 Relationship of cake solids content and sludge volume

Figure 2–4 displays a typical sludge treatment process. It is believed that optimization of this process, especially conditioning and dewatering, could result in minimization of biosolids produced before being sent to further treatments for biosolids disposal and reuse. Main stages of the processes (such as thickening, stabilization, conditioning and dewatering) will be discussed in more detail in the following sections.

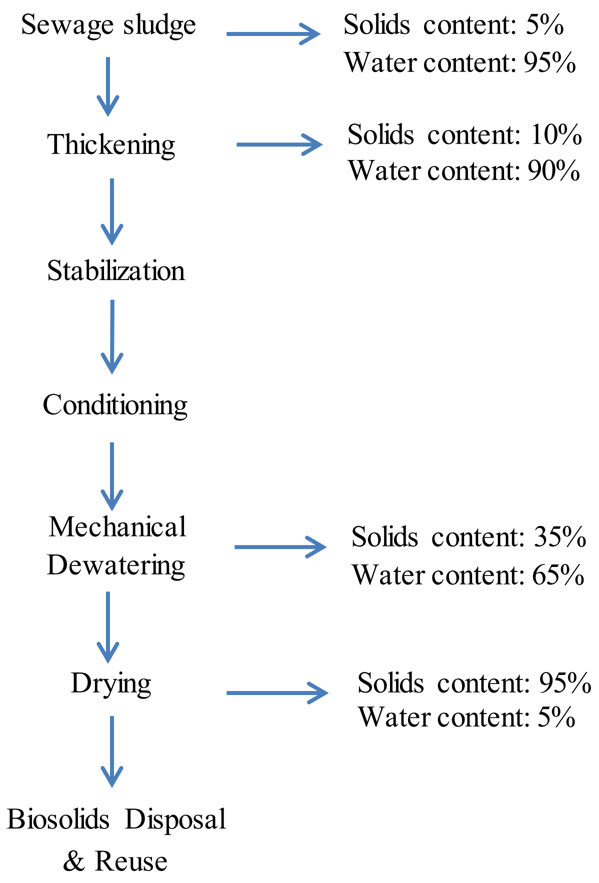


Figure 2–4 A typical sludge treatment process and dry solids content of sludge after different treatment steps (Manzel 1989)

2.2.1. Sludge thickening

The purpose of thickening process is to reduce the biosolids volume to be stabilized, dewatered or transport (Water Pollution Control Federation 1980). There are several methods of sludge thickening which were described in detail by Sanin et al. (2011). They are:

- **Gravitational Thickening**: uses gravity to compact sludge solids. It is typically carried out in a tank which resembles a settling tank, therefore, works best with heavy sludge such as raw sludge.
- **Floatation Thickening**: uses tiny air bubbles created by a dissolved air floatation system, which is often used to thicken activated sludge before digestion.
- **Gravity Belt Thickening**: is a solids–liquid separation process that relies on coagulation and flocculation of a dilute sludge and drainage of free water from sludge through a moving fabric–mesh belt. The method works well with most types of sludge, especially WAS.
- **Centrifugal Thickening**: uses the centrifugal force to separate solid and liquid, effective for thickening WAS.

For stabilization, a thicker sludge would lead to smaller digesters, which help to save a significant cost of expensive commodity in wastewater treatment as well as bisolids transport. For dewatering, thickening substantially removes the soluble biopolymers attached to the liquid phase which are considered as the major reason for a poor dewaterability of sludge (Shammas & Wang 2007). Besides, it has been proved that the moisture of dewatered cake decreased with the increase in feed solids content of sludge (Figure 2–5), showing the importance of thickening before mechanical conditioning.

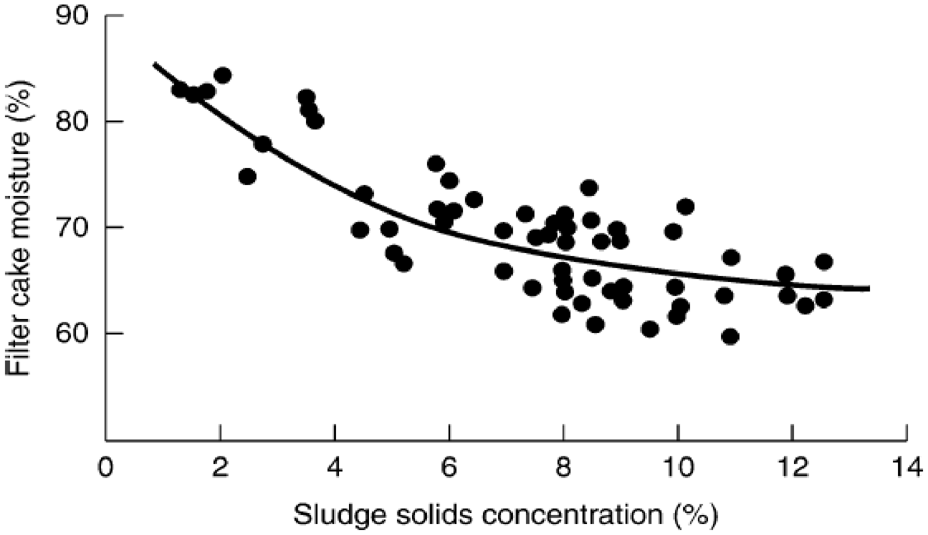


Figure 2–5 Effects of feeding solids on performance of a rotary vacuum filter (EPA 1984)

Although both thickening and sludge dewatering result in sludge volume reduction, the difference is the degree of reduction. Thickening can be defined as the concentration of solids to less than 15% while dewatering to greater than 15% (Sanin et al. 2011). Table 2–3 summarizes typical solids concentration achieved by various thickening methods.

Table 2–3 Typical solids concentration for various thickening methods

Thickening methods	Solids concentration (%)	
	Range	Typical
Gravity thickening		
- Primary sludge	4–12	6
- WAS	2–4	3
- Combined primary and WAS	2–6	4
Floatation thickening of WAS		
- With chemicals	4–6	5
- Without chemicals	2–5	4
Gravity Belt thickening of WAS		
- With chemicals	4–6	5
Centrifuge thickening of WAS		
- With chemicals	4–8	5
- Without chemicals	3–6	4

Source: Turovskiy and Mathai (2006)

2.2.2. Sludge stabilization

Stabilization is commonly used for reducing detrimental undesirable effects of sludge on environment, including the elimination of pathogens and the reduction of volatile solids (or biodegradable organic matter), and offensive odours (Novak et al. 2003). These three parameters are often used as measures of sludge stability. Stabilization methods are classified into 3 main categories (Sanin et al. 2011):

- **Biological stabilization**: anaerobic digestion, aerobic digestion, composting, vermistabilization
- **Chemical stabilization**: lime stabilization, chemical fixation, chlorine oxidation, wet air oxidation
- **Physical stabilization**: heat stabilization, irradiation

Among these methods, digestions are the oldest and most widely used processes for wastewater sludge stabilization. Table 2–4 presents advantages and disadvantages of the two conventional digestion processes which are aerobic and anaerobic digestions. The former is often used in wastewater treatment plants with average flows less than 20,000m^3/d while the latter is applied for plants treat greater than 20,000m^3/d (Turovskiy & Mathai 2006). Despite of high capital cost, anaerobic digestion is still a preferred option compared to aerobic one by virtue of highly stability of anaerobically digested sludge and useful by–product (Biogas).

Table 2–4 Comparison of anaerobic and aerobic digestions

Digestion processes	Advantages	Disadvantages
Anaerobic digestion	Methane gas produced is a source of usable energy 30–65% of raw sludge solids are destroyed => reduce cost of sludge disposal Digested sludge free of offensive odors Digested biosolids contain nutrients and organic matter => improve soil fertility High rate of pathogen distribution	High capital cost Large reactors required Anaerobic microorganisms are sensitive to small changes in the environment Produces a poor quality side-stream, especially dewatering
Aerobic digestion	Low capital cost Odorless end product VS reduction slightly less than that of anaerobic digestion Easier to operate Lower BOD, TSS and ammonia nitrogen in supernatant liquor No potential for gas explosion and less potential for odor problems	The operating cost is higher (power cost for supplying oxygen required) Methane gas is not produced Dependent on temperature (efficiency reduced during cold weather) Performance affected by solids content, sludge type, location and type of mixing–aeration system

Source: Turovskiy and Mathai (2006)

In the past, most of researches mainly focused on the efficiency of digestions processes themselves rather than on their effects on downstream processes such as conditioning and dewatering. Some studies indicated that digestion generally improves sludge dewaterability (Rudolfs & Heukelekian 1934, Brooks 1970, Lawler et al. 1986), while other studies have reported both aerobic and anaerobic digestions lead to poor dewaterability of sludge as well as high polymer demand for sludge conditioning (Novak et al. 1977, Katsiris & Kouzeli-Katsiri 1987, Bruss et al. 1993). Several investigators proposed the reason for these negative effects that anaerobic digestion results in the change of particle size distribution which is one of the key factors in controlling sludge dewaterability (Karr and Keinath 1978, Nellenschulte & Kayser 1997). The high polymer demand for conditioning of digested sludge is attributed to the increase in soluble biopolymers, mainly protein and polysaccharides, which are released into supernatant solution during digestion (Novak et al. 2003). These protein and polysaccharides take up a major portion of polymers used for conditioning and make them unavailable for flocculation of the sludge particles.

2.2.3. Sludge conditioning

Conditioning is necessary for improving solid–liquid separation of mechanical thickening and dewatering of sludge. Conditioning of sludge can be performed by physical or chemical processes, as listed in Table 2–5. These methods are used to change the sludge characteristics to achieve high dewatering performance in 3 different ways (Mowla et al. 2013):

- Coagulation/flocculation of sludge particles => improve settleability
- Reducing sludge compressibility => improve cake filterability
- Disintegration of sludge flocs or cells => release trapped water

Chemical conditioning with either organic (polymers) or inorganic (Ferric chloride, lime, alum) additives have been widely used for sludge treatment in most of WWTPs. Whilst, other conditioning methods are used for laboratory–scale researches and rarely applied in full–scale.

Factors affecting efficiency of chemical conditioning processes and selection of suitable conditioners for effective thickening or dewatering include:

- Sludge type and properties (solids concentration, particle size and distribution, surface charge and degree of hydration, etc.)
- Conditioner type and properties (polymer molecular weight, charge type, charge density, etc.)
- Solution physical chemistry: greatly influences both organic and inorganic conditioners. pH and alkalinity primarily affect the performance of inorganic additives.
- Other factors: Thickening or dewatering methods, storage, pumping, mixing conditions.

Table 2–5 Summary of sludge conditioning methods

Conditioning methods	Descriptions
Physical conditioning	
Non–chemical additives	Addition of some high porous inert minerals (fly ash, lime, gypsum) or carbonaceous materials (coal, wood chips, wheat dregs, lignite, etc.) which act as skeleton builders or filter aids => improve mechanical strength and permeability of solids during compression
Cavitation pre–treatment	Producing a shock wave causing high temperature (500–15,000K) and high pressure (10–500MPa) locally in the media at a lifetime of a few microseconds => desired changes in biological processes. Effective methods of cavitation generation are acoustic and hydrodynamic cavitation
Thermal pre–treatment	Liquid sludge is heated up in the temperature range 60–180^{o}C => sludge gel network is broken and water affinity of the sludge solid is decreased
Freeze/Thaw pre–treatment	Sludge is first frozen around -15^{o}C and kept at this state for some time, then it is thawed at room temperature => change floc structure and reduce bound water content in sludge
Elutriation	Sludge is washed either by fresh water or plant effluent to reduce sludge alkalinity and fine particles => decrease coagulant amount required
Chemical conditioning	
Polymer conditioning	Addition of polyelectrolytes (polymers) => improve mechanical dewaterability of sludge. Conditioning process could be explained by 2 mechanisms: charge neutralization and inter-particle bridging. There are 3 types of polymer: cationic, anionic and non–ionic
Other chemical conditioning	
- Inorganic additives	Addition of inorganic chemicals (ferric chloride, lime, alum) or oxidizing agents (ozone (sludge ozonation) or Fenton and Fenton–like reagents (advanced oxidation process))
- Dual conditioning	Addition of different polymer types (Cationic/Anionic, Cationic/Non–ionic) or both organic and inorganic agents (Cationic/Ferric Chloride) => exploit advantages of each conditioner

Sources: Mowla et al. (2013), Wang et al. (2007), Metcalf et al. (1991)

2.2.4. Sludge dewatering

The objective of sludge dewatering is to remove as much water as possible from the sludge, leading to the reduction of biosolids volume and, as a result, the cost of transport. Dewatering of sludge is often required prior to thermal drying or incineration to reduce fuel demand as well as landfill disposal to minimize leachate production (Turovskiy & Mathai 2006).

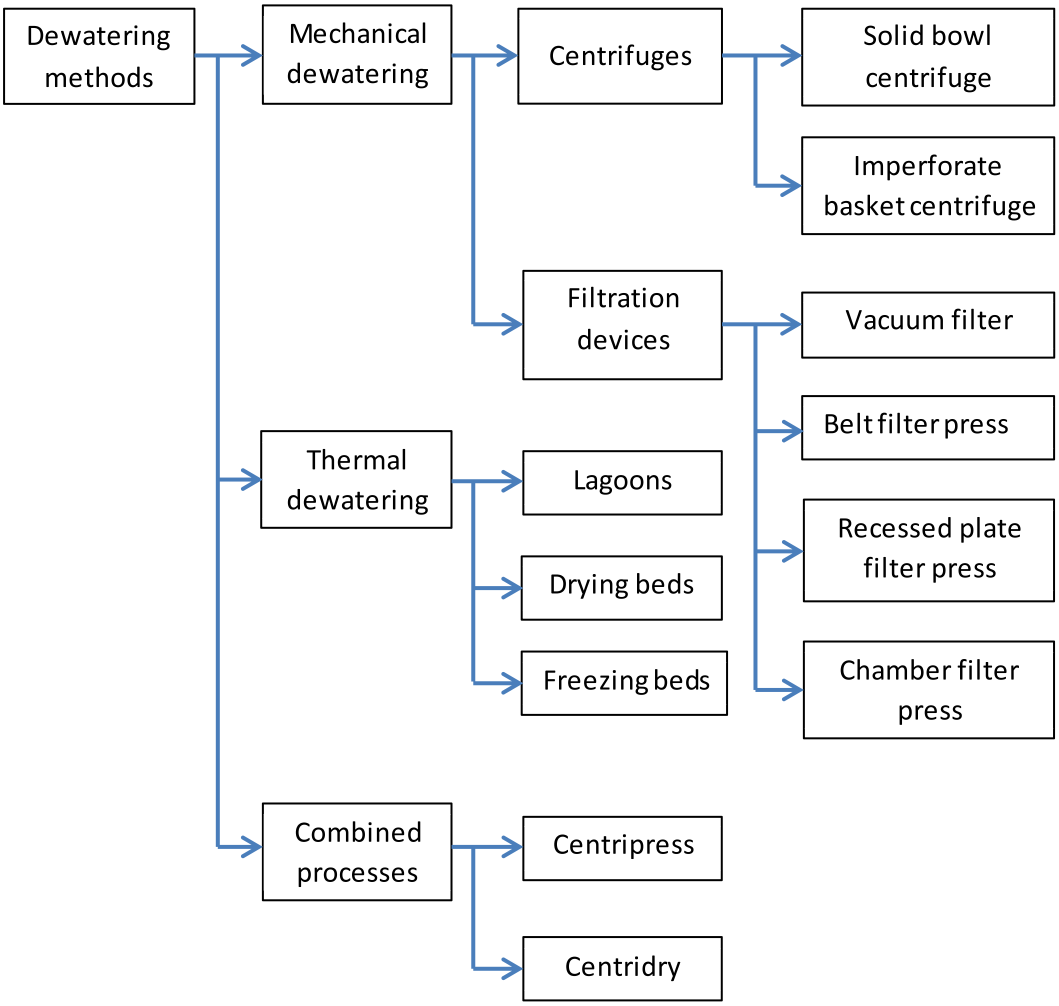


Figure 2–6 Summary of dewatering methods (Sanin et al. 2011, Turovskiy & Mathai 2006, Vigneswaran & Ben Aim 1989)

Dewatering processes that are commonly used include mechanical processes and thermal processes (Figure 2–6). Before mechanical dewatering, sludge often requires conditioning treatment to enhance water removal. The selection of particular process is based on sludge volume and characteristics. When taking economy into consideration, mechanical dewatering processes are preferred over thermal ones (Wakeman 2007). Table 2–6 summarizes the relative merits of different mechanical dewatering devices.

There are two main parameters used as representatives of dewatering performance, which are solid cake concentration and centrate quality. Since one of the crucial roles of dewatering process is to increase the solid content of sludge in order to reduce the sludge volume, dry solid content should be defined as a parameter representing for the efficiency of the process. Whilst, centrate quality reflects the efficiency of the capture of solids during the conditioning and dewatering process, especially when centrifuge is used as dewatering process. For successful operation of the sewage treatment, it is important to remove as much solids as possible during conditioning and dewatering. This minimizes the recycle of solids to the plant inlet when the centrate is sent back to the head–of–works. The target of sludge dewatering in all sewage treatment plants is to produce a clear centrate while also achieving a cake high in solids (Sanin et al. 2011).

Table 2–6 Comparison of typical mechanical dewatering equipment

Dewatering Equipment	Cake solids content (%)		Solids capture efficiency (%)		Advantages	Disadvantages
	Range	Typical	Range	Typical		
Vacuum filter					Skilled personnel not required Maintenance requirements are low for continuously operating equipment	Highest energy consumed per unit of sludge dewatered Continuous operator attention required Vacuum pumps are noisy
- With chemicals	15–30	20	90–98	95		
Belt filter press					Relatively low capital, operating and power costs Simple to manage and maintain Easier to shut down the system	Low levels of dry matter achievable Very sensitive to feeding sludge properties Sensitive to polymer type and dosage rate Significant consumption of belt wash water Short media life compared to other devices using cloth media
- With chemicals, raw sludge	18–30	23	90–98	95		
- With chemicals, digested sludge	12–25	18	90–98	95		
Pressure filter press					High cake solids content Efficient capture of solids Good dewatering process for hard–to–handle sludge	Batch operation, high capital and labor costs Require skilled maintenance personnel Often require inorganic chemical conditioning that produces additional solids
- With chemicals	20–50	38	90–98	95		
Centrifuge					Produces relatively dry sludge cake Relatively less space required Fast start-up and shutdown capabilities Does not require continuous operator attention Clean appearance and minimal odor problem	Relatively high capital cost Consumes more direct power per unit of product produced Requires grit removal from feed sludge and possibly sludge grinder in the feed stream Requires periodic repair of scroll Requires skilled maintenance personnel Moderately efficient capture of solids
- With chemicals	15–35	24	85–98	92		
- Without chemicals	10–30	18	55–90	80		

Sources: Metcalf et al. (1991), Turovskiy and Mathai (2006)

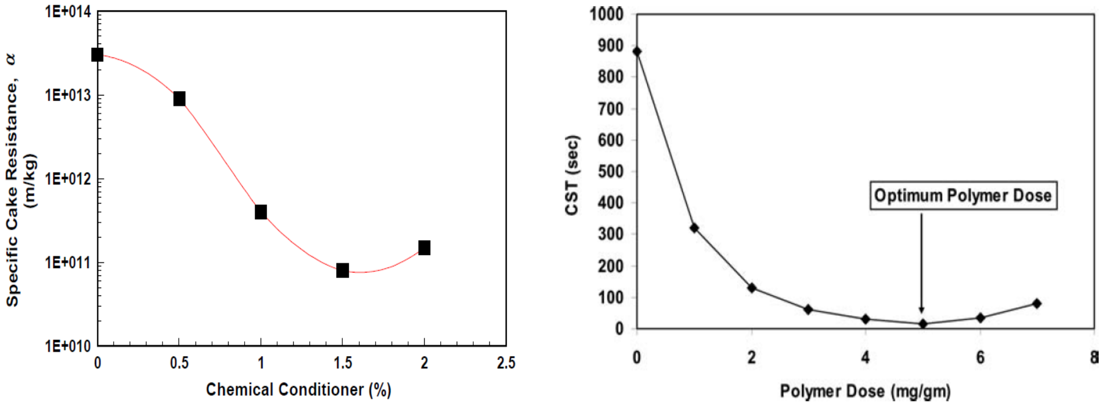
2.3. Chemical conditioning of sludge

2.3.1. Polymer conditioning

2.3.1.1. Polymer demand for conditioning

It has been known that conditioning treatment is necessary for most of sludge types to enhance their dewaterability. The biosludges, in particular, are proved to be naturally difficult to dewater. Among various conditioning methods, polymer conditioning has been the most frequently used for mechanical dewatering.

The polymers used in water treatment systems are classified as anionic, cationic or non-ionic (Mowla et al. 2013). Charge neutralization and bridging formation are 2 key mechanisms for conditioning, and the optimal polymer demand (OPD) theoretically occurs when particle charge is neutralized. The OPD for a given sludge in one treatment plant may be different from that of the same sludge in another plant due to the difference in operation of dewatering devices. The required polymer demand for conditioning of a particular sludge is typically determined by using bench–scale tests (such as Capillary Suction Time (CST) or Specific Resistance to Filtration (SRF)). The minimum cake resistance or CST corresponds to the OPD (Figure 2–7). These indicators are discussed more detail in section 2.4.2.



(a) (b)

Figure 2–7 Determination of optimal polymer dose for sludge conditioning using (a) SRF (Sanin et al. 2011) and (b) CST measurements (Novak 2006)

Past studies in the plant focused on optimizing the conditioning regimes, such as polymer types, optimal polymer demand, mixing intensity, and neglected the effect of dewatering devices on conditioned sludge (Vaxelaire & Olivier 2006). Novak et al. (1999) reported that the two fundamental equipment used for sludge dewatering, which are belt filter presses and centrifuges, have different conditioning demands. This implied that the selection of conditioning agents is based on not only the nature of the sludge but also the type of mechanical dewatering system. Higgins et al. (2006) also found that optimal polymer dose depends on the shear intensity of dewatering equipment. However, only a few studies focused on determining the relationships between efficiencies of conditioning and dewatering (Pan et al. 2003).

2.3.1.2. Mixing intensity for conditioning

In order to select the most suitable polymer types and doses for a proper sludge conditioning, the determination of mixing intensity of conditioning process is important. Mixing intensity has been defined as multiplication (or product) of the mean velocity gradient, G (s^{-1}), and mixing time, t (s) (i.e. Gt) (Werle et al. 1984). This unitless parameter, or Gt value, can be used to examine the impact of shear on sludge conditioning (Novak et al. 1988, Novak & Lynch 1990). As mixing intensity increased, polymer demands also increased, which has been considered as the general response of a given sludge to mixing during polymer conditioning. Lynch & Novak (1991) stated that shear occurring during sludge conditioning, which is represented by Gt values, affects the performance of dewatering devices. They also suggested that it is possible to use the shear or Gt value to characterize dewatering equipment as well as allow polymer doses to be predicted by using a bench–scale mixing device (set at the Gt of the dewatering device used in practice). The G value for a given mixer can be determined by establishing a curve of G versus mixer speed (Figure 2–8), using the method described by Werle et al. (1984).

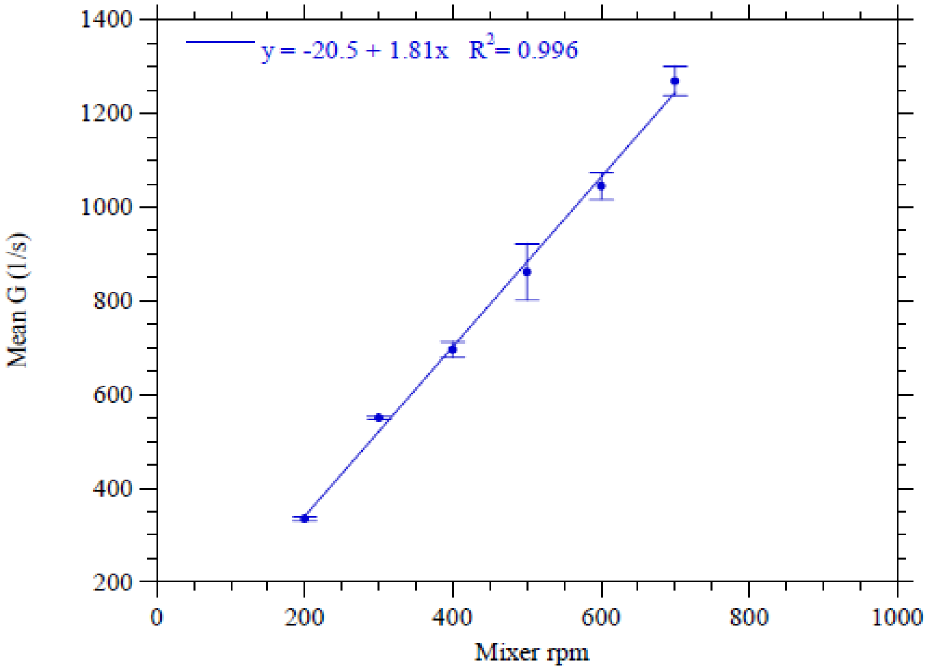


Figure 2–8 Calibration curve for determining velocity gradient (G) as a function of mixer speed (rpm) (Higgins et al. 2006)

2.3.2. Other chemical conditioning methods

2.3.2.1. Dual conditioning

Besides the transportation cost of biosolids, the cost of polymer used for conditioning has been also considered as one of bothersome issues in sludge treatment. Cationic polymers are traditionally used as conditioning agents in the wastewater industry and in sludge conditioning in particular; however, they are still considered as expensive chemicals. For this reason, concurrent with developments of various types of polymers in terms of their functions and costs, one should look for ways to reduce polymer requirement. There are a number of methods to reduce cationic polymer dose in sludge conditioning. Some of the measures are to use combinations of different conditioners or adjusting dewatering operations (Higgins et al. 2006). The use of multiple chemical additives for sludge conditioning may have difficulties in determining proper dose combinations; however, this might help to improve the efficiency of water removal and solids capture of dewatering process compared to the single use of polymers (Chitikela & Dentel 1998, Glover et al. 2004). Dual conditioning where the sludge is treated by using a combination of a cationic polymer and another organic or inorganic conditioner has caught attention of numerous investigators working on this field (Agarwal et al. 2005, Ayol et al. 2005, Fan et al. 2000, Chitikela & Dentel 1998, Senthilnathan & Sigler 1993). This study focused mainly on two dual conditioning methods, namely cationic/anionic polymer conditioning and iron/cationic conditioning.

2.3.2.1.1. Cationic/Anionic polymer conditioning

Among various dual polymer conditioning methods, the combinations of cationic and anionic polymer seems to be the most popular, both from technical and economic points of view. Although the consumption of dual polymers is less in comparison with their single use, however, the total cost of conditioning is not reduced (Sanin et al. 2011). Thus, the major benefit of these dual–polymer systems is to create stronger flocs to better withstand the high shear during dewatering process (Chitikela & Dentel 1998, Lee & Liu 2001). The study of Glover et al. (2004) examining the effect of dual–polymer flocculation by measuring the compressive yield stress of conditioned suspensions showed that dual–polymer flocculants of opposite charge give a higher solids cake than dual flocculants of like charge. Also, Agarwal et al. (2005), utilizing CST as dewaterability indicator, highlighted the positive effect of cationic/anionic polymer conditioning on sludge dewatering. Nonetheless, they suggested that full–scale tests are needed to determine whether this conditioning regime leads to a desirable dewatering performance.

Besides identifying proper doses of dual–polymers, the dosing sequence is also important in determining the mechanisms of conditioning. It has been demonstrated that sequential addition is better than co–addition. The mechanism is shown in Figure 2–9. For bio–sludge of which negatively charged fraction is more dominant, the addition of cationic polymer followed by anionic polymer is preferable. On the other hand, alum sludge is often preconditioned with anionic polymers (Fan et al. 2000).

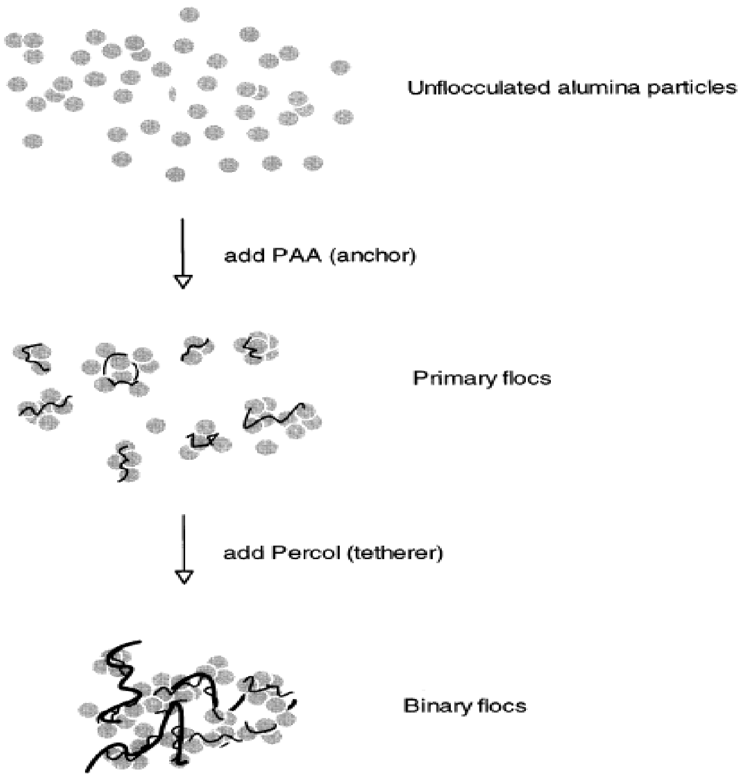


Figure 2–9 Mechanism of alum sludge conditioned with combination of anionic polymer (PAA) and cationic polymer (Percol) (Fan et al. 2000)

2.3.2.1.2. Iron/Cationic conditioning

Ferric chloride is also a popular flocculant in wastewater treatment. In the past, ferric chloride is commonly used with lime for solids conditioning. Like many other inorganic conditioners, ferric chloride conditioning alone typically cannot produce a solids cake concentration that can be achieved with much lower dose of polymer (Chitikela & Dentel 1998). That is the reason why organic polymers have been widely used in conditioning and dewatering processes despite of their high cost. However, Christensen & Wavro (1981) indicated that inorganic conditioners are less sensitive to changes in doses than polymer, leading to a more stable dewatering process. The conjunction of cationic polymers and ferric chloride may exploit the advantages of both conditioners.

The main mechanism of ferric chloride conditioning is charge neutralization due to the formation of positively charged iron–hydroxide precipitate. As a result, it could be substituted for expensive polymers to neutralize the “charge” of the suspending medium. Once the “charge” has been neutralized or increased to nearly zero level, the expensive high molecular flocculating polymers can be added at a much lower concentration (dose) to actually flocculate the particles making them amenable to dewatering. Besides charge neutralization, bridge formation among particles also contributes to sufficient sludge dewatering.

From the economic point of view, the use of ferric chloride as a pre–conditioner can reduce the polymer demand for conditioning; however, whether this is a cost effective method depending on the specific polymers used and chemical prices relevant to the site (Chitikela & Dentel 1998).

2.3.2.2. Advanced oxidation (Fenton) conditioning

Although the polymers used in water treatment systems are sometimes biodegradable, they are generally toxic to human and the aquatic environment at high concentration (Bolto & Gregory 2007). Therefore, a non–organic polymer approach for sludge conditioning has been proposed as a response to problems related to potential risks of using polymers. Fenton’s reagent is one of potential alternative conditioners for bio–sludge conditioning (Dewil et al. 2005, Mowla et al. 2013). Fenton’s reagent is a solution of hydrogen peroxide (H_2O_2) and an iron catalyst (Fe^{2+}) that is used to oxidize contaminants, especially toxic organic compounds in wastewater (Buyukkamaci 2004). Fenton peroxidation has been demonstrated to be a promising advanced sludge treatment method where it is used to rupture flocs or cells to release the trapped water molecules from extracellular polymeric substances (EPS) (Liu et al. 2013). Lu et al.

(2003) reported that the moisture of solid cake treated with Fenton's reagent was 75.2% while those of sludge treated by other processes were about 85%. In terms of sludge CST and SRF, these values decreased with increasing H_2O_2 and Fe^{2+} concentrations in almost all cases (Buyukkamaci 2004).

Major problem of Fenton oxidation conditioning is to identify the optimal dosages of Fe^{2+} and H_2O_2. Besides, the organic content of the supernatant and the cost of Fenton's reagent should also be taken into consideration. Latter studies have developed the use of Fenton's reagent as alternative conditioner of polymers but in combinations with physical conditioners, also known as skeleton builders, to form porous structure in sludge cakes, which have the ability to withstand high pressure in some dewatering devices (Qi et al. 2011).

2.4. Indicators for sludge dewaterability

2.4.1. Challenges in measuring sludge dewatering performance

Together with improvements in sludge dewatering to achieve the highest solid content sludge cake, it is necessary to establish a reliable dewatering index that can fully express how easily sludge releases its water (Pan et al. 2003). To date, however, there is no universal indicator yet to properly represent the solid–liquid separation ability of sludge. The main reasons for this problem are linked to different aspects of sludge properties, conditioning and dewatering methods.

As mentioned earlier, sewage sludge can vary enormously in terms of physical, chemical and biological characteristics, leading to its relatively unpredictable behaviour, especially dewatering behaviour (Colin et al. 1988). This makes it difficult to quantify most of the parameters (Sanin et al. 2011). Although some parameters can be quantified, it has never been easy to correlate these properties with sludge dewatering. Despite this impediment, various typical sludge properties such as pH, particle surface charge, organic content, porosity, compressibility, particle size, rheological characteristics, bound water content and solid concentration – variables that can influence dewaterability of sludge – have been investigated in some studies. These are summarized in more detail by Karr & Keinath (1978). However, a consensus is still lacking on which ones have the greatest impact on sludge dewatering.

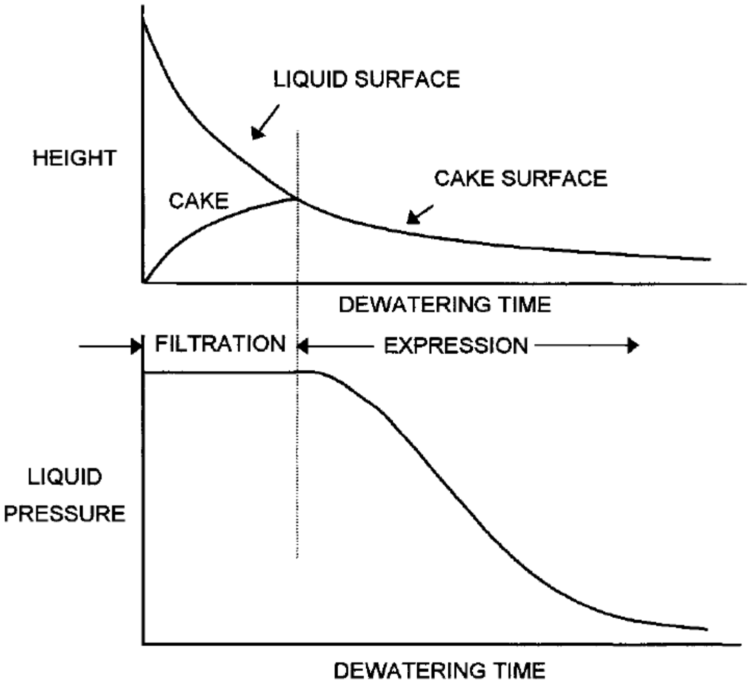


Figure 2–10 Two phases of sludge dewatering (Novak et al. 1999)

Many studies have suggested that dewatering by filtration equipment consists of two main phases (Figure 2–10), these being filtration and consolidation or expression (Lee & Wang 2000). Sørensen et al. (1996) described sludge as a solid–liquid mixture where solids are either in free suspension or packed closely together to form a cake. The former is called filtration phase while the latter is known as expression phase. Novak et al. (1999) stated that the amount of water extracted by filtration alone is not enough to achieve a desired cake solid; and expression phase accounts for most water removal.

They also highlighted that utilizing chemical conditioners can help increase the rate of filtration, but generally do not increase the cake solids content. On the other hand, although high expression pressure may not increase the rate of water removal, it can actually raise the total amount of released water. This explains why high–pressure devices are often used for sludge dewatering. Unfortunately, most traditional dewaterability measuring techniques, including Capillary Suction Time (CST) and Specific Resistance to Filtration (SRF), often measure the rate of filtration only and overlook the considerable contribution of expression. Therefore, to better understand the limits of dewatering, it is necessary to focus not only on the rate of filtration but also on the rate of expression, which is considered to be most important for achieving drier solid cakes.

The last but not least major problem with most traditional dewatering index procedures is that they barely resemble the actual sludge dewatering processes (Lynch & Novak 1991), except for SRF measurement, which is quite similar to belt presses, pressure filters and vacuum filters (Vaxelaire & Olivier 2006, Christensen & Dick 1987). It is known that different dewatering devices have different operations and intensity, which greatly affects the efficiency of sludge dewatering. Consequently, there should be a method that can estimate the final cake concentration and simulate real dewatering processes. This also suggests that it is not feasible to use only one dewaterability indicator for all dewatering processes. This is because the liquid–solid separation is influenced by numerous parameters, and a single index is hardly sufficient to fully describe the whole process (Vaxelaire & Cézac 2004). Hence, along with developing accurate measurements of sludge dewatering performance, selecting a proper index for different methods of dewatering is also significantly important (Pan et al. 2003). However, the problem is that it is not easy to simulate the real processes occurring in dewatering equipment. In the present work, besides SRF which can mimic filtration processes, another tool that can be applied to other popularly used dewatering equipment, the centrifuge, is also recommended.

2.4.2. Indicators for dewatering by filtration processes

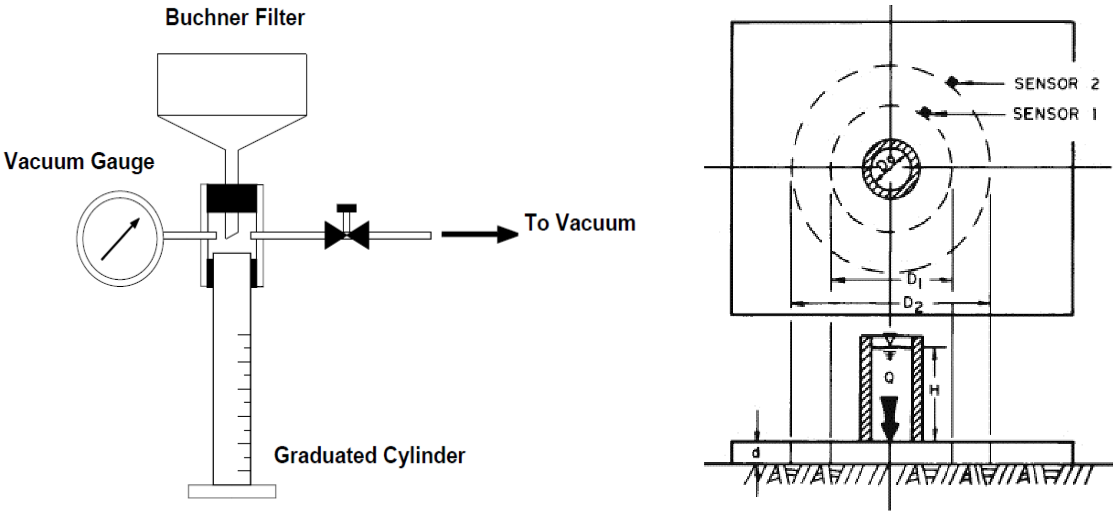
Specific Resistance to Filtration (SRF) and Capillary Suction Time (CST) are two most popular indices which have been conventionally used for assessing sludge filterability (Vesilind 2000) or dewatering rates (Novak 2006).

SRF test, the very first widely used technique developed by Coackley & Jones (1956) has several important advantages such as independent of solids concentration. It can especially be used for estimating the final cake concentration after dewatering (Mininni et al. 1984). Most of techniques developed for measuring dewatering efficiency of filtration devices such as vacuum filters, belt presses and filter presses were modifications of SRF measures (Table 2–7). However, these tests were time–consuming and procedures are quite complicated requiring high skills to perform (Vesilind 2000).

Table 2–7 Techniques for predicting dewatering performance of filtration devices

Filtration devices	Techniques for dewaterability measurement	Authors
Filter press	Filter pressing test	Mininni et al. (1984)
Vacuum filter	Filter – leaf test	Vesilind (1974)
Belt filter press	Drainage tests + Piston press	Baskerville et al. (1978)
	Modified Filtration Test	Heide et al. (1982)
	CST measures + Gravity drainage + Vacuum filtration	Spinosa & Mininni (1984)
	Crown Press	Severin & Collins (1992)
	Wedge Zone Simulator	Novak et al. (1993)

In comparison, CST measurement developed by (Baskerville & Gale 1968) is much quicker and easier test and requires fewer skills than SRF (Sanin et al. 2011), making it increasingly popular recently. CST was originally developed as a substitute for SRF to measure dewatering rate. Despite of that, CST, in fact, is still not considered as a fundamental measurement methods for sludge dewaterability. Unlike SRF, CST is affected by the concentration of solids and cannot predict the final cake solids achievable by dewatering devices. Besides, CST test is not effective in determining optimum polymer dose (OPD) for well–flocculated sludge, which often occurs around OPD point, due to the too–fast escape of water from the floc (Sanin et al. 2011). Another reason for the unreliability of CST is that since little hydraulic pressure is applied during CST measurement, it may not truly reflect the floc strength or resistivity to shear during dewatering stage (Pan et al. 2003).



(a) (b)

Figure 2–11 (a) A traditional SRF measurement apparatus set–up (Sanin et al. 2011) and (b) the schematic diagram of the CST apparatus (Vesilind 1988)

Various studies have tried to investigate and model the relationship between CST and SRF with the purpose of obtaining the averaged specific resistance of filtration cake from the data generated by CST tests. Lee & Hsu (1994) proposed a method that allowed SRF to be calculated without the liquid invasion volume measurement using capillary suction apparatus. A similar study by Herwijn et al. (1995) presented a newly developed model of CST apparatus able to determine specific cake resistances of both unflocculated and flocculated sludges. Sawalha & Scholz (2010) provided a mathematical model which related CST, SRF to other parameters, such as temperature and solids content. These can also predict the results of SRF tests from those of CST tests. More recently, Peng et al. (2011) obtained a relatively good correlation between normalized CST and SRF (R^2 = 0.9450). They concluded that it is not necessary to use both these parameters simultaneously to evaluate the dewatering rate.

2.4.3. Indicators for dewatering by centrifugation processes

Besides filtration devices, centrifuge has been also commonly used for sludge dewatering and increasingly popular by virtue of its high performance of producing drier cake solids which can be up to 30% from anaerobically digested biosolids (Higgins et al. 2006). As a consequence of distinctions in operations and conditioning requirements, filtration and centrifugation effectiveness should be evaluated differently. If filterability has been used to assess the efficiency of filtration, centrifugability has been defined as the ability to dewater sludge of centrifugation. Numerous factors have been proved to affect centrifugability and various attempts have been made to determine reliable indicators for sludge centrifugation performance. However, there seems not to be an appropriate parameter yet due to difficulties of reproducing the processes taking place inside the full–scale centrifuge on a laboratory–scale (Spinosa 1985). Unlike filtration types, filter skin formation of sludge during filtration, leading to the extent phase of dewatering, may not occur in centrifugal processes. Therefore, Novak et al.

(1999) suggested that a theoretical assessment of the stresses on sludge during dewatering would be useful in the case of centrifuge.

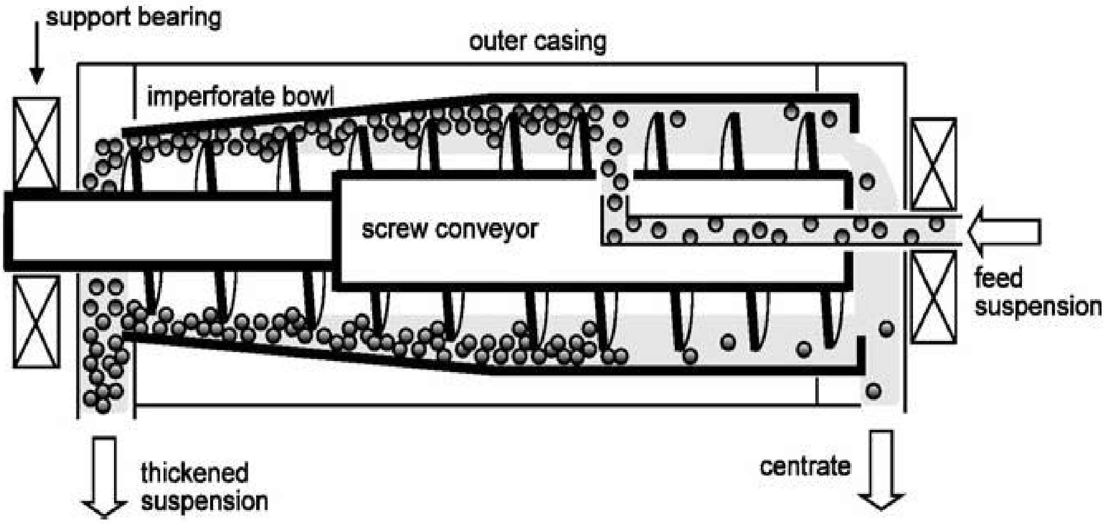


Figure 2–12 The schematic diagram of centrifuge (Wakeman 2007)

Regarding the particular operation of centrifuges, the centrifugabilty could be defined as the ease to be conveyed by the screw of the feeding sludge (Figure 2–12). Spinosa and Mininni (1984), as a consequence, reported that sludge settleability, scrollability and floc strength were major sludge characteristics influencing centrifugability. Unfortunately, no standard methods are available in which the above properties are considered as a whole.

Compactibility, which was defined as cake solids content of sludge after centrifugation, has been used by a number of studies (Erdincler & Vesilind 2000, Emir 2002, Emir & Erdincler 2006) to indicate sludge dewaterability, nevertheless, cannot quantify the stress imparted on sludge cake during dewatering by centrifuge. Chu & Lee (2001) introduced an arm–suspended centrifuge (Figure 2–13) to investigate the centrifugal separation of moisture from conditioned activated sludge and determine an optimal rotational speed for maximum moisture removal. However, the final cake solids achievable cannot be predicted using this method.

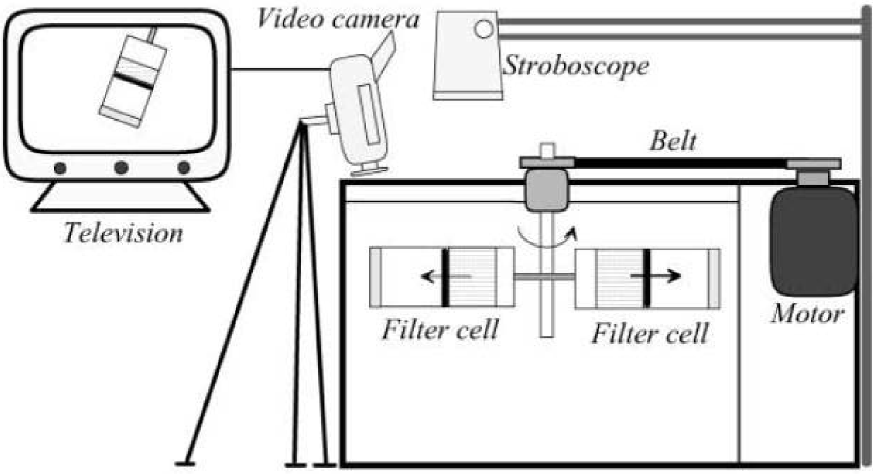


Figure 2–13 Schematics of the arm–suspended centrifuge (Chu & Lee 2001)

Modified Centrifugal Index (MCI) test – A new centrifuge based laboratory scale sludge dewatering

The crucial role of dewatering is to maximise the dry solids. For the centrifugal process, dewatered cake with dry solids content are typically in the range of 26 – 30%, while dry solids content of less than 22% is considered as ineffective dewaterability (Table 2–8) (Vigneswaran & Ben Aim 1989). Conventional methods for measuring dewaterability barely resemble the actual sludge dewatering processes (Lynch & Novak 1991). SRF can be used to simulate the operation of a filter press (Vaxelaire & Olivier 2006, Christensen & Dick 1987) but not a centrifuge. Thus, one should establish a method that has the ability to not only estimate the final cake solids concentration but also simulate the real dewatering process, especially for dewatering by centrifuge.

It was found that the stresses imparted to sludge during dewatering have a significant impact on dewatering efficiency in terms of solids cake content. Higgins et al. (2006)

utilized Gt value in determining the effect of shear or mixing intensity on OPD using a calibrated lab–scale mixer. Here, G was velocity gradient (s^{-1}) and t is time of mixing (s). By using this dimensionless parameter, they determined the stress of full–scale dewatering devices using shear stress as equivalent. However, there is a major drawback that the final cake solids achievable at full–scale cannot be predicted using this bench–scale method (Dentel & Dursun 2009). Besides, the shear imparted on the sludge cake during dewatering is different from that applied to the sludge liquid during conditioning.

Table 2–8 Sludge dewaterabililty classifications for centrifuge

Dewaterability	Cake solids content (%)
Good	26 – 30
Sufficient to medium	22 – 26
Bad	8 – 22

Source: Vigneswaran & Ben Aim (1989)

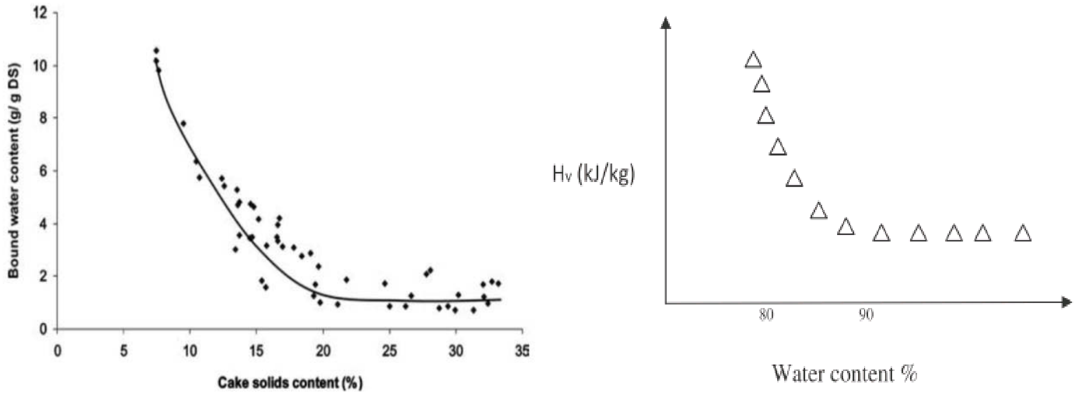
Recently, a modified lab–scale centrifuge device, namely modified centrifugal index (MCI) was suggested and investigated to overcome the difficulties encountered in the traditional dewaterability indicators. The method proposed by Higgins and colleagues at Bucknell University (Higgins et al. 2014) has been used by us to evaluate the sludge dewaterability of centrifugation (To et al. 2014). Here the stress of centrifuge, or the centrifugal force, is measured using a dimensionless parameter gt, which is the product of times gravity g (which is related to centrifuge rotating speed and rotor radius) and centrifugation time t (s).

2.4.4. Other techniques for dewaterability measurements

Using moisture content or rheology of sludge as assessing parameters of sludge dewatering efficiency are interesting and promising approaches, which have attracted attention of numerous investigators recently. Many of them have put efforts on determining the correlation between these parameters and sludge conditioning and dewatering.

2.4.3.1. Moisture distribution

Sewage sludge is hydrophilic by nature and typically has 98 to 99.7% moisture content which is generally difficult to remove (Smollen 1988). The reduction of sludge volume is fundamentally achieved by maximizing the cake solid content, or in another word, minimizing the water content (Figure 2–14a). As a result, a comprehensive understanding of water distribution in sludge and their relation to sludge dewaterability may be useful for improving the performance of dewatering system. A relationship between dewatering energy requirement and sludge water content (Figure 2–14b) shows that only about 20% of water is easily removed, even for conditioned sludge, but once water content is reduced to below 80%, the dewatering energy demand dramatically increases (Lee & Hsu 1994, Chu & Lee 1999, Wang et al. 2010, Mowla et al. 2013). This implies that the sludge can no longer be mechanically dewatered to obtain a smaller residual water content, which is also considered the limit of sludge mechanical dewatering.



(a) (b)

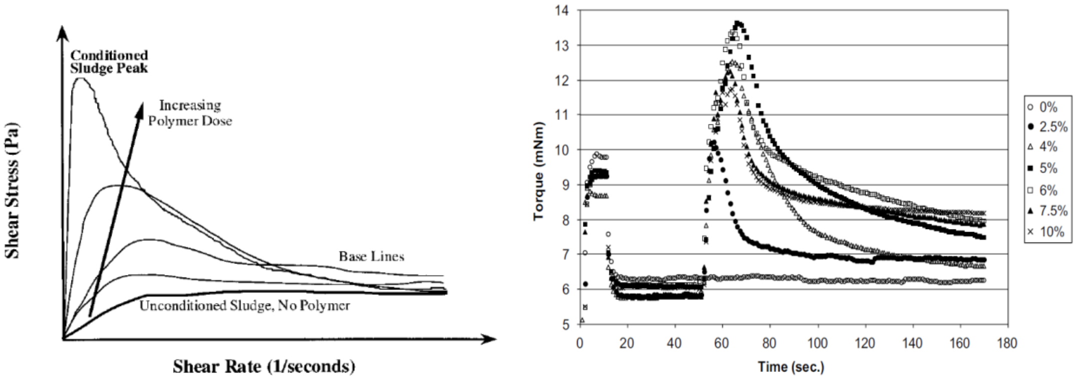
Figure 2–14 (a) Relationship between bound water content and cake solid concentration (Subramanian 2005) and (b) relationship between sludge water content and dewatering energy demand (Mowla et al. 2013)

Over the years, various techniques have been proposed to measure the moisture distribution in general and the bound water content in particular such as drying test, dilatometry, expression test, centrifugal settling test (Vaxelaire & Cézac 2004). It is notable that these techniques imitate different methods of sludge dewatering such as drying beds (drying test), freezing beds (dilatometry), filter presses (expression test) and centrifuges (centrifugal settling test). However, different techniques with different principles have led to difficulties in comparing the results of different studies. It is also evident that the various definitions of water types can cause some confusion. Despite of that, several works have put efforts on identifying correlations between water distribution and sludge dewaterability. However, results actually depend on the measurement techniques used in these studies. For instances, when using drying test for measurement, no significant correlation was obtained with CST and cake solid content (Smollen 1990). Whilst, strong correlations with SRF (Robinson & Knocke 1992) and cake solids content (Heukelekian & Weisberg 1956, Forster & Lewin 1972) were detected when using dilatometry technique.

2.4.3.2. Rheology

Rheology is the science that deals with the flow and deformation of fluids and solids under the influence of stresses, which has been becoming an important tool in characterizing waste sludge, especially sewage sludge (Abu-Orf & Dentel 1999, Örmeci 2007). Although the early works on rheological behaviour of sewage sludge have already been conducted since the thirties of the last century, most of them were motivated by the need to predict pumping requirements. Until recently, more studies have put effort into examining the rheology in relation to sludge dewaterability with the desire of predicting, controlling and optimizing conditioning and dewatering processes (Marinetti et al. 2010).

The rheological behaviours of a certain fluid can be schematically described by flow curves, also known as rheograms. Various researchers have employed rheograms of conditioned sludge with different polymer doses for determining the OPD (Örmeci 2007). Figure 2–15 displays two commonly used types of rheograms for polymer dose assessment, shear stress–shear rate (Figure 2–15a) and torque–time curves (Figure 2–15b). Besides, these rheograms could also allow mixing conditions to be determined but also the best performing polymers to be selected.



(a) (b)

Figure 2–15 (a) Shear stress–shear rate rheogram (Abu-Orf & Dentel 1999) and (b) torque rheogram of unconditioned and conditioned sludge with different polymer doses (Örmeci 2007)

Rheological characteristics are indicative of floc strength. Therefore, most of the rheology studies on the topic of dewaterability were based on determining relationships between floc strength or network strength and sludge dewatering properties (Dentel & Dursun 2009, Abu-Orf & Dentel 1999, Marinetti et al. 2010, Abu-Orf & Dentel 1997, Yen et al. 2002, Hou & Li 2003). However, none provided a strong correlation between rheological parameters and sludge dewaterability as measured by standard test methods.

2.4.5. Assessment of dewaterability indicators

Evaluation of sludge dewaterability is critically necessary for any sludge treatment system where optimizing the dewatering process is the aim. However, this work is relatively challenging due to the unpredictable and elusive behaviour of all sludge type, especially bio–sludge as well as variations in solid–liquid separation methods. Since the establishment of the very first dewatering indices, various indicators for dewatering process have been developed and applied over the years in tandem with dewatering technology. Despite these advances, however, there is as yet no universal dewatering index which can fully reflect the ability to dewater sludge. It is believed that a reliable dewatering index should not only simulate the real water extraction process but also estimate the maximum solid content of sludge cake achievable. Conventional dewatering indices seem to lack one or both of these, and consequently they hardly express the efficiency of dewatering properly.

SRF, while it was cumbersome in equipment and proved to be time-consuming, can nonetheless estimate the cake solid content of sludge after filtration. On the other hand, CST is increasingly popular due to its ease of measurement; however, it fails to predict solid concentration of dewatered cake. In fact, CST and SRF may be correlated strongly with free water (Peng et al. 2011), which only takes part of approximately 20% of total water content (Mowla et al. 2013). On the other hand, bound water content because it takes up the bulk of sludge total moisture content, should also be taken into consideration. It is therefore suggested that to properly evaluate the dewatering efficiency of sludge, different parameters should be included. For example, CST and SRF, which often serve to register the dewatering rate, could be combined with bound water or dry solids content in the dewatered cake and this will indicate the extent of dewatering.

Rheology represents a potentially powerful tool for controlling and optimizing conditioning, but it is not sufficient to predict the performance of full–scale dewatering systems. This is because the method has targeted the floc strength rather than the cake solids content. In addition it cannot reproduce the real dewatering process. It is also suggested that along with developing accurate measurements of sludge dewatering performance, selecting a proper index for different methods of dewatering is critical.

Finally, with reference to filtration equipment, SRF is possibly the most appropriate efficiency indicator, while, for centrifugation devices, compactibility and MCI can be promising dewaterability measurements. The major difference between these two techniques is that the latter can quantify the stress imparted on sludge during dewatering by centrifuge, which can reflect the influence of dewatering equipment on how well the solid–liquid separation process performs.

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FACULTY OF ENGINEERING AND IT

CHAPTER 3

MATERIALS AND METHODS

3.1. Materials

3.1.1. Sludge

Different types of sludge were obtained from 3 WWTPs of Sydney Water, Australia. They were anaerobically digested sludge (ADS) from Wollongong WWTP (7 sampling times from May 1st 2013 – March 25th 2014), aerobically digested sludge (AEDS) from St. Marys WWTP (6 sampling times from October 25th 2013 – June 24th 2014) and waste activated sludge (WAS) from Quakers Hill WWTP (7 sampling times from October 25th 2013 – June 24th 2014). These sludges were blends of primary and secondary sludges. General information on sludge treatment of these WWTPs, in terms of sludge pre–treatment processes, conditioning and dewatering, is summarized in Table 3–1. Cake solids content was used as efficiency indicator since reducing sludge volume is the ultimate target of dewatering process. Besides, centrate quality was also taken into in assessing sludge dewatering efficiency. Centrate quality was expressed in terms of suspended solids content in the effluent.

Samples were collected from a sampling point before being conditioned and dewatered and then were immediately transferred to the laboratory for characterizing their physical and chemical parameters (temperature, pH, zeta potential (ZP), capillary suction time (CST), dry solids (DS) content, volatile solids (VS) content, soluble COD (sCOD), soluble protein (sP) and polysaccharides (sPS)) on the same day itself. Samples used for conditioning test was stored at 4°C (in order to minimize the microbial activity) and used for experiments within 4 days from sampling date. All experiments were conducted in duplicate.

Table 3–1 General information on 3 WWTPs studied

WWTPs	Pre–treatment processes[a]	Dewatering devices	Typical cake solids content (%)	Typical SS[b] in centrate/filtrate (mg/L)	Polymers used for conditioning	Typical polymer dosage (kg/t DS[c])
Wollongong	Centrifuge thickening + Anaerobic Digestion	Solid Bowl Centrifuge	27 – 29	<100	Zetag8165	9 – 12
St. Marys	DAF[d] + Aerobic Digestion	Belt filter press	15 – 19	<100	Zetag8180	9 – 10
Quakers Hill	IDAL[e] + Gravity thickening	Solid Bowl Centrifuge	19 – 21	1000 – 4000	Zetag8165	6 – 8

Source: Sydney Water Corporation (2014)

[a] Sludge pre–treatment processes includes thickening and digestion

[b] SS: Suspended Solids

[c] DS: Dry solids

[d] DAF: Dissolved Air Flotation (thickening method)

[e] IDAL: Intermittently Decanted Aeration Lagoons

** Treatment diagrams of 3 WWTPs studied are presented in the Appendix*

The dewatered cake and centrate (filtrate) were also collected on the outlets of dewatering devices on the same day to evaluate the sludge dewatering performance. These were measured in terms of cake solids and suspended solids (SS), respectively.

Wastewater sludge possesses highly complicated nature and behaviour, thus it is not easy to characterize it inclusively. The present study selected the most representative parameters (as shown in Table 3–2). These parameters were then related with sludge conditioning and dewatering. The sludge parameters studied were:

a. As–received sludge (before conditioning and dewatering)

Zeta potential (ZP): Since the main mechanism for polymer conditioning is charge neutralization, zeta potential measurement was made. This helps to determine the effective charge at the particle surface and can be used as an indirect measure to estimate polymer dose (Stoll 2013). The more the negative zeta potential, the more the polymer needed for charge neutralization. Besides, zeta potential of sludge also decides the type of polymer (cationic or anionic) to be used.

Capillary suction time (CST): CST is the most common parameter used in practice to evaluate the solid–liquid separation ability as it is a quick and easy test and does not require high skill to perform (Sanin et al. 2011).

Table 3–2 Sludge characteristic parameters measured in the study

	pH	ZP (mV)	CST (s)	DS (%)	VS (%)	sCOD (mg/L)	sP (mg/L)	sPS (mg/L)	SS (mg/L)
As–received sludges	✓	✓	✓	✓	✓	✓	✓	✓	
Dewatered cake				✓					
Centrate /Filtrate	✓	✓							✓

Dry solids (DS) and Volatile solids (VS) contents: DS and VS are the two important parameters which are often used to calculate the amount of conditioning polymer for a given sludge. The polymer dosage is often expressed on a mass basis, commonly expressed as kilo–grams of polymer per ton of dry solids (kg/t DS).

Soluble Protein (sP) and Soluble Polysaccharides (sPS): Novak et al. (2003) found that soluble biopolymers, mainly protein and polysaccharides, which are released into supernatant solution during the digestion, take up a major portion of the polymers used for conditioning and does not make it available for flocculation of the sludge particles.

Soluble COD (sCOD): Higgins et al. (2006) reported that soluble COD and soluble biopolymers have relatively good correlations among them. Since soluble protein and polysaccharides analyses are not typically used for field measurements due to their specific equipment and reagent requirements, soluble COD could be used as a substitute to represent the contents of sP and sPS.

b. Dewatered cake and centrate/filtrate

DS of dewatered cake (cake solids content) and SS in centrate/filtrate are the two major controlling parameters that reflect the effectiveness of dewatering operation. The objective of sludge dewatering is to produce a clear centrate while also achieving a cake high in solids. The cake solids content was measured using gravimetric method.

ZP of centrate/filtrate was measured as an indicator to prevent over–dosing. When ZP of centrate is positive, it could be an indication of excessive polymer dose. In fact, charge neutralization does not need to be completely achieved in sludge conditioning since effective flocculation is obtained by both charge neutralization and bridging formation mechanisms concurrently. Therefore, even ‘zero’ or low negative surface charge is possibly considered as over–dosing already (Abu-Orf & Dentel 1997, Novak

& Haugan 1979, Agarwal et al. 2005). ZP of the centrate can be used as a qualitative parameter to quickly check whether any excess amount of cationic polymer used still remains in the centrate.

Besides physical and chemical characterization, morphology of samples, for example, shape of dewatered cake and colour of centrate, was also investigated:

- **The shape and the dryness level of dewatered cake** give information on dewatering devices used and to some extent the efficiency of dewatering. The cake from centrifuge looks drier than that of belt filter press. Cake from centrifuge has pellet shape while cake of belt press has flat shape.
- **The colour of the centrate** can also be used as an indicator of the centrifuge performance, for instance, black or gray or foaming centrate is indicative of a problem in operation.

3.1.2. Chemicals

Table 3–3 summarizes characteristics of polymers used in the study in terms of charge density, configuration and molecular weight.

Table 3–3 Properties of the polymer used in the study

Trade name	Charge type	Configuration	Charge density	Molecular weight
Zetag8165	Cationic	Linear	Medium–high	Very high
Zetag8180	Cationic	Linear	High	High
Zetag4110	Anionic	Linear	Low	High
Zetag4145	Anionic	Linear	Medium–high	Very high

Source: BASF Australia Ltd.

Cationic polymers: This study used cationic polymers currently utilized at the 3 WWTPs, with Zetag8165 at Wollongong WWTP and Quakers Hill WWTP and

Zetag8180 at St. Marys WWTP. Polymer solutions were prepared by dissolving these powdered polymers in distilled water at same concentrations used at the 3 WWTPs in order to imitate their full–scale conditioning processes (Table 3–4).

Table 3–4 Concentration of conditioning polymers at 3 WWTPs studied

WWTPs	Polymer name	Solution concentration (w/v)
Wollongong	Zetag8165	0.1
St. Marys	Zetag8180	0.3 – 0.4
Quakers Hill	Zetag8165	0.2 – 0.3

Source: Sydney Water Corporation (2014)

Anionic polymers: Anionic polymers with different molecular weights and charge densities (recommended by the chemical supplier, BASF Australia Ltd.) were also used to evaluate the effect of dual polymers on conditioning. All anionic polymer solutions were prepared at concentration of 0.1% w/v.

Fenton's reagent: As mentioned above, Fenton's reagent is defined as the mixture of H_2O_2 and Fe^{2+}. The present study used $FeCl_2.4H_2O$ as the source of Fe^{2+} and H_2O_2 at 30% w/v solution.

Ferric chloride ($FeCl_3$): $FeCl_3$ solution was prepared at a concentration of 0.01% w/v.

3.2. Experimental studies

Sludge samples were warmed to room temperature (20 – 25°C) before all experiments. Each test was done in duplicate and the average value is reported.

3.2.1. Sludge characterization

3.3.1.1. Filtrate preparation

The purpose of this step is to extract the soluble biopolymers from the sludge. As–received sludge was centrifuged at 3000 rpm for 15 minutes then the supernatant was filtered using a Whatman filter paper No. 542 (with 2.7µm pore size) to measure soluble COD, protein and polysaccharides. The selection of filter paper pore size was based on the study of Higgins et al. (2006). They concluded that soluble biopolymers, mainly the ones consisting of protein and polysaccharides with sizes less than 3.0µm account for much of polymer demand for sludge conditioning.

3.3.1.2. Analysis methods

Soluble COD was analysed using Hatch COD vials while soluble protein and polysaccharides were measured using modified Lowry (Lowry et al. 1951) and Phenol–Sulphuric (Dubois et al. 1956) methods, respectively. DS, SS and VS were conducted following Standard methods 2540B, 2540D and 2540E (APHA 1995), respectively. CST was determined using 304B Portable CST Unit, Triton Electronics Ltd, UK. The details on the procedure are given elsewhere (Vesilind 1988). Temperature and pH of sludge before conditioning were measured by pH meter (Hana, model HI 9025C). Zeta potential (ZP) was measured using Malvern Instruments Zeta Sizer Nano ZS–90.

3.2.2. Conditioning tests

Table 3–5 summarizes the chemicals used for conditioning tests of the present study.

Table 3–5 Conditioning tests and chemicals used

Conditioning tests	Chemicals used
Determination of: - Optimal mixing intensity - Optimal polymer demand (OPD)	- Zetag8165 (ADS and WAS) - Zetag8180 (AEDS)
Cationic/Anionic polymers conditioning	- Cationic polymers: zetag8165 (ADS and WAS) and zetag8180 (AEDS) - Anion polymers: Zetag4110 and Zetag4145
Iron/Cationic polymer conditioning	- Cationic polymers: zetag8165 (ADS and WAS) and zetag8180 (AEDS) - $FeCl_3$ solution
Advanced oxidation (Fenton) conditioning	- $FeCl_2$ solution - H_2O_2 30% (w/v)

3.2.2.1. Polymer conditioning – Determining optimal conditioning regimes

a. Optimal mixing intensity

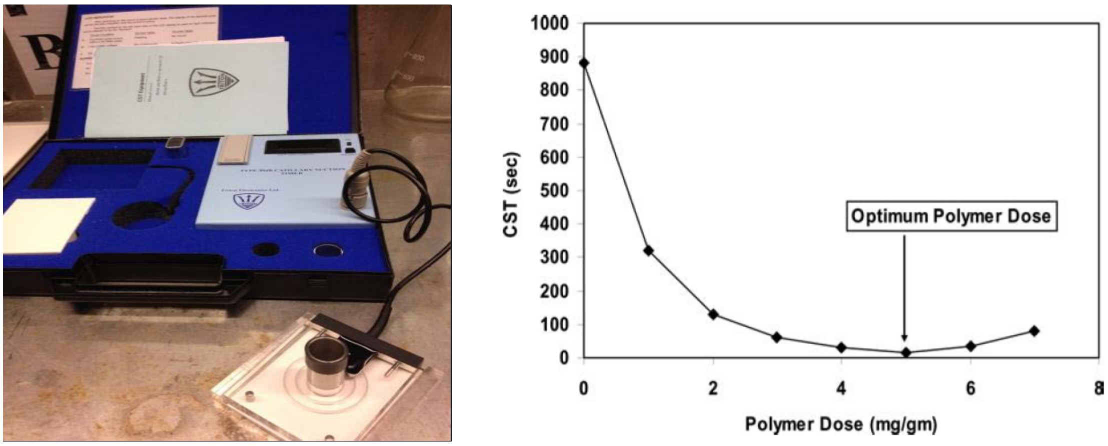
Experiments were carried out by pouring 500 mL of sludge sample into a 1 L beaker. Pre–determined amount of polymer was mixed with the sludge using a bench–scale agitator (as shown in Figure 3–1). Optimal mixing intensity including mixing time and speed were figured out through screening tests. Sludge was conditioned at the currently used polymer dose at the WWTPs studied with different mixing speed (100 – 500rpm) for different periods of time (30 – 300s). Then samples of the conditioned sludge (less than 5mL) were withdrawn and used for the CST test (Figure 3–2a) to identify mixing condition that led to the lowest value of CST.

Figure 3–1 Bench–scale agitator used for conditioning tests in the study

b. Determining optimal polymer demand (OPD)

Similarly, different pre–calculated amounts of polymer (currently used at the WWTPs studied) were mixed with as–received sludge at optimal mixing condition. These conditioned sludge samples were also used for the CST test to determine OPD. OPD was the dose that resulted in the shortest CST (Figure 3–2b). These tests were done in duplicate. The remaining conditioned samples were used for ZP measurement and Modified Centrifugal Index (MCI) test.

ZP measurement: ZP values of both as–received and conditioned sludge were measured after these sludge samples were diluted 50 times. For conditioned samples, sludge flocs were first shaken to break them into small particles and the supernatant was taken 10 minutes later for measurement. Polymer dose leading to 0 mV of ZP was considered as charge neutralization point of conditioning process.



(a) (b)

Figure 3–2 (a) The standard CST apparatus and (b) determination of optimal polymer dose for sludge conditioning using CST test (Novak 2006)

c. Shear sensitivity test

A calibrated lab – scale mixer was applied for the test. Effects of shear intensity (which was measured by the value of Gt, where G is gradient velocity (s^{-1}) and t is mixing time (s)) on OPD were investigated through a series of conditioning tests at different Gt values (8,000 – 110,000). OPD was determined for each shear intensity value and graphs of OPD versus Gt value were established.

3.2.2.2. Conditioning using other chemicals

a. Dual conditioning tests

- **Cationic/Anionic polymer conditioning**

Two different types of anionic polymers supplied by BASF Australia Ltd., were used in conjunction with currently used cationic polymers at the 3 WWTPs to study the effect of dual polymer addition during conditioning. The selection of anionic polymers was based on their charge density and molecular weight: one with low in charge and high molecular weight (Zetag4110); and other with medium to high charge and high molecular weight (Zetag4145). The sludge was first mixed with cationic polymer with a dose less than the currently use at the 3 WWTPs and then a pre–calculated amount of anionic polymer was added to the mixture while being stirred. CST test was also used to measure dewaterability of conditioned sludge.

- **Iron/Cationic polymer conditioning**

The procedure was the same as that of dual polymer conditioning, except that the sludge was dosed with different quantities of ferric chloride prior to the addition of cationic polymer.

b. Advanced oxidation (Fenton) conditioning

A Jar test was used to test the advanced oxidation conditioning. Different Fe^{2+}/ H_2O_2 concentrations (Fenton's reagent) were tested to determine the most appropriate dosages. 500 mL of sludge was placed in a 1 L beaker then pH was adjusted to 3 using HNO_3. After that, the pre–determined amounts of Fe^{2+} ($FeCl_2$) and H_2O_2 solutions were added into the sludge and the mixture was mixed at 100rpm for 30min. The CST of conditioned sludge was then measured.

3.2.3. Modified centrifugal index (MCI) test

In this study, a modified bench–scale centrifuge apparatus was used to determine cake solids content of ADS before and after conditioning. This method was developed by Higgins et al. (2014). In the present study, a lab–scale centrifuge and modified centrifuge tubes as shown in Figure 3–3, were employed for the test. A support was provided to hold the filter paper (Whatman paper No. 4 with 20µm pore size) about half way from the bottom of the centrifuge tube. The sludge sample was placed right on the filter paper and the centrifuge was operated at different gt values (100,000 – 1,000,000). After the centrifugation, the corresponding cake solids were measured to evaluate the dewatering efficiency. Graph of gt values versus cake solids content (%) was made and compared at different polymer doses to evaluate the effect of both polymer conditioning and shear intensity on the efficiency of sludge dewatering.

(a) (b)

Figure 3–3 (a) Lab – scale centrifuge and (b) Modified centrifuge cup before (left) and after (right) MCI test

Values of gt were determined by the following formula:

$$gt = g \times t \qquad (1)$$

Here g is times gravity (or centrifugal force) which is related to centrifuge rotating speed and rotor radius; t is centrifugation time (s). Table 3–6 displays the conversion between centrifuge speed (rpm) and times gravity (g).

Table 3–6 Conversion between times gravity and centrifuge rotor speed for 7cm of rotor radius

Centrifuge rotor speed (rpm)	Times gravity (xg)
2000	313
2500	489
3000	704
3500	959

Source: www.thermo.com/pierce

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CHAPTER 4

RESULTS AND DISCUSSION

4.1. Sludge characterization

4.1.1. Wollongong WWTP

4.1.1.1. Anaerobically digested sludge (ADS)

(a) (b) (c)

Figure 4–1 (a) ADS; (b) Dewatered cake and (c) Centrate of Wollongong WWTP

ADS collected from Wollongong WWTP looked viscous, fluffy and black (Figure 4–1a); had bad odour and poor settleability. The characteristics of this ADS are summarized in Table 4–1. It shows that this sludge sample represents a typical biologically digested sludge, with DS about 25g/L (≈ 2.5%) and VS/DS around 62%. It also has been noticed that the CST value of ADS was relatively high (1610 ± 75s), indicating poor dewaterability of this sludge (Vesilind 1988). This result is in agreement with previous studies which showed that both aerobic and anaerobic digestions deteriorate the sludge dewatering properties (Novak et al. 2003, Bruss et al. 1993, Novak et al. 1977). Zeta potential of ADS at pH = 7.4 is highly negative (-29.6 ± 0.9mV), which is considered responsible for hydration and electrostatic repulsion preventing the particles to naturally form flocs (Turovskiy & Mathai 2006). The protein concentration of ADS was about three times higher than the polysaccharide concentration. This result is similar to prior finding by Novak et al. (2003) who concluded that under anaerobic conditions, the concentration of soluble protein is considerably greater than that of polysaccharides. Protein may have a more important role in determining the polymer demand.

4.1.1.2. Dewatered cake and centrate

- **Dewatered cake**

The dewatered cake was also characterized to evaluate the efficiency of the dewatering system. Dewatered cake looked dry and had pellet shape (Figure 4–1b) resulted from the effect of high–speed centrifuges. However, sticky cake, which could be due to the excess amount of conditioning polymer, made it difficult in conveying.

It can be seen from Table 4–1, after conditioning and dewatering, the cake solids increased from 2.5% to almost 29%. It was classified as a good dewatering performance for centrifuge (Vigneswaran & Ben Aim 1989) despite the fact that characteristic profile of ADS indicated a poor dewaterability. It was suggested that this improvement could be attributed to the effects of both anaerobic digestion and conditioning, which will be studied in detail latter.

- **Centrate quality**

Centrate quality is one of main controlling parameters reflecting the efficiency of the solids capture during conditioning and dewatering processes, specifically when centrifuge is used for dewatering. For plant operation, it is important to remove as much solids as possible during dewatering operation. This helps minimize the recycle of solids to the plant inlet when the centrate is sent back to the head–of–works. SS in centrate is applied for representing the centrate quality. SS in centrate of Wollongong

Table 4–1 Characteristics of ADS, dewatered cake and centrate of Wollongong WWTP

Sludge types	pH	ZP (mV)	CST (s)	DS (%)	VS (%)	VS/DS (%)	sCOD (mg/L)	sP (mg/L)	sPS (mg/L)	sP/sPS	SS (mg/L)
ADS	7.4 ±0.1	-29.6 ±0.9	1610 ±75	2.5 ±0.27	1.5 ±0.09	62 ±5	1337 ±71	244.9 ±12	76.5 ±2.4	3.1 ±0.3	-
Dewatered cake	-	-	-	27 – 29	-	-	-	-	-	-	-
Centrate	8.1 ±0.2	(-7.8) - (-1)	-	-	-	-	-	-	-	-	60 – 90

Sampling times: 7 (May 1st 2013 – March 25th 2014)

WWTP was typically under 100mg/L (Table 4-1), which can be considered as clear centrate (Figure 4–1c).

Although obtaining high DS in dewatered cake, ZP of centrate was negative, ranging from -1 to -7.8mV (Table 4–1).It strengthens the concept that neutralization of charge is not the only mechanism governing the sludge conditioning. Polymer bridging formation is also an important mechanism.

4.1.2. St. Marys WWTP

4.1.2.1. Aerobically digested sludge (AEDS)

(a) (b) (c)

Figure 4–2 (a) AEDS; (b) Dewatered sludge and (c) Filtrate of St. Marys WWTP

AEDS looked viscous and blackish brown (Figure 4–2a), had bad odour and a better settleability than that of Wollongong WWTP but not as well as Quakers Hill WWTP. The feeding sludge had the lowest DS (about 2%) and a moderate VS/DS (64%) among all 3 WWTPs. Zeta potential of AEDS was moderately negative compared to Wollongong and Quakers Hill WWTPs (≈ -26mV) while CST value was not so high (≈ 300s). Soluble COD and soluble biopolymers concentrations were medium compared to the other two WWTPs and the ratio of sP to sPS was about 2.5.

Table 4–2 Characteristics of AEDS, dewatered cake and filtrate of St. Marys WWTP

Sludge type	pH	ZP (mV)	CST (s)	DS (%)	VS (%)	VS/DS (%)	sCOD (mg/L)	sP (mg/L)	sPS (mg/L)	sP/sPS	SS (mg/L)
AEDS	7 ±0.06	-26.3 ±0.3	494 ±62	2.2 ±0.3	1.4 ±0.08	64 ±5	702 ±49	91 ±5.1	36.7 ±4.7	2.5 ±0.1	-
Dewatered cake	-	-	-	15 – 19	-	-	-	-	-	-	-
Filtrate	8.1 ±0.2	-5.5 ±0.4	-	-	-	-	-	-	-	-	34 – 82

Sampling times: 6 (October 25th 2013 – June 24th 2014)

Similar to ADS, characteristics of AEDS were quite stable at different sampling times due to the effect of stabilization or digestion process. This makes it easier to precisely estimate the polymer demand for sludge conditioning.

4.1.2.2. Dewatered cake and filtrate

- **Dewatered cake**

Dewatered cake looked wet and had flat shape (Figure 4–2b), which was representative for dewatering by belt filter presses. It has been known that, belt presses are not effective in sludge dewatering when compared to centrifuges, especially the high–speed ones (Metcalf et al. 1991). As a result, the typical cake solids contents of St. Marys WWTP were only 15 – 19%.

- **Filtrate**

Despite the low cake solids content, filtrate quality of dewatering system was good and looked clear (Figure 4–2c), with SS often less than 100mg/L. Zeta potential of filtrate obtained at different sampling times stabilized at around -5mV (Table 4–2) possibly because of steady properties of AEDS as well as operational conditions of the plant.

4.1.3. Quakers Hill WWTP

4.1.3.1. Waste activated sludge (WAS)

(a) (b) (c)

Figure 4–3 (a) WAS; (b) Dewatered sludge and (c) Centrate of Quakers Hill WWTP

WAS appeared to be highly viscous and yellowish to brown in colour; had really bad odour and good settleability (Figure 4–3a). This waste sludge collected from IDALs underwent gravity thickening stage; thus, had relatively high DS (up to 3.7%) and VS/DS (about 68%) in comparison with Wollongong and St. Marys WWTPs.

Compared to the typical zeta potential of waste activated sludge, which is -30mV (Böhm & Kulicke 1997, Chitikela & Dentel 1998), the negative surface charge of Quakers Hill WWTP's WAS was much lower (≈ -21mV), possibly leading to a low polymer demand for sludge conditioning. Besides, low values of CST (71±11s) could favour dewatering capacity.

Quakers Hill WWTP's sludge had the lowest concentrations of soluble COD, protein and polysaccharides among 3 sludge types. This could be due to the effect of thickening stage which substantially removed the soluble biopolymers attaching with the liquid phase. It, as a result, may require a small amount of polymer for conditioning. The content of sP was also higher than that of sPS, nonetheless, the ratio of sP to PS was lower than those of digested sludges, with sP/sPS about 1.7.

Unlike the other 2 sludge types, characteristics of WAS collected at different sampling times relatively fluctuated in terms of all parameters, expressing a complex and elusive nature of WAS. This may be due to the lack of stabilization stage (digestion) before dewatering at the plant, which could make sludge treatment more difficult.

4.1.3.2. Dewatered cake and centrate

- **Dewatered cake**

In the case of Quakers Hill WWTP, polymer conditioning also helped improve WAS dewaterability. However, the improvement of cake solid concentration was not as significant as that of Wollongong WWTP. It led to only about 18 – 19% of cake solid content although Quakers Hill WWTP also utilized high–speed centrifuges for dewatering. This was contrary to WAS characterization that indicated a better dewatering efficiency.

The following reasons may lead to bad dewatering efficiency of Quakers Hill WWTP:

- Regarding sludge properties: WAS was proved to be sensitive to high shear (Higgins et al., 2006) and easy to be broken even after conditioning. This led to a centrate with high SS concentration.
- Regarding conditioning regimes: Inefficient mixing time for sludge conditioning could result in ineffective flocculation.
- Regarding dewatering equipment: Old centrifuge did not work properly.

Table 4–3 Characteristics of WAS, dewatered cake and centrate of Quakers Hill WWTP

Sludge type	pH	ZP (mV)	CST (s)	DS (%)	VS (%)	VS/DS (%)	sCOD (mg/L)	sP (mg/L)	sPS (mg/L)	sP/sPS	SS (mg/L)
WAS	6.7 ±0.2	-20.2 ±1.6	71 ±11	3.3 ±0.3	2.0 ±0.42	68 ±3	365 ±16	72.5 ±7.3	43.4 ±5.3	1.7 ±0.06	-
Dewatered cake	-	-	-	19 – 22	-	-	-	-	-	-	-
Centrate	7.0 ±0.2	(-10.5) - 8.8	-	-	-	-	-	-	-	-	1065-3970

Sampling times: 7 (October 25th 2013 – June 24th 2014)

- **Centrate**

Centrate of Quakers Hill WWTP looked 'dark' in colour (Figure 4–3c), with SS in centrate typically over 1000mg/L and even up to 4000mg/L (Table 4–3). Zeta potential of centrate ranged from -10mV to 8.8mV, which was possibly due to under–dosed (-10mV) or over–dosed (8.8mV) conditioning at the plant in different sampling times. Unlike the other 2 plants, the operational conditions (such as polymer doses, dewatering intensity) at Quakers Hill WWTP are adjusted every day, from 6 to 8kg/ton DS. These adjustments were based on DS of feeding sludge and centrate quality.

4.1.4. Feed sludge characterization – Prediction of sludge conditioning demand and dewaterability

- **Dry solids (DS) content of feed sludge**

DS content of feeding sludge is the most common parameter which has been often used for sludge characterization and calculation of conditioning polymer demand. A previous study demonstrated that higher performance of a rotary vacuum filter relates to the increase in feeding solids content (Fan et al. 2000), which highlights the effect of thickening on dewatering as well as the relationship between feeding DS and dewaterability. In this study, WAS had the highest DS (up to 3.7%) due to post treatment by gravity thickening while ADS and AEDS had lower DS (2.2 – 2.5%), perhaps resulted from digestion processes, even though they were both thickened previously. Thus, it could be suggested that WAS may have better dewaterability than ADS and AEDS without conditioning treatment.

- **Zeta potential**

Zeta potential (ZP) is an important surface property of sludge flocs in terms of flocculation and dewatering (Sanin et al. 2011). Typically, sewage sludges originated from WWTPs usually have negative ZP (Christensen & Wavro 1981). The distinct feature among them was how much negative values of ZP. It has been confirmed that the larger magnitude of ZP, the more stability of colloids. It may lead to smaller probability of flocculation occurring (Christensen & Wavro 1981, Bolto & Gregory 2007) and possibly poorer dewaterability. In this study, the order of absolute ZP value for sludge studied were ADS > AEDS > WAS (Tables 4–1, 4–2 and 4–3), which means digested sludge may require higher polymer demand for neutralizing the surface charge and could be more difficult to be dewatered than WAS.

- **CST**

Lee & Liu (2001) measured the CST values of different feeding sludge types and they found the mean CST decreased in the order: digested sludge > activated sludge > raw sludge > mineral sludge. The present study results are in agreement with their finding. CST values of ADS and AEDS were much higher than that of WAS, especially ADS with CST over 1600s (Tables 4–1, 4–2 and 4–3). CST is an indication of dewaterability. It is harder to extract water from digested samples with higher CST than WAS. This also proves that digestion could be one of major reasons of sludge dewatering reduction before conditioning (Bruss et al. 1993, Novak et al. 1977, Novak et al. 2003).

- **Soluble substances**

Soluble biopolymers (mainly protein and polysaccharides) which are produced during digestion process, especially in anaerobic digestion, have been demonstrated to be responsible for high polymer demand for sludge conditioning (Higgins et al. 2006, Novak et al. 2003). In the present study, in terms of quantity of biopolymers, ADS had the highest amount, protein in particular, while the other 2 sludge types had lower amounts, with AEDS slightly higher than WAS (Tables 4–1, 4–2 and 4–3). This supports the earlier work of Novak et al. (2003) that protein is released into solution during anaerobic digestion. In addition, the ratios of sP to sPS were increased by digestion process. This increases the polymer demand for sludge conditioning. Soluble COD was proved to have good relationships with soluble biopolymer and OPD (Higgins et al. 2006, To et al. 2014). Based on these data, it may be suggested that the order of polymer demand for sludge conditioning is: ADS > AEDS > WAS.

4.2. Effects of sludge characteristics on sludge conditioning and dewatering

4.2.1. Sludge properties in relationships with conditioning and dewatering

One of main objectives of this study was to establish correlations between dewatering indices and sludge characteristics to identify the most influencing factors of sludge conditioning and dewatering. Thus a number of feeding sludge properties were measured and related to CST values of feeding sludge and optimal polymer demand (OPD). The OPD in this study was measured by CST test. Besides, relationships between soluble biopolymers and soluble COD were also investigated to clarify whether soluble COD could be used as a substitute for soluble protein and polysaccharides to estimate the polymer requirement for conditioning.

4.2.1.1. For each sludge type

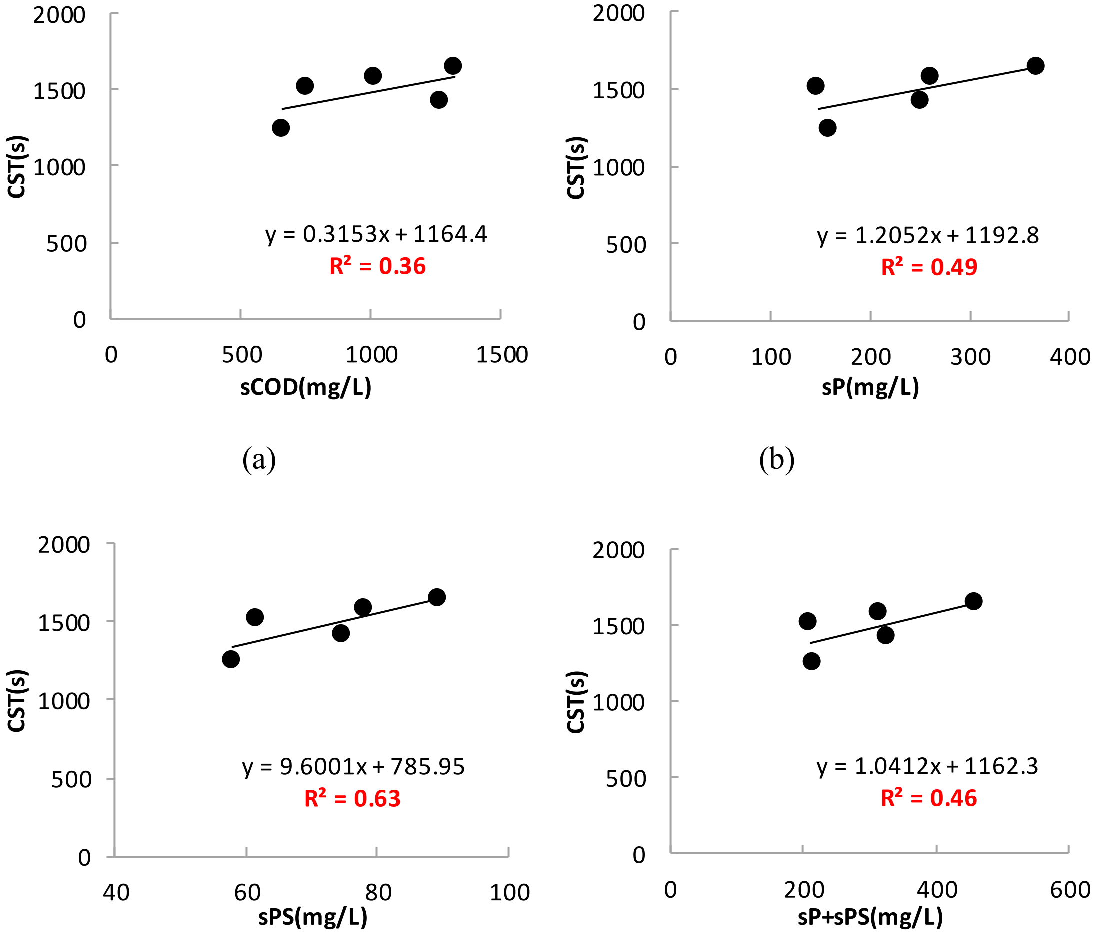
4.2.1.1.1. ADS

- **Dry solids (DS) content and Volatile solids (VS) content**

DS and VS are considered as two important parameters that are often used to calculate the amount of conditioning polymer for a given sludge. The original concept of conditioning is the neutralization of the surface charge of sludge particles using oppositely charged conditioners, which primarily decides the polymer demand for conditioning, until the idea of soluble biopolymers emerged. Results from Table 4–4 show that correlations of DS with both CST (R^2 = 0) and OPD (R^2 = 0) did not exist. This is in conflict with a previous study of Vesilind (1988), who found a linearly positive relationship between CST and solid concentration of a mixed digested sludge (feeding sludge). Similarly, VS also correlated insignificantly with CST (R^2 = 0.02), however, better with OPD (R^2 = 0.20) compared to DS. This may be because VS is a parameter representative of the organic matter content, therefore it could have impact on polymer demand for conditioning. Nevertheless, low correlation coefficient value could be due to the fact that VS consists of many different types of organic substances but not all of them require polymer for conditioning.

- **Soluble substances**

Among the parameters studied, soluble biopolymers, mainly sP and sPS, correlated well with CST both separately (R^2 = 0.49 for sP; R^2 = 0.63 for sPS – Figure 4–4) and together (R^2 = 0.46 for sP+sPS – Figure 4–4). sCOD had a slightly weaker relationship (R^2 = 0.36 – Figure 4–4) with CST. This implies that these soluble substances, especially soluble biopolymers, hinder sludge dewaterability.

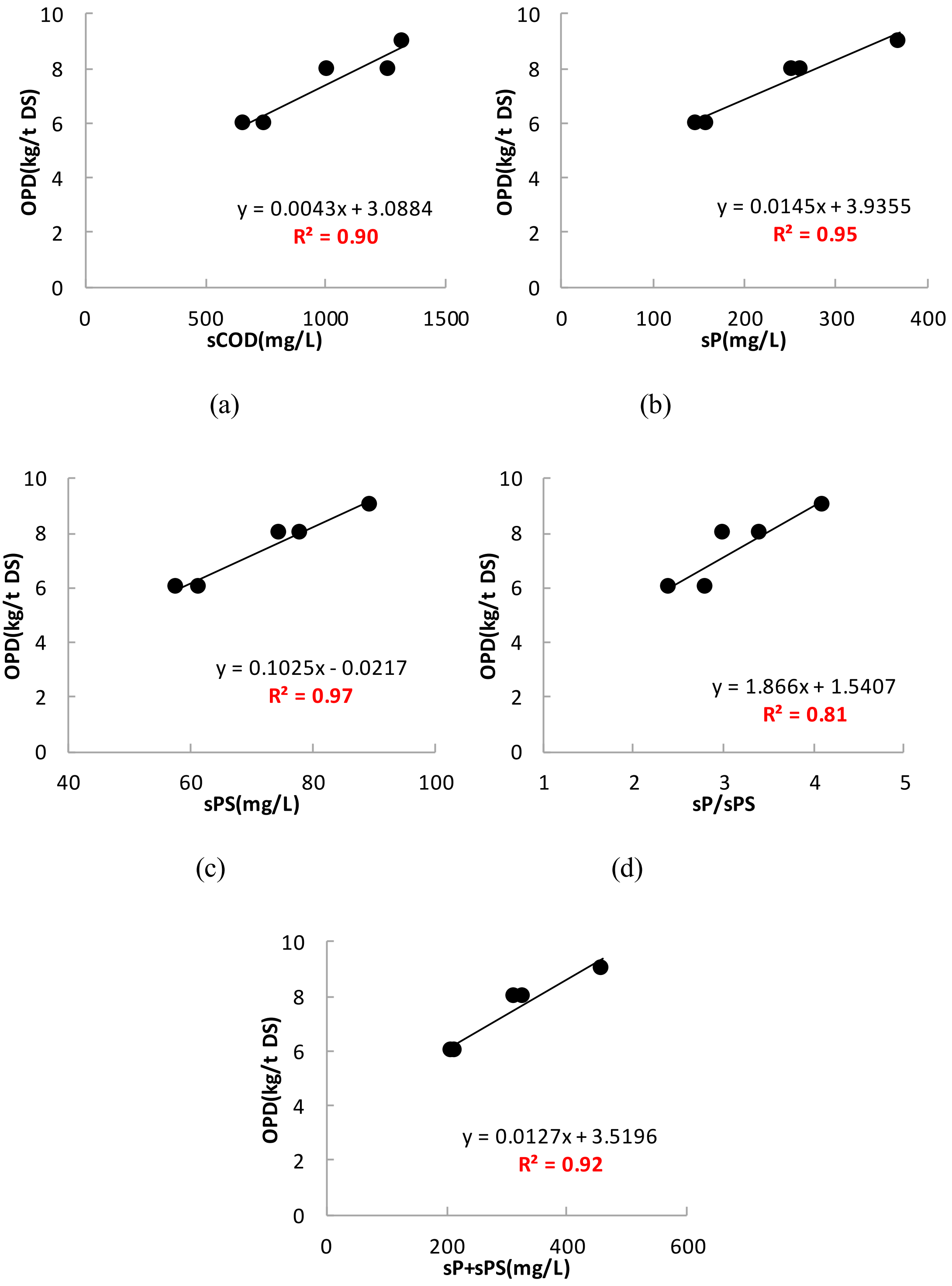


(a) (b)

(c) (d)

Figure 4–4 Relationships between CST and sludge characteristics including: (a) Soluble COD; (b) Soluble Protein; (c) Soluble Polysaccharides and (d) Total soluble biopolymers for ADS

Novak et al. (2003) found that soluble biopolymers are responsible for the excessive polymer for conditioning. Similar results were obtained in this study. Both soluble protein and PS had good correlations with OPD (R^2 = 0.95 for sP and R^2 = 0.97 for sPS – Figure 4–5). These results confirm that soluble biocolloid contents can be used as an important factor in determining as well as predicting the OPD for sludge conditioning. Additionally, a good relationship between sCOD and OPD were also recorded, with R^2 = 0.90.



(a)

(b)

(c)

(d)

(e)

Figure 4–5 Relationships between OPD and sludge characteristics including: (a) Soluble COD; (b) Soluble Protein; (c) Soluble Polysaccharides; (d) sP/sPS and (e) Total soluble biopolymers for ADS

Since both soluble biopolymers contribute to the polymer demand, correlation could be better when considering these two components together (Higgins et al. 2006). The data displayed relatively good correlations between OPD and total soluble biopolymer contents ($R^2 = 0.92$); and OPD and ratio of sP to sPS ($R^2 = 0.81$).

- **Zeta potential (ZP)**

It has been known that main mechanism for coagulation/ flocculation is charge neutralization (Gregory 1993). Our results showed a weak negative linear trend ($R^2 = 0.25$) between ZP and CST. This could imply that the more negative ZP, the less effective the sludge dewatering. Similarly, a weak correlation of ZP and OPD was observed as shown in Table 4–4 ($R^2 = 0.19$). Despite of insignificant relationships with sludge conditioning and dewaterability, this index can give useful indirect information on determining the conditioning polymer demand based on charge neutralization (Chitikela & Dentel 1998).

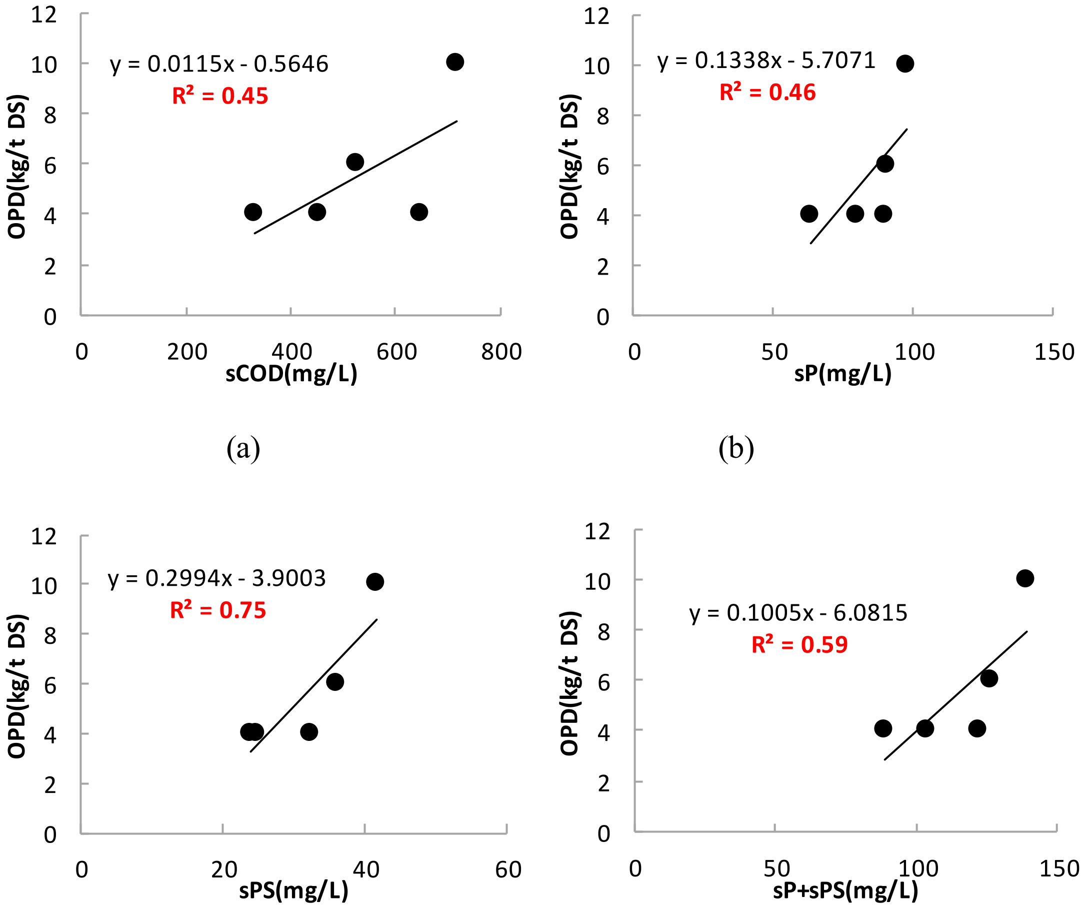
4.2.1.1.2. AEDS

- **Sludge properties in relationships with CST**

For AEDS, as can be noticed from Table 4–4, no significant correlations were observed between ZP, DS, VS, soluble substances (sCOD, sP, sPS, sP+sPS, sP/sPS), except for VS/DS, and CST. VS/DS was negatively linear with CST, with $R^2 = 0.81$, which means the more the VS content, the better the sludge dewatering. This is in disagreement with prior discussion that increase in VS should have led to poorer sludge dewaterability. This uncommon feature could be attributed to insufficient experimental data.

- **Sludge properties in relationships with OPD**

Similar to ADS, soluble substances also correlated well with OPD, especially sPS with R^2 = 0.75 then sP+sPS, sP, sCOD with R^2 =0.59, R^2 = 0.46, R^2 = 0.45 respectively (Figure 4–6). It could imply that, for AEDS, sPS possibly plays a more important role in deciding polymer demand for conditioning. Weak or insignificant relationships with OPD were observed for ZP, DS, VS and VS/DS.



(a) (b)

(c) (d)

Figure 4–6 Relationships between OPD and sludge characteristics including: (a) Soluble COD; (b) Soluble Protein; (c) Soluble Polysaccharides and (d) Total soluble biopolymers for AEDS

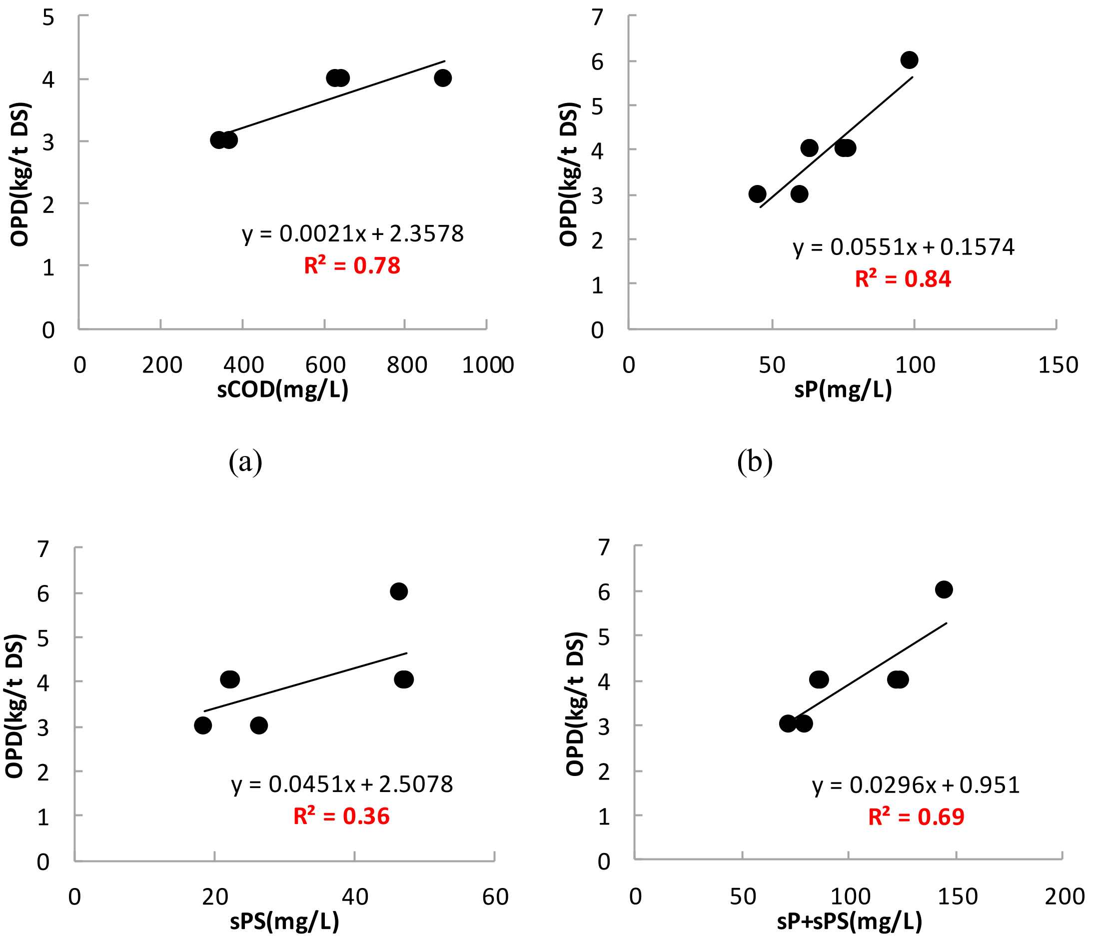
4.2.1.1.3. WAS

- **Sludge properties in relationships with CST**

Unlike ADS and AEDS, DS and VS of WAS produced better relationships with CST, with R^2 = 0.33 and R^2 = 0.53 respectively. sCOD, sP, sP+sPS and sP/sPS were related weakly with CST while no relationship was noticed with the other parameters.

- **Sludge properties in relationships with OPD**

In contrast with AEDS, sP of WAS seemed to play a more important role in estimating OPD (with R^2 = 0.84) than sPS (with R^2 = 0.36) (Figure 4–7). sCOD and total soluble biopolymers also correlate well with OPD, with R^2 = 0.78 and R^2 =0.69 respectively (Figure 4–7). Not much correlation with OPD has been observed for DS, VS VS/DS and ZP of WAS.



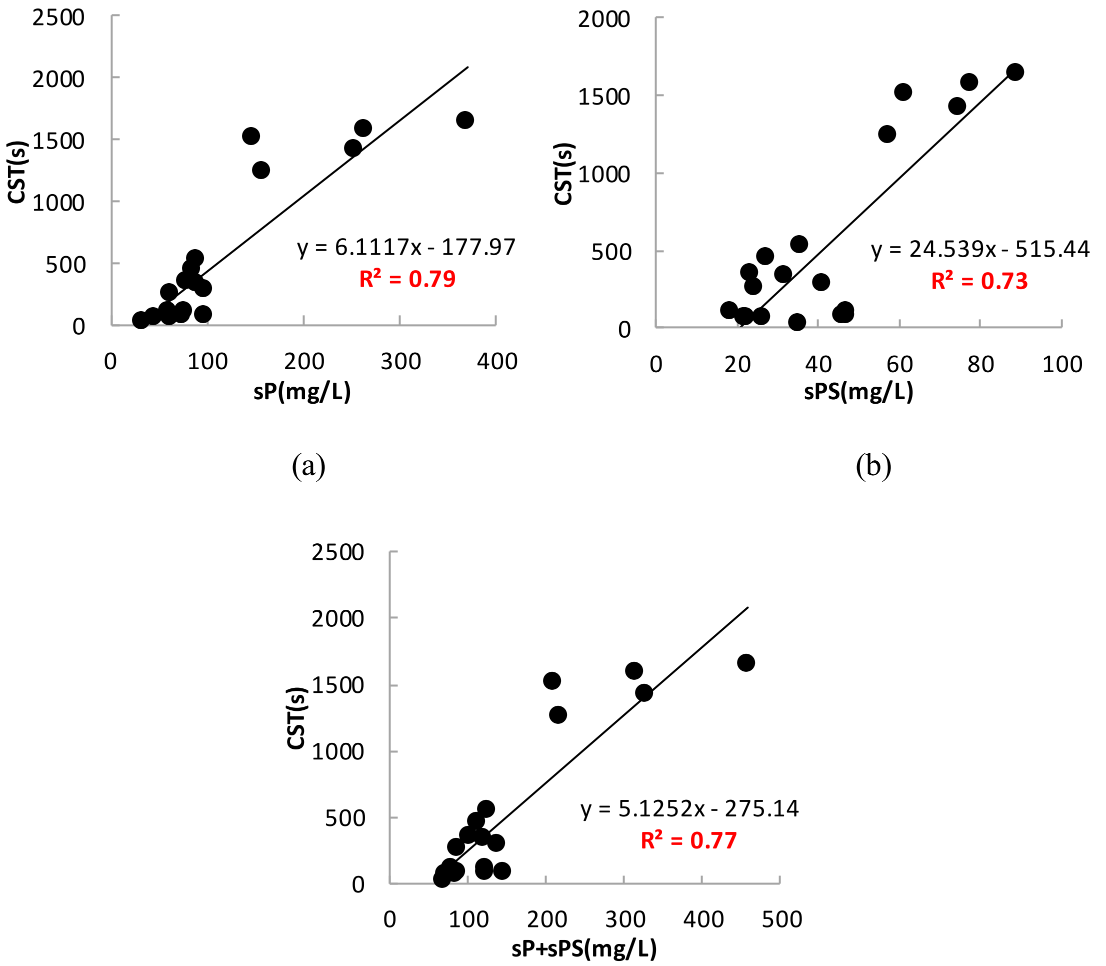
(a) (b)

(c) (d)

Figure 4–7 Relationships between OPD and sludge characteristics including: (a) Soluble COD; (b) Soluble Protein; (c) Soluble Polysaccharides and (d) Total soluble biopolymers for WAS

4.2.1.2. For all sludge types

While soluble biopolymer were denoted to have insignificant relationship with CST for each sludge type individually, better correlations was observed between soluble biopolymers and CST when taking all sludge types together into consideration (R^2 = 0.79 for sP, R^2 = 0.73 for sPS and R^2 =0.77 for sP+sPS). ZP was also correlated well with CST, with R^2 = 0.72. Results are shown in Figure 4–8.



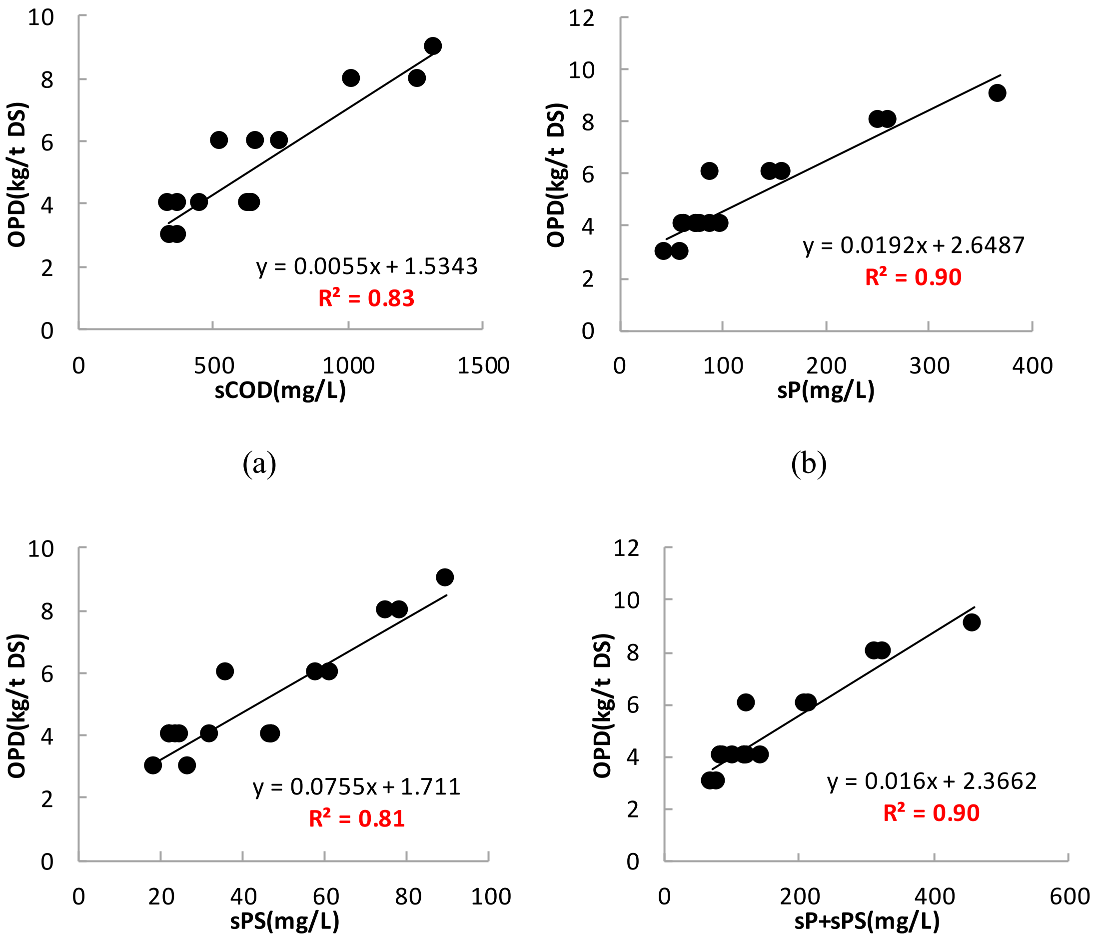
(a)

(b)

(c)

Figure 4–8 Relationships between CST and sludge characteristics including: (a) Soluble Protein; (b) Soluble Polysaccharides and (c) Total soluble biopolymers for all sludge types

Strong correlations between soluble biopolymers (alone and together) and sCOD with OPD were also noticed for all sludge types (Figure 4–9), which confirms that soluble biocolloids create additional polymer demand.



(a) (b)

(c) (d)

Figure 4–9 Relationships between OPD and sludge characteristics including: (a) Soluble COD; (b) Soluble Protein; (c) Soluble Polysaccharides and (d) Total soluble biopolymers for all sludge types

Table 4–4 summarizes the correlation coefficients (R^2) of sludge characteristics with sludge conditioning and dewaterability for each as well as all sludge types of the 3 WWTPs studied. In general, most of good relationships were noticed with ADS compared to the other 2 sludge types. The most noticeable feature was that good correlations were witnessed between soluble biopolymers and OPD for both single sludge type and all sludge types, which highlights the major role of soluble biopolymers in deciding conditioning polymer demand.

Table 4–4 Relationships (R^2) of sludge characteristics with OPD and CST for ADS, AEDS, WAS and all sludge types

Sludge types		ZP	DS	VS	VS/DS	sCOD	sP	sPS	sP+sPS	sP/sPS
ADS	CST	-0.25	0.00	+0.02	+0.01	+0.36	+0.49	+0.63	+0.46	+0.22
	OPD	-0.19	0.00	+0.20	+0.06	**+0.90**	**+0.95**	**+0.97**	**+0.92**	**+0.81**
AEDS	CST	-0.15	0.00	-0.03	**-0.81**	+0.05	+0.11	+0.01	+0.02	+0.07
	OPD	-0.12	-0.06	-0.01	+0.20	+0.45	+0.46	**+0.75**	0.59	-0.41
WAS	CST	+0.04	+0.33	+0.53	+0.14	+0.33	+0.43	+0.01	+0.26	+0.24
	OPD	-0.04	+0.12	+0.25	0.00	**+0.78**	**+0.84**	+0.36	+0.69	-0.03
All sludge types	CST	**-0.72**	-0.03	-0.11	-0.31	+0.55	**+0.79**	**+0.73**	**+0.77**	+0.29
	OPD	-0.64	-0.09	-0.22	-0.26	**+0.83**	**+0.90**	**+0.81**	**+0.90**	+0.32

‘ – ‘: negative linear; ‘ + ’: positive linear

4.2.1.3. Soluble COD as a surrogate measure of soluble biopolymers

Since soluble protein and polysaccharides analyses are not typically used for field measurements due to the specific equipment and reagents requirements, soluble COD could be used as a representative surrogate parameter because of its frequent use in many treatment facilities (Higgins et al. 2006).

Table 4–5 presents strong relationships between sCOD and soluble biopolymers both individually and altogether (except for sP/sPS) for each and all sludge types. However, as can be observed from table 4–4, in all cases, soluble COD did not correlate with OPD as well as biopolymers, which was not in agreement with previous report of (Higgins et al. 2006). Therefore, it is not convincing to use sCOD as a surrogate simple measure of biocolloid concentration.

Table 4–5 Relationships (R^2) of sCOD with soluble biopolymers for ADS, AEDS, WAS and all sludge types

	ADS	AEDS	WAS	All sludge types
sP	**0.81**	**0.88**	**0.75**	**0.75**
sPS	**0.83**	**0.71**	**0.60**	**0.70**
sP/sPS	**0.78**	0.00	0.00	0.27
sP+sPS	**0.83**	**0.88**	**0.74**	**0.77**

(All relationships were positive linear)

4.2.2. Selection of appropriate polymer type for an effective sludge dewatering

Selection of appropriate polymer types and demand for effective sludge conditioning and dewatering is a function of three main factors which are sludge types, polymer properties and dewatering equipment. Previous parts focused mainly on sludge types in relationships with conditioning. However, polymer properties such as charge density, configuration and molecular weight also have significant impact on OPD. The study have developed a method that has ability to determine appropriate polymer type and dose for an effective dewatering using relationship graphs of sludge properties and OPD. Here, soluble biopolymers were representative for sludge characteristics since they were demonstrated to correlate well with OPD in the earlier parts. Then effects of these polymers on dewatering performance were evaluated through shear sensitivity tests of conditioned sludge, which considers the influence of shear created by dewatering devices on OPD. ADS and WAS were chosen to test the method since they are 2 common sludge types at the WWTPs.

Charge neutralization and polymer bridging are two main mechanisms of sludge conditioning. In fact, there is one process among two that predominantly governs the flocculation and it depends on both sludge characteristics and polymers types used. A concept of 'y – intercept' in the OPD versus soluble biopolymer content curve (Figure 4–10) proposed by Higgins et al. (2006) is believed to identify PD for both charge neutralization and bridging formation in sludge conditioning. The concept was based on the relationship between OPD and soluble biopolymers (total sP and sPS) which were demonstrated to have major role in deciding conditioning PD. As can be seen in Figure 4–10, the y – intercept for the graph is about 2kg/t DS. It suggests that this amount of polymer was not used for charge neutralization since this case presents no soluble biocolloids. Therefore, 2kg/t DS can be thought of as the polymer used for bridging formation and the rest of OPD was utilized to neutralize surface charge. Comparing these two polymer quantity can decide which mechanism is predominant. For ADS, PD for charge neutralization was superior compared to polymer bridging, as a result, the former prevailed in flocculation. By contrast, WAS conditioning was governed by bridging phenomena since PD for this process was dominant.

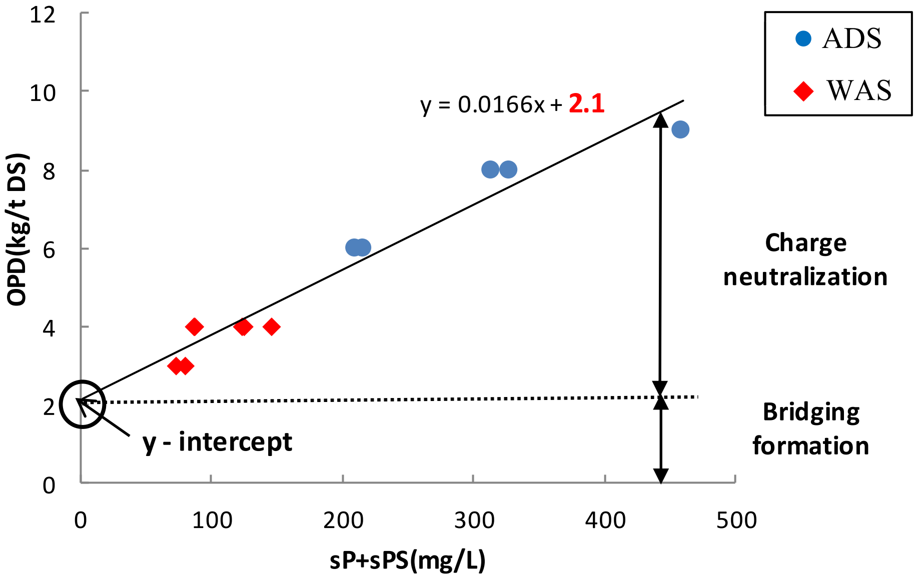


Figure 4–10 Conditioning mechanisms based on relationships between OPD and soluble biopolymer content of ADS and WAS.

Besides interactions between sludge particles and polymers during conditioning, response of both sludge and polymers to shear during dewatering is necessary to optimize sludge conditioning and dewatering. Higgins et al. (2006) carried out a set of experiments to examine the response to shear of different sludge types and concluded that WAS is the most sensitive and ADS is the least sensitive to shear. It means WAS flocs are easy to be broken during high speed dewatering while ADS has more inherent floc strength to withstand the shear.

Conditioning polymers are available in different types of charge density, molecular weight and structure, which interact differently with sludge particles during conditioning. Since cationic polymers with high and very high molecular weight are most widely used for conditioning of wastewater sludge (Spinosa & Vesilind 2001), the other two characteristics are of more concern for flocculation. As discussed in the last section, ADS conditioning is mainly controlled by charge neutralization, as a result, polymers with high charge density or mole charge could favour this process. On the other hand, delicate WAS flocs require structured polymers such as branched or cross–linked polymers to 'embrace' tightly or incorporate these sludge flocs into the larger ones through bridging formation mechanism.

According to the above results, not only OPD but also suitable polymer types could be predicted for an effective sludge conditioning. Conceptually, this study suggests the use of high mole charge and branched cationic polymers for better ADS and WAS conditioning and dewatering, respectively. Effects of these polymers on dewatering performance were evaluated through shear sensitivity tests of conditioned sludge. This paper only presents the experiment results of ADS.

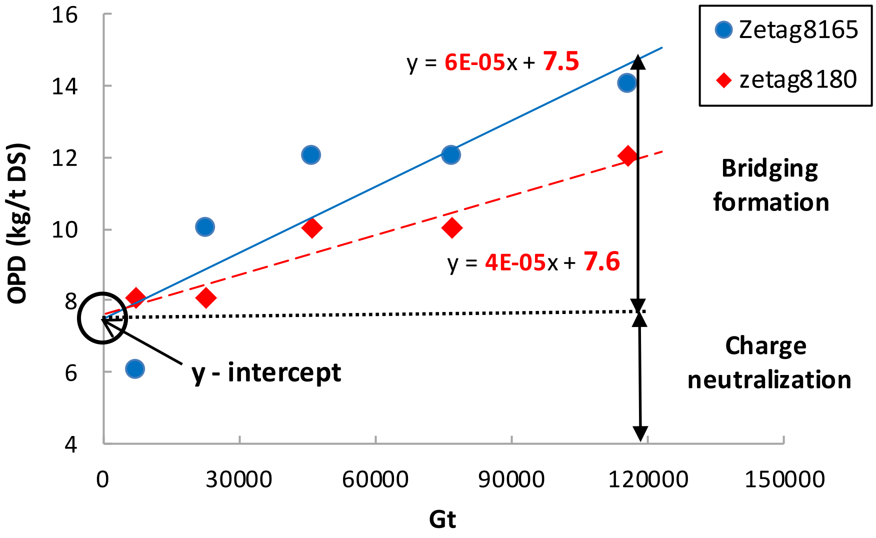


Figure 4–11 Relationships between OPD and shear intensity (Gt) for ADS conditioned with zetag8165 and zetag8180

The above suggestion of polymer type for conditioning was only based on relationship between sludge and polymer properties, which has not taken the effect of dewatering equipment into account. The shear sensitivity test examines the response of polymer to shear. Effect of shear intensity (Gt), which represents the dewatering stress, on cake solids content of ADS is shown in Figure 4–11. Two linear, high molecular weight cationic polymers with different mole charge (zetag8165 with 60% mole charge and zetag8180 with 80% mole charge) were tested to elucidate their impacts on OPD. Similar trends were observed for both polymers with OPD increasing with higher Gt values. The additional PD could be used for preventing flocs from breakup when exposing to high shear.

In contrast with the last section, y – intercept in the OPD – shear intensity relationship indicates the PD needed to neutralize biocolloidal particles at ‘zero’ shear. Figure 4–11 illustrates that higher mixing intensity or Gt values resulted in higher OPD for ADS conditioning and the additional PD can be considered as demand for bridging formation among broken flocs during shear.

Besides the y – intercept, slopes of OPD – shear intensity relationships were also considered for the purpose of comparing the effects of 2 different types of cationic polymers, in terms of mole charge, on ADS conditioning and dewatering. The y – intercepts of the 2 polymers were similar (about 7.5kg/t DS – Figure 4–11) whilst the slope of higher mole charge polymer was less than that of the lower one. This implies a lower OPD as well as higher resistance to shear of ADS when conditioning with the higher mole charge polymer.

4.3. Conditioning tests – Determination of optimal conditioning regimes

4.3.1. Determination of optimal mixing intensity

In order to identify the OPD for a specific sludge, it is necessary to determine the optimal mixing speed and mixing time for conditioning of each sludge type. This study, bench–scale experiments were carried out by varying mixing speed (100 – 500rpm) and time (30 – 300s) to determine the most appropriate regimes. Digested sludge from 3

WWTPs were conditioned with currently used polymer types and doses at these WWTPs. CST tests were used to determine the OPD in each case and the mixing speed and time that resulted in minimum values of CST were considered as optimal. Table 4–6 presents the suitable conditioning regime for 3 WWTPs studied.

Table 4–6 Optimal mixing intensity for conditioning of ADS, AEDS and WAS

Sludge types	Optimal mixing speed (rpm)	Optimal mixing time (s)
ADS	200	60
AEDS	400	60
WAS	400	60

It should be noted that these mixing conditions were tested using lab–scale tests only. In fact, mixing process at the plants occurs within a short time (even a few seconds such as Quakers Hill WWTP) at a high mixing speed (more than 3500 rpm). It was observed from the experiment that high mixing speed could easily break the sludge flocs formed during conditioning which resulted in dark centrate. On the other hand, short mixing time, less than 60s, would not be enough for an effective flocculation and consequently resulting in bad dewatering performance. Similar to previous researches, here Gt value has been used to measure the shear exerted on sludge floc during mixing.

4.3.2. Determination of optimal polymer demand (OPD)

CST tests and charge neutralization have been commonly applied for OPD determination in many studies by virtue of their simple and rapid measurement. The present study also utilized these tests to identify the OPD for each sludge type. Results show that OPD values determined by CST tests were much lower (up to 50%) while ZP indicated much higher doses than PD used at the WWTPs, which were seen for all 3 sludge types.

4.3.2.1. Wollongong WWTP – ADS

Table 4–7 presents the values of OPD determined by CST and ZP tests at different sampling times. It was noted that the CST values rapidly decreased with increasing polymer dose till a dose of 6 – 9 kg/t DS and remained almost constant afterwards. Thus this dose was taken as OPD for the sludge used. This value was much lower (up to 50%) than the currently used polymer dose at the WWTP (12kg/t DS).

Table 4–7 Comparison of OPD determined by traditional indicators (CST and ZP) with the polymer dose currently used at Wollongong WWTP

Sampling dates	OPD determined by CST (kg/t DS)	OPD determined by charge neutralization (kg/t DS)	Polymer dose at the WWTP (kg/t DS)
03/09/2013	8	-	12
08/10/2013	9	14	12
04/12/2013	6	9	12
07/02/2014	6	10	9
25/03/2014	6	10	9

In comparison with CST tests in determining OPD, using ZP or charge neutralization to estimate the optimum of polymer dose may result in over – dosed conditioning. Results showed that OPD indicated by ZP was about 1.5 times greater than that indicated by CST (Table 4–7). This may be due to the fact that charge neutralization may not be the only flocculation mechanism. Polymer bridge formation also plays a role to achieve efficient flocculation. ZP indicates the PD necessary for charge neutralization only.

4.3.2.2. St. Marys WWTP – AEDS

OPD necessary for conditioning of AEDS was 4 – 6kg/t DS which again was lower than the current PD being used at St. Marys WWTP (9 – 10kg/t DS) (Table 4–8). The trend of CST reduction was similar to the case of Wollongong WWTP.

Table 4–8 Comparison of OPD determined by traditional indicators (CST and ZP) with the polymer dose currently used at St. Marys WWTP

Sampling dates	OPD determined by CST (kg/t DS)	OPD determined by charge neutralization (kg/t DS)	Polymer dose at the WWTP (kg/t DS)
20/11/2013	4	12	9
03/03/2014	6	12	10
22/05/2014	6	-	10
24/06/2014	6	-	10

Unlike the other 2 plants, St. Marys WWTP utilizes belt filter press for sludge dewatering. As a result, centrate quality was never their major problem thanks to the operation of filter press. However, dewatered cake with high moisture content has been a big issue in this plant. A highly compressible sludge floc was observed after polymer conditioning, especially in the case of over – dosed conditioning. During dewatering by pressure filtration, cake blinding may occur and reduce the cake porosity as well as increases the cake specific resistance, which in turn deteriorates sludge filterability (Qi et al. 2011). The present study also suggested 2 solutions that may help increase cake solids content for St. Marys WWTP:

- Replacing belt filter presses with high–speed centrifuges.
- Using skeleton builder aids that can assist filtration of digested sludge (such as lignite, fly ash, lime, iron chloride, etc.) for sludge conditioning.

4.3.2.3. Quakers Hill WWTP – WAS

Results from Table 4–9 illustrate that the range of OPD for WAS conditioning were typically 3 – 4kg/t DS (except for the last sampling) which was the lowest among 3 sludge types studied. This support our prediction earlier that the polymer amount used for WAS conditioning may be smaller than that used for ADS and AEDS conditioning. This OPD range was also lower than the currently used polymer doses (6 – 8kg/t DS) at the plant. The operators at Quakers Hill WWTP add more conditioning polymer to improve centrate quality. However, lab–scale experiments show that over–dosed conditioning could bring about adverse effect on sludge dewaterability.

Table 4–9 Comparison of OPD determined by traditional indicators (CST and ZP) with the polymer dose currently used at Quakers Hill WWTP

Sampling dates	OPD determined by CST (kg/t DS)	OPD determined by charge neutralization (kg/t DS)	Polymer dose at the WWTP (kg/t DS)
20/11/2013	3	7.5	8
17/12/2013	4	5	8
03/03/2013	4	7	6
24/06/2014	4	-	8.5
28/07/2014	6	-	7

Figure 4–12 presents results of CST tests for WAS conditioning. It can be noticed that CST reduced with the increase in PD (up to a dose of 4kg/t DS). However, when PD was increased to more than 4kg/t DS, the CST values started to rise again. This may be due to the absorption of water molecules onto the excess polymer particles, which prevented moisture coming out of sludge (Chu & Lee 1999). Besides, these excess

amounts of polymer also lead to charge reversal phenomenon, causing disaggregation and redispersion of the sludge flocs (Sanin et al. 2011).

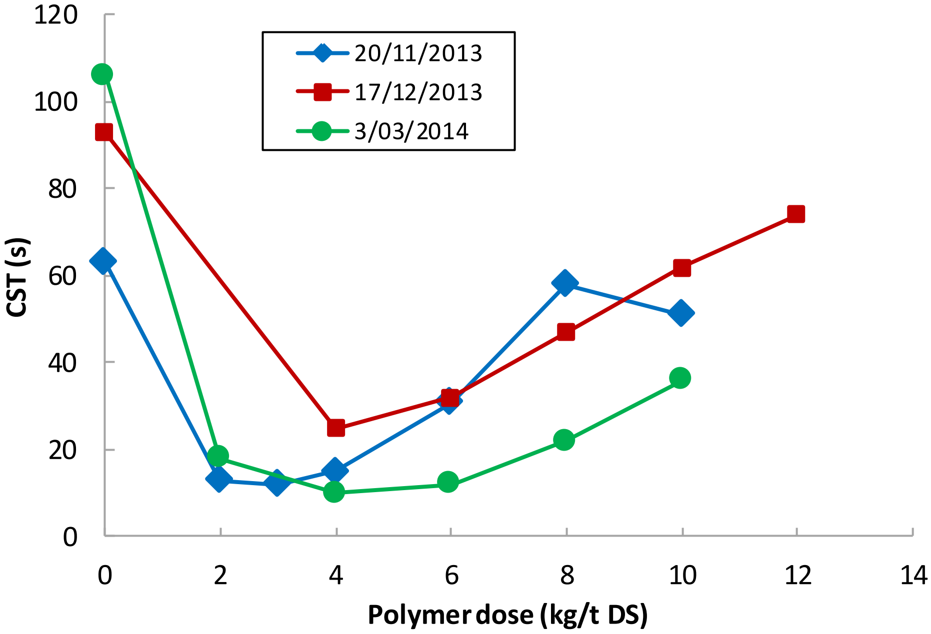


Figure 4–12 OPD determination by CST tests for WAS conditioning

However, the major difference in a full–scale centrifuge from CST tests is the applied shear during dewatering, which creates more polymer demand. It is also understandable that the plant operators tend to add extra polymer to ensure that the solids capture is maximized. Hence, there would always be more than what "theoretically" is needed. Therefore, these results do not guarantee that these lower doses could work in the field. In this case, MCI tests, which can reproduce the centrifuge stresses exerting the sludge flocs or cake, could tackle this problem.

4.4. Modified centrifugal index (MCI)

4.4.1. Effects of centrifugal intensity (gt) on solids cake content

The MCI measurement (more representatives to field condition) was used to measure the dewatering efficiency and OPD. The original concept of MCI test is the application of cake solids content for evaluating dewatering efficiency since reducing sludge volume is the ultimate objective of dewatering (To et al. 2014). Besides, this method also utilizes centrifugation intensity or gt value to investigate the influence of dewatering equipment, specifically centrifuge, on sludge cake. Generally speaking, increasing gt value resulted in the improvement of cake solids content (Figure 4 –13, 4–14 and 4–15). However, beyond a certain gt, there were plateaus in solids concentration of dewatered cake indicating a limitation of dewatering by centrifuge.

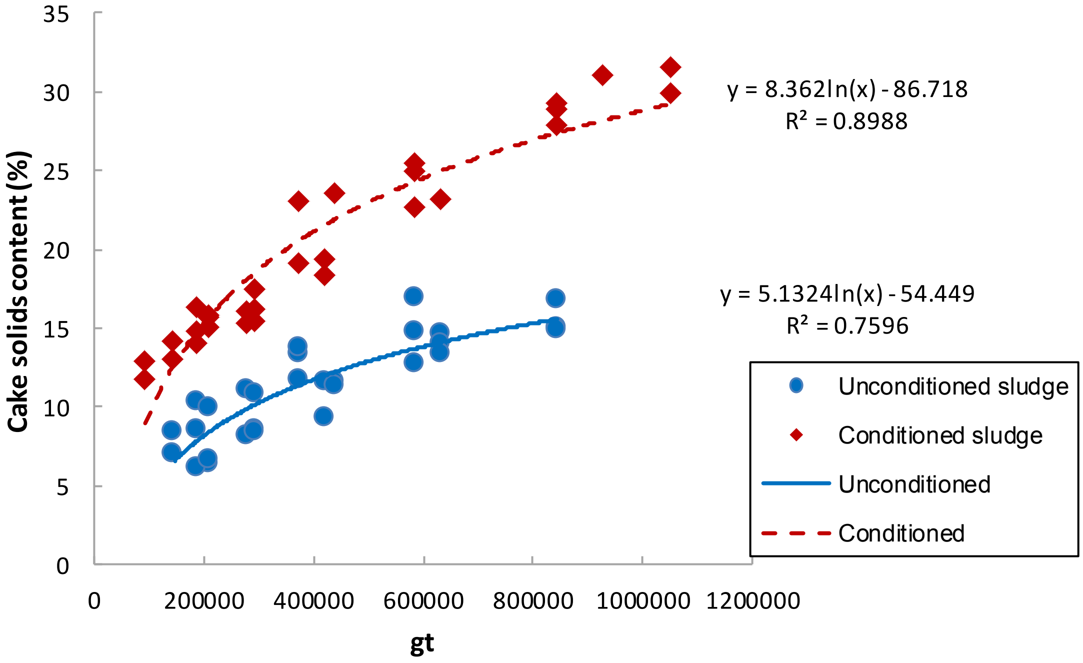


Figure 4–13 Effect of gt on cake solids content of unconditioned and conditioned ADS (PD = 12kg/t DS)

Even though similar trends were observed for MCI tests of sludge with and without conditioning, there are several important differences between the two which could reflect effects of not only conditioning but also dewatering devices on sludge dewaterability. Firstly, solids contents of sludge cake were significantly improved after conditioning, especially for ADS (from 16% to almost 30% - Figure 4–13) and AEDS (from 19% to around 27% - Figure 4–14). WAS cake solids content, however, did not change that much with conditioning (only from 19% to 23% - Figure 4–15) despite of that all characteristics of this sludge type favour its dewaterability.

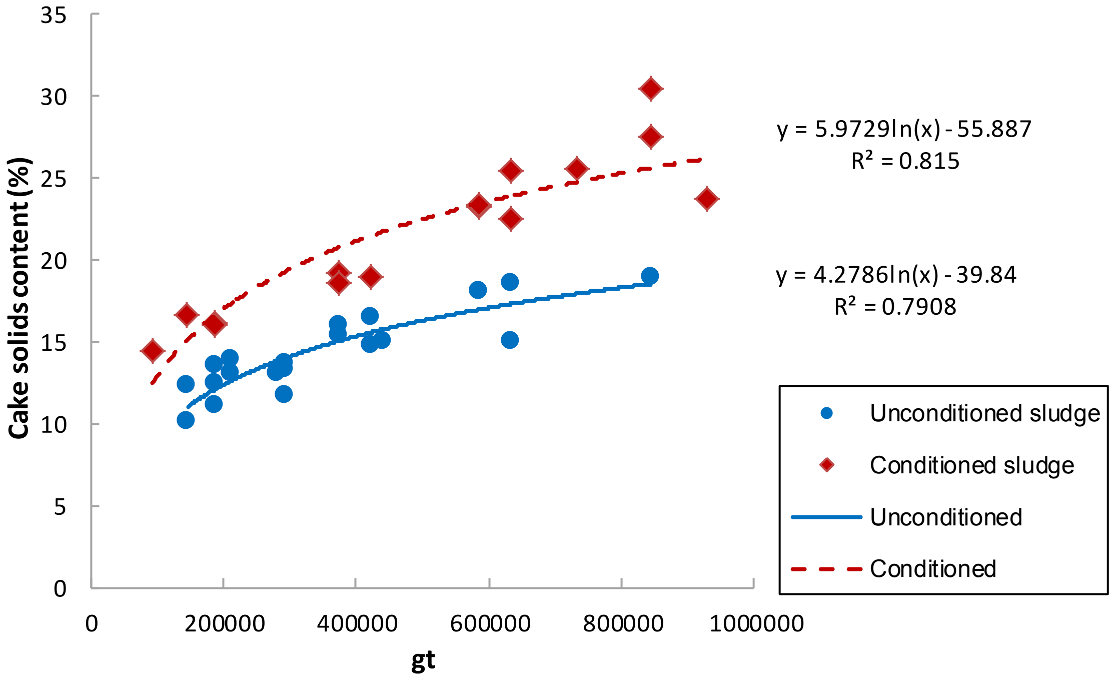


Figure 4–14 Effect of gt on cake solids content of unconditioned and conditioned (PD = 10kg/t DS) AEDS

Secondly, same cake solids content of unconditioned sludge can be obtained at much lower centrifugation intensity for conditioned one, which implies that dewatering rate was considerably enhanced by conditioning treatment. For instance, 16% of ADS could be achieved at 200000 of gt after conditioning instead of 800000 of gt (Figure 4–13) before conditioning. This reduction in centrifugation intensity could suggest an energy–saving solution for dewatering equipment. Thus, MCI test can be successfully used to determine the optimum gt value of the centrifuge corresponding to the maximum cake solids content.

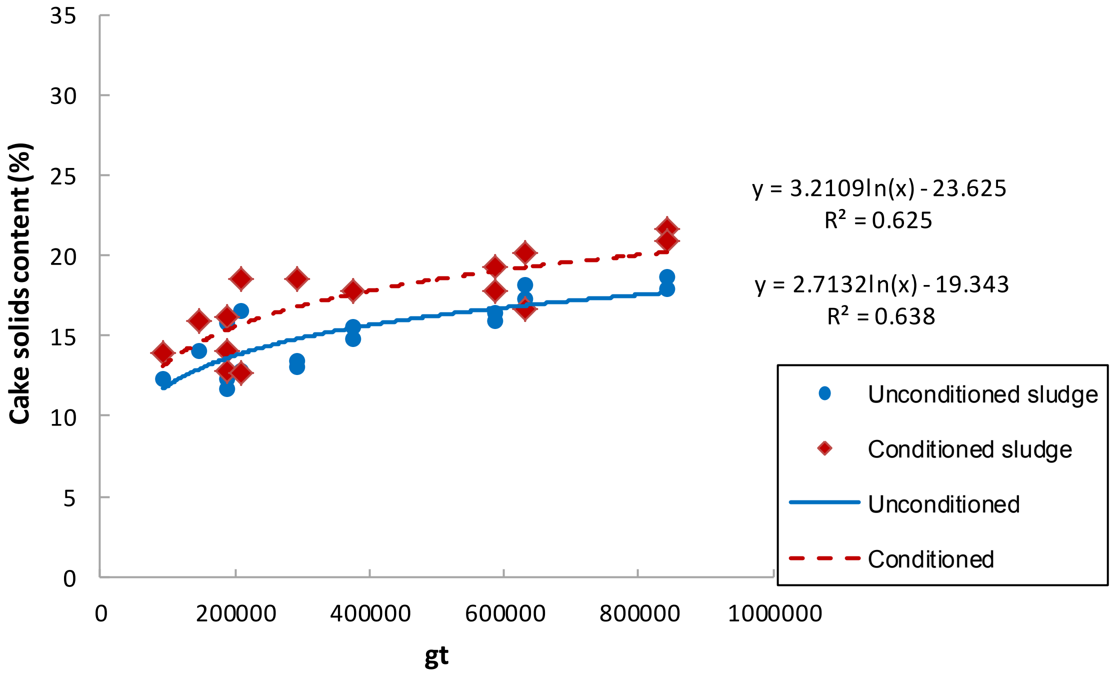


Figure 4–15 Effect of gt on cake solids content of unconditioned and conditioned WAS (PD = 6kg/t DS)

Chen et al. (1996) stated that sludge dewaterability by filtration processes can be characterized by the residue moisture or cake solids cake content and the ease or rate of the filtration process. Based on the above results, MCI test is demonstrated to be appropriate for estimating the final cake content as well as reflecting the dewatering rate. Besides, this method can simulate the prototype dewatering process of centrifuge. However, in order to fully apply this technique for evaluating sludge dewaterability like any other previous indicators, further work need to be done to investigate the influencing factors of MCI tests.

4.4.2. MCI tests – Prediction of maximum cake solids content achievable by centrifuge

Estimation of maximum cake solids content achievable is one of important application of MCI test. In order to assess the reliability of this method for predicting cake solids content, this study compared results of MCI with full–scale tests. As observed from Table 4–10, after conditioning with the same PD used at the WWTPs, maximum cake solids content of ADS and WAS determined by MCI tests were quite similar to the typical solids content of cake in those plants. However, the cake solis content of AEDS was much higher than full–scale results.

Table 4–10 Maximum cake solids content determined by MCI tests and full–scale processes for 3 sludge types

Sludge types	Maximum cake solids determined by MCI tests (after conditioning[a]) (%)	Typical cake solids at the WWTPs (%)
ADS	28.9 ± 0.9	27 – 29
AEDS	26.2[b] ± 1.1	15 – 19[c]
WAS	22.6 ± 0.6	19 – 22

[a] After conditioning at PD used at the WWTPs

[b] Cake solids achievable by lab – scale centrifuge

[c] Cake solids achievable by full – scale belt press

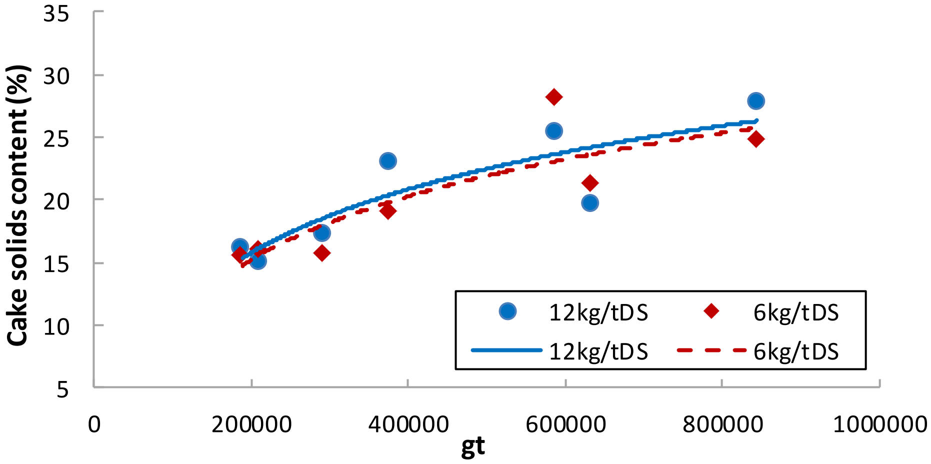
To explain this difference, it should be noted that Wollongong (ADS) and Quakers Hill (WAS) WWTPs are applying high–solids bowl centrifuges for sludge dewatering while St. Marys (AEDS) WWTP is using belt filter press (Table 3–1). This could be the reason for the lower dewatering efficiency at St. Marys WWTP since belt press is proved to be not effective in sludge dewatering as centrifuge. It also suggests that centrifuge may be a preferred option for this plant compared to belt press. In case of WAS, dewatering performance is not effective (only 15 – 19%) even though high–speed centrifuges have been used to dewater sludge. It could be due to the sludge itself that leads to poor dewaterability and, as stated in the last section, digestion is perhaps a solution for this obstacle.

The above results show that MCI test is an appropriate method for predicting maximum cake solids content achievable by centrifuge. Besides, it can help the WWTPs identify their problems of ineffective sludge dewatering such as St. Marys WWTP with inefficient dewatering equipment and Quakers Hill with undigested feeding sludge. Nevertheless, solids cake content should be considered as major not exclusive indicator for dewatering since this process is impacted by numerous factors.

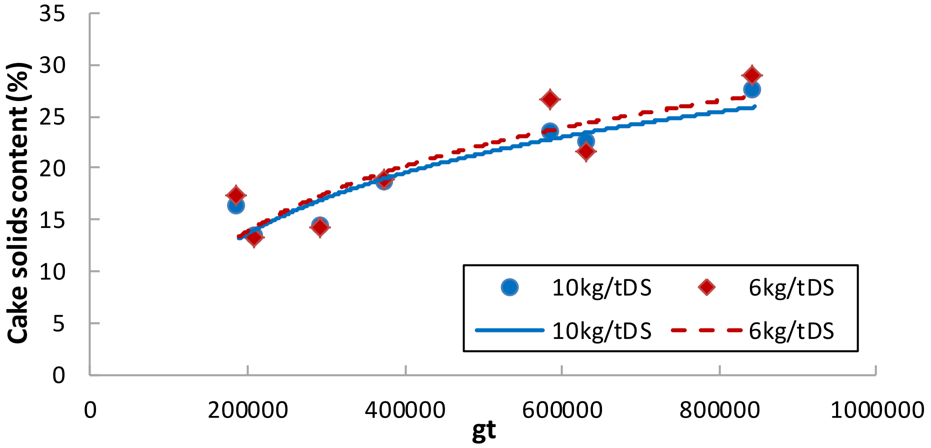
4.4.3. MCI tests – Determination of Optimal Polymer Dose (OPD)

MCI tests were carried out at OPD determined by CST and PD at the WWTPs studied for 3 types of sludge. As can be seen from Figure 4–16, solids cake content with 2 different doses were quite similar for ADS (Figure 4–16a) and AEDS (Figure 4–16b), with solids content almost 30% for both. This means same dewatering efficiency could be achieved by using half of the polymer amount used for conditioning at these WWTPs. In fact, the amounts of polymer used for conditioning at the WWTPs are often based on DS of feeding sludge or the experience of the operators. This may result in over–dosing or under–dosing situations, which probably incur in higher cost for the same performance.

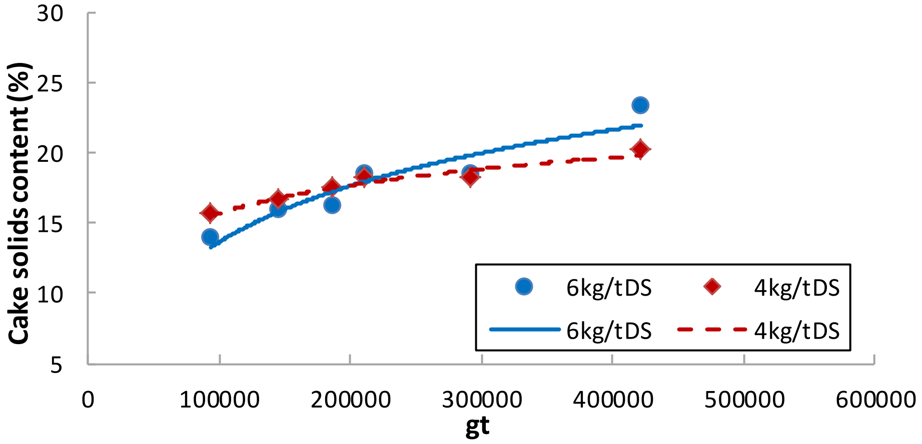
For WAS, nonetheless, OPD indicated by CST led to lower cake solids (about 20%) than PD at the plant (almost 23%) as shown in Figure 4–16c. This data implies that cake solids content of WAS may be more sensitive to the reduction in polymer dose than that of digested sludge possibly due to the effect of digestion processes.



(a)



(b)



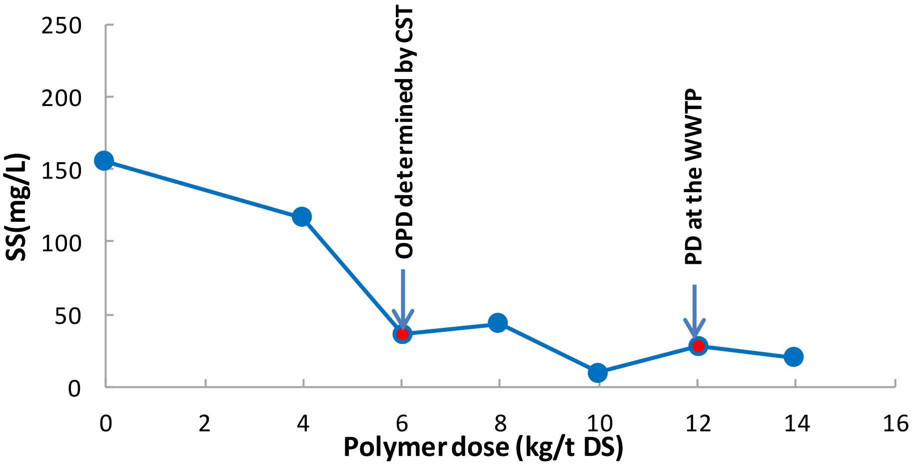
(c)

Figure 4–16 Cake solids content of conditioned (a) ADS; (b) AEDS and (c) WAS at different polymer dosages

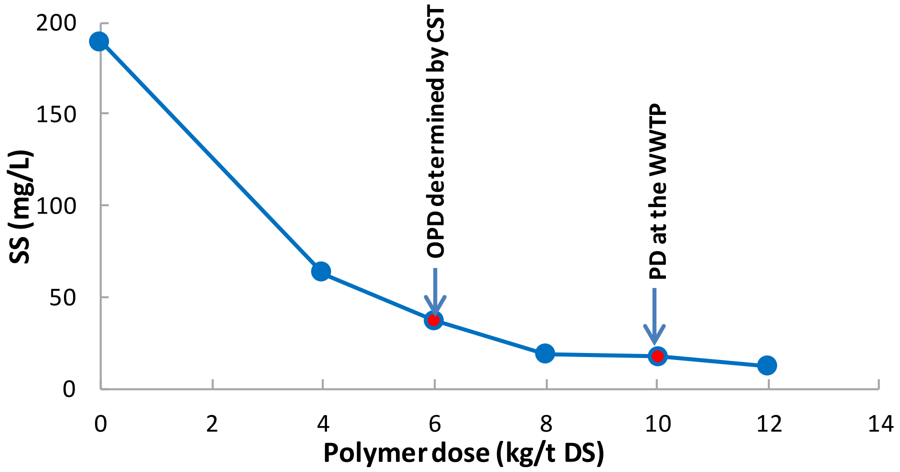
Centrate quality as a controlling parameter of sludge conditioning and dewatering

The above results show that the OPD determined by both CST and MCI tests were much lower than the current polymer dose used at the 3 WWTPs (especially at Wollongong and St. Marys WWTPs). However, as mentioned earlier, OPD determination using CST tests does not guarantee the correct or reliable value. In addition, the reduction of the polymer dose can lead to reverse effect on centrate quality, which is also a controlling parameter of dewatering operation (Sydney Water 2013). Therefore, it should also be taken into consideration together with cake solids content. In order to evaluate the effect of polymer dose on the SS in centrate, the centrate from MCI tests was collected and its SS content was measured. The variation of SS based on polymer dose is presented in Figure 4–17. In general, SS in centrate decreased with increasing PD until it reached a plateau at which point reduction was insignificant.

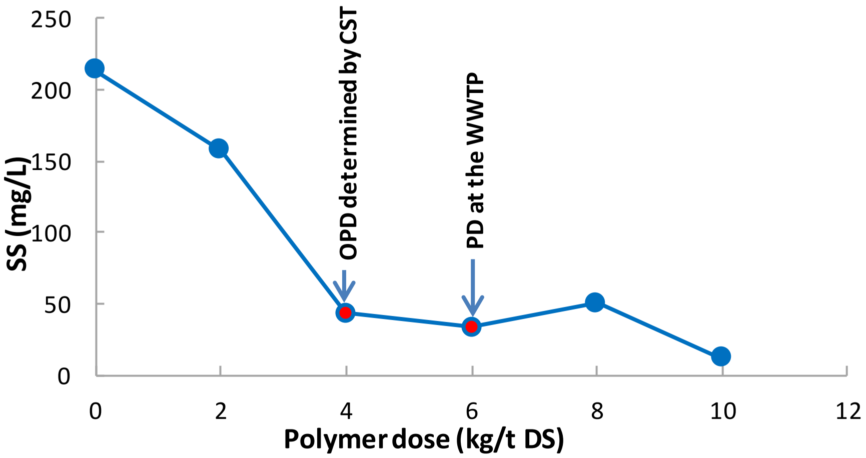
For ADS, SS in centrate hit the lowest value at a polymer dose of 10kg/t DS (Figure 4–17a). The reduction of polymer dose from 10 to 8 and 6kg/t DS increased the SS in the filtrate to 43 and 37mg/L respectively. However, these values were only slightly higher than that of polymer dose of 12kg/t DS (28 mg/L). These results show that a lower dose (less than 10kg/t DS) can be applied in Wollongong WWTP. This results is similar to previous report of Higgins et al. (2006) who found that polymer dose of 9.1kg/t DS is the OPD for a comparable ADS (COD, soluble Protein and polysaccharides of 1048, 285 and 51mg/L respectively).



(a)



(b)



(c)

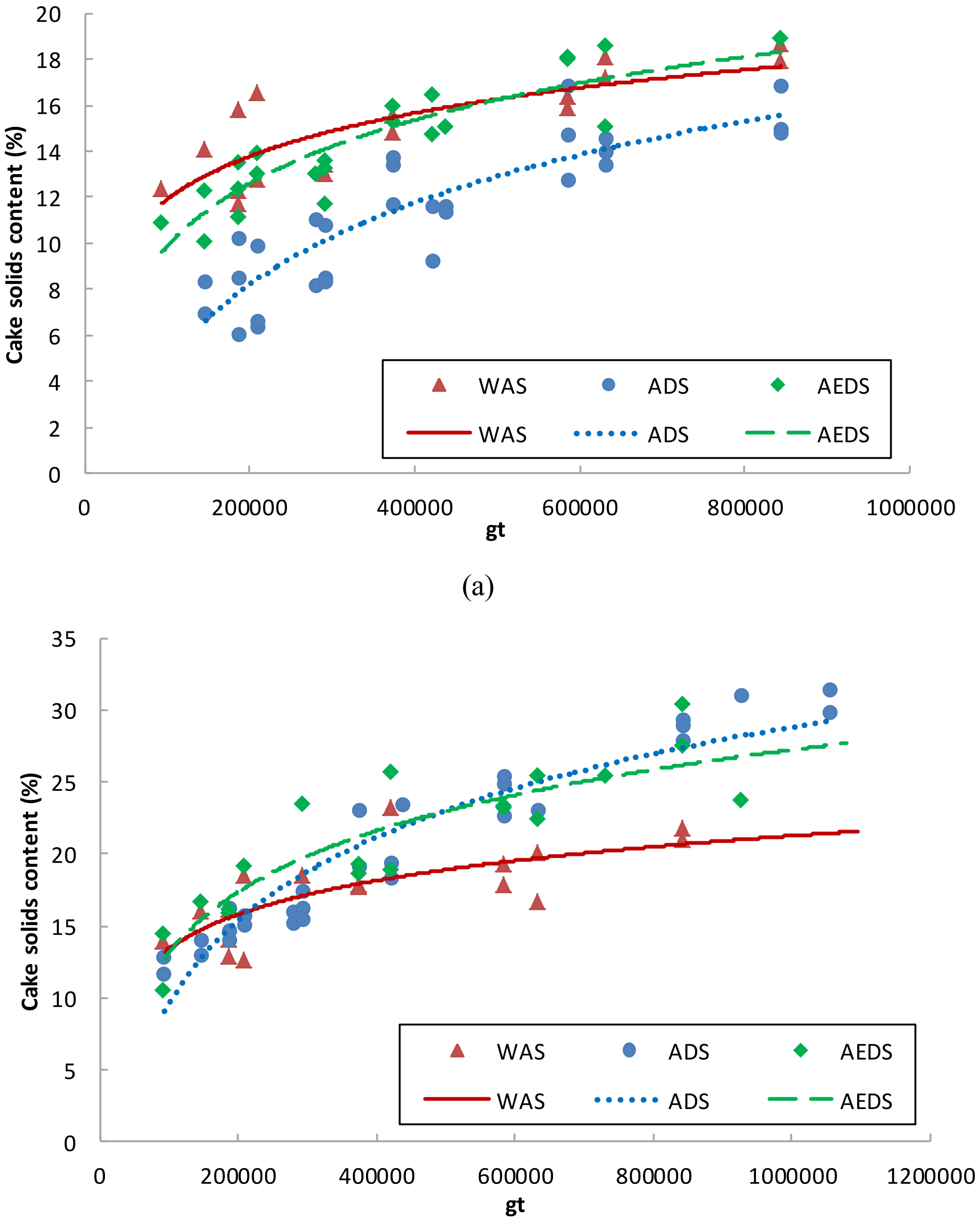
Figure 4–17 Effect of polymer dose on SS in the centrate of the MCI tests for (a) ADS; (b) AEDS and (c) WAS

For AEDS, as mentioned above, due to the operation of belt filter press, centrate quality is not considered as a big issue to the plant, which means the variation of PD mostly impacts on solids cake content. Figure 4–17b shows that when decreasing PD for AEDS from 10 to 6kg/t DS, it led to a significant increase in SS in centrate, from 17 to 37mg/L. As a result, it is not safe to apply the 6kg/t DS for full–scale process. In this case, 8kg/t DS could be a better choice.

For WAS, SS in centrate at the doses of 4 and 6kg/t DS were quite similar (43 and 34mg/L respectively – Figure 4–17c). However, 4kg/t DS resulted in lower cake solids content (Figure 4–16c). Thus, both centrate quality and solids content should be considered in the selection of PD.

4.4.4. MCI tests – Effect of digestion on sludge dewaterability

As stated earlier, all typical sludge properties studied indicated the difficulty in dewatering ADS (as well as high polymer demand for its conditioning) compared to AEDS and WAS. This supports the idea that digestion processes, especially anaerobic digestion, deteriorate sludge dewaterability. Results of MCI tests, however, show that this idea is only true with sludge before conditioning, which solids cake of ADS were lower than those of the other sludge types, with solids content 16% for ADS and 18% for both AEDS and WAS (Figure 4–18a).



(a)

(b)

Figure 4–18 Effect digestion on dewaterability (cake solids content) of (a) unconditioned and (b) conditioned ADS, AEDS and WAS

On the other hand, after conditioning, dewaterability of ADS was the best among all sludges, with dewatered cake reaching almost 30%, followed by AEDS with 26% and then WAS with 22% as shown in Figure 4–18b. Digestion may lead to poorer sludge dewaterability and higher polymer demand, nevertheless, after conditioning, dewatering of digested sludge was much better than the one without digestion. In other words, pre–treatment by digestion possibly helps to improve subsequent dewaterability of conditioned sludge. However, these are only external phenomena, additional studies should be done to better understand how digestion affects sludge dewaterability. The present study attributes this phenomenon in terms of soluble biopolymers or extracellular polymeric substances (also known as bioflocculants). They are released during digestion processes.

4.5. Other chemical conditioning methods

4.5.1. Dual conditioning

4.5.1.1. Dual polymer conditioning – Cationic/Anionic polymers conditioning

Two different types of anionic polymers were used after the addition of currently used cationic polymer at the 3 WWTPs to study the effect of dual polymer addition during conditioning. The selection of anionic polymers was based on their charge density and molecular weight: one is low in charge, high molecular weight (zetag4110) and the other is medium to high charge and high molecular weight (zetag4145). The effect of using dual polymers for conditioning on CST of conditioned sludge is presented in Table 4–11.

The experimental results demonstrate that, in comparison with the addition of only cationic polymer, dual addition of anionic and cationic polymers were more effective in reducing CST (Table 4–11). The anionic polymer Zetag4110 led to a slightly better result than that with Zetag4145 for all 3 sludge types. This result can be explained by considering the effect of polymer properties such as charge density and molecular weight on the interactions between the polymers and particles.

Table 4–11 Effects of dual polymer conditioning on CST values of conditioned sludge

Sludge types	Cationic polymer dose (kg/t DS)	Anionic polymers			
		Zetag4110		Zetag4145	
		Dose (kg/t DS)	CST (s)	Dose (kg/t DS)	CST (s)
ADS	0	0	1303	0	1303
	12*	0	12	0	12
	8	2	16	2	32
	6	2	49	2	135
AEDS	0	0	283	0	283
	10*	0	13	0	13
	6	2	11	2	17
	4	2	19	2	34
WAS	0	0	63	0	63
	6*	0	31	0	31
	4	2	14	2	18
	2	2	26	2	35

* Currently used polymer doses at the WWTPs

Molecular weight of a polymer is one of the key parameters significantly impacting on sludge conditioning. Both charge neutralization and polymer bridging contribute to better dewatering. In this study, both anionic polymers used were high molecular weight; hence, the flocculation is governed by polymer bridge formation (Vaxelaire & Olivier 2006). Additionally, a previous report had shown that lower charge density polymers use their charge density more efficiently than the ones with higher charge density due to their better adsorption to the particle surface (Gregory 1993). This could be the reason that Zetag4110 with lower charge resulted in lower CST values compared to Zetag4145.

These results support the theory that the use of anionic polymer along with cationic polymer improves sludge conditioning. Since anionic polymers are often less expensive than other types (Sanin et al. 2011), reducing cationic polymer demand may help to minimise the significant cost of the polymer. The polymer cost is almost half of the sludge dewatering and disposal cost (Vaxelaire & Olivier 2006). Besides its economic benefits, it is also believed that dual polymer conditioning creates stronger flocs to better withstand the high shear during centrifuge (Lee & Liu 2001). However, additional tests, especially full – scale or MCI test, are needed to prove this theory. Screening tests are also necessary to determine the most suitable anionic polymer type and dose for a given sludge.

4.5.1.2. Iron/Cationic polymer conditioning

The combinations of inorganic conditioner, which is ferric chloride in this study, and cationic polymers may utilize the advantage of both flocculants for improving sludge dewaterability. For instance, inorganic conditioners cannot produce the solid cakes that are attainable with much lower dosages of polymers; however, they are less sensitive to changes in dosage than polymers.

Effect of this dual conditioning measured in terms of CST is illustrated in Table 4–12. Results showed considerable reduction in CST values for all sludge types after the addition of two conditioners together. This led to decrease in cationic polymer demand for conditioning compared to the currently used polymer dose at the WWTPs. Especially for ADS, the dual conditioning helped to significantly reduce the PD from 12kg/t DS to 4kg/t DS (by three times), which may result in substantial saving of chemical cost for the plant. Whilst, there was a decrease in PD for AEDS and WAS, it was insignificant compared to ADS.

This dual conditioning should be tried in full – scale in the plants. However, due to the difficulties in additional installation of chemicals feeding equipment at the plants studied, it is not feasible to conduct full–scale trials. In this case, MCI tests may be a good solution to investigate the actual benefit of applying iron along with cationic polymer for enhancing sludge dewatering efficiency. Another problem with this conditioning method is the limitation of iron content contained in dewatered cake which is strictly controlled by local and governmental regulations.

Table 4–12 Effects of Iron/Cationic polymer conditioning on CST values of conditioned sludge

ADS			AEDS			WAS		
$FeCl_3$ (mg/L)	Cationic polymer (kg/t DS)	CST (s)	$FeCl_3$ (mg/L)	Cationic polymer (kg/t DS)	CST (s)	$FeCl_3$ (mg/L)	Cationic polymer (kg/t DS)	CST (s)
0	0	1246	0	0	283	0	0	63
0	12*	35	0	10*	13	0	6*	31
1	4	26	-	-	-	-	-	-
3	4	28	-	-	-	-	-	-
5	4	34	5	8	10	5	4	13
10	4	52	10	8	11	10	4	12

* Currently used polymer dose at the WWTPs

4.5.2. Advanced oxidation (Fenton) conditioning

The effect of Fenton's reagent on dewaterability of sludge from 3 WWTPs was evaluated for various Fe^{2+} and H_2O_2 dosages, as shown in Table 4–13, in order to identify the optimal condition. The reduction in CST for all sludge types shows the positive effect of advanced oxidation treatment of sludge.

In the case of ADS, CST value of oxidized sludge significantly decreased from 1513s to lower than 100s, but, slightly went up when increasing Fenton's reagent dosage was increased. Similar trends were observed for AEDS and WAS. However, since CST values of these feeding sludges were not high, especially for WAS (CST_{feed} = 63s), the improvement of conditioning method using Fenton oxidation in terms of CST were not significant.

According to the screening tests, 0.5mmol/L Fe^{2+} and 50mmol/L H_2O_2 could be selected as an optimal dosage for sludge conditioning. However, these doses were observed based on CST tests. To confirm this finding, MCI test or full–scale trials are needed as well to elucidate the actual effect of advanced oxidation conditioning method on sludge dewaterability. Since oxidised sludge is quite toxic and harmful to both equipment and human health, it is necessary to handle, store and transport this conditioned sludge with great care.

Table 4–13 Effects of Fenton oxidation conditioning on CST values of conditioned sludge

Fe^{2+} dose (mmol/L)	H_2O_2 dose (mmol/L)	CST (s)		
		ADS	AEDS	WAS
0	0	1513	334	63
0.5	10	178	-	-
0.5	20	41	-	-
0.5	40	45	-	-
0.5	**50**	**34**	**26**	**34**
0.5	150	35	30	29
0.5	250	36	47	31
0.5	400	33	38	43
0.5	600	58	37	44
0.1	50	49	-	-
0.3	50	54	-	-
0.7	50	53	-	-
1	50	55	-	-

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CHAPTER 5

CONCLUSION

5.1. Conclusion

5.1.1. Sludge characteristics in relationships with sludge conditioning demand and dewatering

Most of typical sludge properties such as feeding DS, ZP, CST and soluble substances (soluble biopolymers and sCOD) indicated that ADS had the poorest dewaterability and required the highest polymer demand for conditioning compared to the other sludges studied. On the contrary, WAS requiring the least amount of polymer had the best dewaterability. These results support the idea that digestions deteriorate sludge dewatering.

There were good correlations between soluble biopolymers and OPD for both single sludge type and all sludge types, which highlights the major role of soluble biopolymers in deciding conditioning polymer demand. Whilst, insignificant relationships were observed when sludge characteristics were related to CST.

Relationships between OPD and sludge characteristics, especially soluble polymers, and shear intensity could provide helpful information on selection of suitable polymer types and dosages for an effective sludge conditioning. Here, this study suggested the use of high mole charge polymers for better ADS conditioning.

5.1.2. Comparisons of different indicators for sludge conditioning and dewatering

5.1.2.1. Traditionally used indicators

Zeta potential (ZP) could give useful indirect information on determining the polymer demand based on charge neutralization, which is one of major mechanisms of flocculation during polymer conditioning. However, the results from the present study showed that using ZP as an OPD indicator may result in over – dosed conditioning since effective flocculation could be achieved both by charge neutralization and polymer bridging formation.

Based on CST test, lower polymer doses were found to be suitable for sludge conditioning of all three WWTPs studied. This could lead to an implication of reducing a significant amount of expensive cationic polymers for sludge conditioning at these plants.

However, the full–scale shear that sludge floc experiences during dewatering may create more polymer demand. Therefore, the lower dose that indicated by CST test was not guaranteed to work in the field. In this case, besides full–scale trials, MCI test that can reproduce the centrifuge stress exerted on sludge cake could tackle this problem.

5.1.2.2. Modified centrifugal index (MCI) – A new centrifuge based laboratory scale sludge dewatering

Modified centrifugal index (MCI) test can be successfully used to evaluate the dewaterability of different sludge types with and without conditioning by estimating the maximum solids cake content achievable by the centrifuge dewatering. The similarity of cake solids content obtained by centrifuge between MCI test and full–scale results has strengthened the reliability of the new method. Besides, it is possible to use this technique for OPD determination when taking both solids cake content and centrate quality into consideration.

In addition, MCI test showed that the idea about deterioration of dewaterability due to digestion was only correct in the case of unconditioned sludge. Reversible order of dewatering efficiency in terms of cake solids content was observed for conditioned sludge which are ADS > AEDS > WAS could be due to the positive effect of digestion on sludge conditioning.

5.1.3. Other chemical conditioning methods as promising solutions for saving of chemical cost

Other chemical conditioning methods, which are dual polymer conditioning, iron/ cationic polymer conditioning and advanced oxidation (Fenton) conditioning, can be promising solutions to reduce the doses of expensive conditioners. Nevertheless, results were based on CST test which is often not a reliable indicator for dewatering. As a result, MCI test or full–scale trials are needed as well to elucidate the actual effect of these conditioning methods on sludge dewaterability.

5.2. Recommendations

Besides sludge characteristics, polymer properties and dewatering equipment should also be considered in relationships with sludge conditioning and dewatering in order to develop comprehensive models of estimating optimal polymer demand as well as selecting appropriate polymer types for the best conditioning and dewatering.

Although MCI was demonstrated to be a potential efficiency indicator for sludge dewatering using centrifuge, further studies are necessary to fully understand MCI tests' influencing factors such as centrifuge speed and time, filter paper pore size and volume of modified centrifuge tubes.

Methods developed for selection of suitable polymers for effective sludge conditioning should be tested on different sludge types as well as applied in full–scale trials.

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APPENDIX

List of Publications based on this research

Journal articles

- Vu Hien Phuong To, Tien Vinh Nguyen, Saravanamuthu Vigneswaran and Huu Hao Ngo (2014). A review on indicators for efficiency evaluation of sludge mechanical dewatering, will be submitted to *Water Science and Technology*
- Vu Hien Phuong To, Tien Vinh Nguyen, Saravanamuthu Vigneswaran, Long Nghiem, Sudhir Murthy, Heri Bustamante and Matthew J. Higgins. (2014). The modified centrifugal index as a parameter to determine polymer demand and achievable dry solids content in the dewatering of anaerobically digested sludge: under review of Sydney Water Corporation, will be submitted to *International Journal of Environmental Science and Technology*.

Conferences

- Vu Hien Phuong To, Tien Vinh Nguyen, Saravanamuthu Vigneswaran, Long Nghiem, Sudhir Murthy, Heri Bustamante and Matthew J. Higgins. (2014). Modified centrifugal index and sludge characteristics in assessing sludge dewatering. *IWA 7th International Young Water Professional Conference*. December 7 – 11, Taipei, Taiwan.
- Vu Hien Phuong To, Tien Vinh Nguyen, Saravanamuthu Vigneswaran, Sudhir Murthy, Heri Bustamante and Matthew J. Higgins. (2014). Sludge dewatering improvement through understanding of interaction mechanisms of conditioning polymers (accepted). *WEF/IWA Residuals and Biosolids Conference 2015*. June 7 – 10, Washington, D.C., USA.

Sludge characteristics on different sampling times

Table A–1 Characteristics of ADS, dewatered cake and centrate Wollongong WWTP

Parameter	Unit	Sampling date						
		1 May 2013	4 Jun 2013	3 Sep 2013	8 Oct 2013	4 Dec 2013	7 Feb 2014	25 Mar 2014
ADS								
Temperature	^oC	22.8	21.9	22.1	22.2	23.3	-	-
pH		7.3	7.5	7.6	7.5	7.4	7.5	7.3
Conductivity	mS/cm	6.02	6.32	6.01	6	4.98	5.1	5.71
Zeta potential	mV			-30.6	-29.7	-28.2	-29.9	-29.5
CST	s	935	1692	1420	1577	1246	1513	1648
Dry solid content	%	2.25	2.67	2.2	2.37	2.8	2.37	2.86
Volatile solid content	%	1.42	1.63	1.49	1.64	1.59	1.43	1.6
Soluble COD	mg/l	1324	1434	1265	1015	663	751	1323
Soluble Protein	mg/l	-	-	253.3	236.4	159.5	148.5	370
Soluble Polysaccharides	mg/l	-	-	74.8	78.2	57.8	61.6	89.5
Dewatered cake								
Dry solid content	%	27.3	27.0	26.1	25.5	27.4	26.7	29.1
Volatile solid content	%	9.95	16.75	17.76	17.16	17.63	17.99	18.9

Parameter	Unit	Sampling date						
		1 May 2013	4 Jun 2013	3 Sep 2013	8 Oct 2013	4 Dec 2013	7 Feb 2014	25 Mar 2014
Centrate								
Temperature	^{o}C					23.1	-	-
pH						8.2	8.31	7.86
Zeta potential	mV					-7.8	-6.9	-5.3
Suspended solids	mg/l					213	60	92

Table A–2 Characteristics of AEDS, dewatered cake and centrate at St. Marys WWTP

Parameter	Unit	Sampling date					
		25 Oct 2013	20 Nov 2013	3 Mar 2014	14 Apr 2014	22 May 2014	24 June 2014
AEDS							
Temperature	^{o}C	23.8	23.5	23	22.7	21.8	19.1
pH		7.0	6.9	7.0	7.5	6.9	7.0
Conductivity	mS/cm	1.83	1.49	1.6	1.66	1.35	-
Zeta potential	mV	-26.3	-26	-26.6	-27.7	-26.5	-25.1
CST	s	283	334	538	450	258	350
Dry solid content	%	1.92	2.18	2.5	0.85	1.89	2.23
Volatile solid content	%	1.32	1.42	1.48	0.52	1.22	1.42
Soluble COD	mg/l	717	647	528	741	333	453
Soluble Protein	mg/l	97.9	90.1	90.5	85.5	63.9	80.02
Soluble Polysaccharides	mg/l	41.7	32.3	36	27.8	24.8	23.83
Dewatered cake							
Dry solid content	%	15.18	15.64	14.86	17.35	13.97	15.07
Volatile solid content	%	10.96	11.27	10.24	11.64	9.27	9.67

Parameter	Unit	Sampling date					
		25 Oct 2013	20 Nov 2013	3 Mar 2014	14 Apr 2014	22 May 2014	24 June 2014
Centrate							
Temperature	°C	24.3	23.03	22.5	23.1	22.2	-
pH		7.1	7.1	7.1	7.8	7.1	-
Zeta potential	mV	-5	-5.8	1.03	-5.59	-1.34	-
Suspended solids	mg/l	69	34	82	54	42	-

Table A–3 Characteristics of WAS, dewatered cake and centrate at Quakers Hill WWTP

Parameter	Unit	Sampling date						
		25 Oct 2013	20 Nov 2013	17 Dec 2013	3 Mar 2014	14 Apr 2014	22 May 2014	24 Jun 2014
WAS								
Temperature	°C	23.8	23	22.2	22.6	22.6	21.7	19.4
pH		6.9	6.8	6.5	6.6	6.8	6.7	6.7
Conductivity	mS/cm	1.21	1.17	1.56	1.75	1.54	1.48	-
Zeta potential	mV	-22	-20	-20.4	-18.2	-23.2	-22.6	-21.1
CST	s	23	63	83	106	107	66	73
Dry solid content	%	2.22	3.18	3.67	3.01	2.97	2.84	2.68
Volatile solid content	%	1.46	2.13	2.45	2.15	2.14	2.12	2.02
Soluble COD	mg/l	136	346	645	895	373	375	633
Soluble Protein	mg/l	34.9	46.1	77.4	75.9	61	64.1	64.5
Soluble Polysaccharides	mg/l	35.5	26.7	47.4	47.3	18.8	22.4	22.6
Dewatered cake								
Dry solid content	%	17.9	18.4	19	19.4	19	18.52	18.50
Volatile solid content	%	13.2	13.4	13.9	14.3	13.7	13.96	14.35

Parameter	Unit	Sampling date						
		25 Oct 2013	20 Nov 2013	17 Dec 2013	3 Mar 2014	14 Apr 2014	22 May 2014	24 Jun 2014
Centrate								
Temperature	^{o}C	26	24.2	23.7	22.7	23.2	22.2	19.8
pH		7.1	7.1	6.8	6.9	7.3	7.0	7.2
Zeta potential	mV	8.8	4.0	-10.5	-7.5	1.3	-9.8	-9.7
Suspended solids	mg/l	272	370	3250	2105	1065	3970	2285

Dewatering equipment in 3 WWTPs studied

Figure A–1 Centrifuges at Wollongong WWTP

(a) (b)

Figure A–2 (a) Centrifuges and (b) polymer feeding point at Quakers Hill WWTP

Figure A–3 Belt filter presses at St. Marys WWTP

Figure A–4 Waste treatment methods in Wollongong WWTP

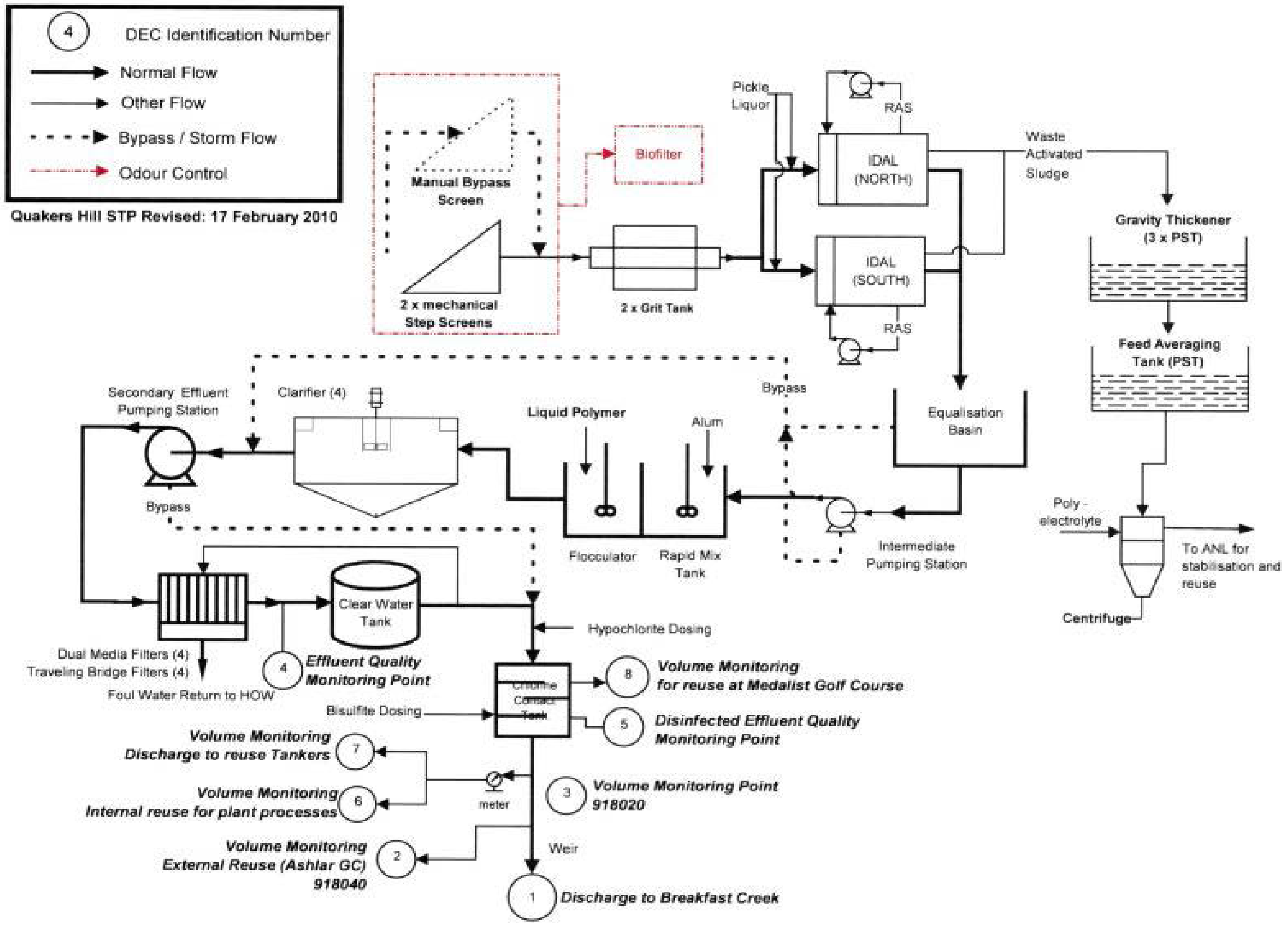

Figure A–4 Waste treatment processes in Quakers Hill WWTP

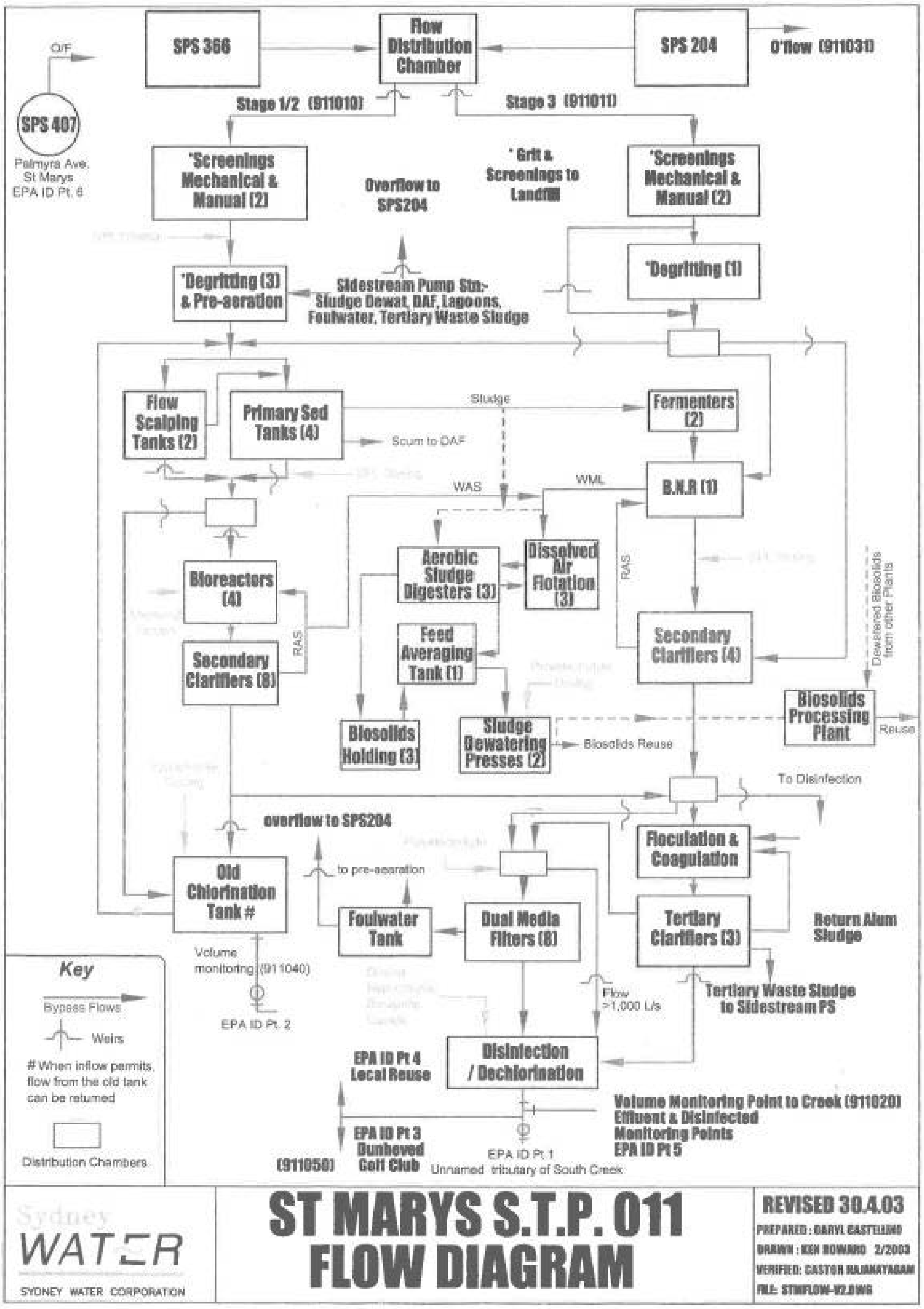

Figure A–5 Waste treatment processes in St. Marys WWTP