School of Chemical and Petroleum Engineering
Department of Chemical Engineering

Studies on Rheological Characteristic of Wastewater Treatment Plant (WWTP) Sludge and Process Optimization

Eugene Ewe Jinn Hong

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature:

Date: 1/12/17

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2. Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016. "Rheological characteristics of municipal thickened excess activated sludge (TEAS): impacts of pH, temperature, solid concentration and polymer dose." *Research on Chemical Intermediates*:1-19. doi: 10.1007/s11164-016-2482-2.
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4. Hong, Eugene, Anteneh Mesfin Yeneneh, Tushar Kanti Sen, Ha Ming Ang, and Ahmet Kayaalp. 2017. "The relationship between physico-chemical and rheological characteristics of digested sludge, biosolid, centrate and the effects on dewatering performance (A case study)." *Journal of Water Process Engineering* no. 19:193-204. doi: https://doi.org/10.1016/j.jwpe.2017.07.022.
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7. Hong, Eugene, Anteneh Mesfin Yeneneh, Tushar Kanti Sen, and Jainita Shah. 2017. "Study on rheological properties of kaolin and bentonite slurry solutions." *Clay Minerals: Properties, Occurrence and Uses*: Nova Science Publishers, Incorporated.

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Abstract

Understanding the flow behaviour and rheological properties of different sludge types is important for sustainable sludge management. Rheology as a fluid property is a crucial factor which influences the design of pumping system, mixing, hydrodynamics and mass transfer rates and performance of various sludge treatment units. Sludge rheological behaviour is highly influenced by many factors such as solid concentration, temperature, pH, sludge treatment methods and organic composition. The rheological behaviour of sludge has a more significant role to play in the dewatering section of the sludge treatment process where sludge conditioning agents are added to flocculate the sludge and achieve high biosolid capture rate. Rheology can be used as a very good monitoring and control tool to optimize this cost and energy intensive process. This can be achieved by investigating the relationship between rheological and physico-chemical characteristics of sludge. Therefore, this particular research has the objective of investigating and determining the rheological characteristics of different sludge types from different sections of a wastewater treatment plant (WWTP) for the purpose of optimizing the dewatering unit.

This study encompasses investigation of the influence of temperature, pH, total solids concentration, mixing-ratio, and polymer dose on rheological properties, determination of the optimum operating conditions for the dewatering unit, and development of predictive rheological model by using historical data and adaptive neuro-fuzzy inference system (ANFIS) tool in MATLAB. A state-at-the-art rheometer was used to generate the rheological results at a shear rate range of $0 – 1000\ s^{-1}$. The applicability of various rheological models such as Bingham, power law (Ostwald), Herschel-Bulkley, Casson, Sisko, Careau and Cross models was also tested. The rheological results from the best fitted models were later used to compute the necessary rheological parameters. In addition, four years of historical plant data was used to develop a prediction model in ANFIS for the optimization of the dewatering process.

Intensive experimental investigations showed that the effects of physico-chemical properties on the rheology and flow behaviour were significant for various sludge types. It was observed that the decrease in concentration resulted in drastic reduction of yield stress. Similarly, viscosity values higher shear rate decreases when the total solid concentration decreases. The impact of mixing ratio (primary to thickened excess activated sludge) were also investigated. It was found that, the decrease in mixing ratio of thickened excess activated sludge to raw primary sludge from 80% to 20% resulted in the decrease of yield stress. This results confirms the significant contribution thickened excess activated sludge have on the flow behaviour of the mixture.

In addition, the impacts of polymer dose on the rheological characteristics and the dewaterability of digested sludge were observed and a relationship between dewaterability and digested sludge rheology was developed. The rheological characteristics of digested sludge during polymer conditioning and flocculation process was significantly affected by temperature and solid concentration; hence, it was observed that polymer dose can be reduced by operating the dewatering process at optimum temperature condition and varying the polymer dose as a function of the total solid concentration and viscosity of the digested sludge. Moreover, it was also observed that volatile solid content and chemical oxygen demand (COD) of digested sludge and centrate showed an inverse relationship with biosolid capture rate. Rheological parameters of digested sludge and centrate, such as yield stress and viscosity, were observed to change proportionally with total solid concentration, volatile solid content, and COD. In brief, polymer dose monitoring and optimization can be conducted by using rheological model parameters, other operating parameters like total solid concentration and volatile solid concentration. As there is no to minimum published work in relation to using rheology as a monitoring tool for dewatering performance enhancement.

In this work, ANFIS was used to find a relationship between rheology and properties of sludge. ANFIS was applied, to model the relationship between biosolid quality (total solid content in biosolid) to various digested sludge properties, and polymer dose. Historical data on various physico-chemical process parameters such as total solid, volatile solid, volatile fatty acid content of digested sludge, total solid content of biosolid and polymer dose from the dewatering section of a WWTP over a period of four years was used for the analysis. The results of the modelling yielded optimum operating conditions, which includes optimum total solid content, optimum volatile solid content and optimum polymer dose. Generally, it is recommended that lower total solid and volatile solid concentration coupled with relatively low polymer dose corresponds to relatively higher biosolid capture rate. The relationships between biosolid capture rate, total solid concentration, volatile solid concentration, volatile fatty acid content and polymer dose can be effectively established and used as a predictions and optimization tool as confirmed from both the experimental investigation and the model based analysis.

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CHAPTER 1
INTRODUCTION

1.1 Background

Sustainable sludge handling and wastewater management is getting increasingly more difficult with the rapid growth of urban population and the demand for environmentally friendly methods for disposal. This subsequently compels the improvement of existing technologies and operation for wastewater treatment plants such as enhancing pumping, hydrodynamics, mass transfer rates, sludge settling, filtration and other related processes. Significant improvement in monitoring, control and performance of wastewater treatment processes can be achieved by investigating flow and rheological behaviour of sludge. There are many reputable studies on the area of sludge rheology (Lotito et al. 1997, Seyssiecq et al. 2003, Baudez et al. 2011, Baroutian et al. 2013, Eshtiaghi et al. 2013, Ratkovich et al. 2013, Markis et al. 2014, Hong et al. 2015a, Hong et al. 2015b, 2016, Yeneneh et al. 2016). Rheology is the study of flow and deformation of materials under applied forces. It is highly influenced by wastewater treatment operating parameters such as source of sewage, total solid concentration of sludge, temperature, and sludge treatment methods (Seyssiecq et al. 2003, Abu-Jdayil et al. 2010, Abu-Jdayil 2011, Markis et al. 2014, Hong et al. 2015b, 2016, Markis et al. 2016, Yeneneh et al. 2016). Studies show that sludge is highly complex in nature and requires in-depth investigation to improve the understanding on the impacts of different operating parameters on the rheological and flow properties of different sludge type (Markis et al. 2014, Yeneneh 2014, Hong et al. 2015b, 2016, Markis et al. 2016, Yeneneh et al. 2016). A typical wastewater treatment plant generally consists of many stages, which are preliminary, primary, secondary, and advanced treatment stages. These treatment stages produce different types of sludge. These sludge types are raw primary sludge, excess activated sludge, and thickened excess activated sludge, mixed sludge, digested sludge and biosolid. The sludge originating from the underflow stream of primary sedimentation tanks, raw primary sludge, is transferred to secondary treatment units of aeration and sedimentation. The secondary treatment is where the sludge will undergo both physical and biological separation and removal where nutrient removal and biomass accumulations take place (Yeneneh 2014). The sludge leaving the secondary treatment, activated sludge, is thickened further in the dissolved air flotation thickener (DAFT) to form thickened excess activated sludge. Thickened excess activated sludge, an intricate colloidal material consisting of organic and inorganic particles, is then mixed with raw primary sludge to form mixed sludge. Mixed sludge is fed to the anaerobic digesters for further degradation to form digested sludge (Clauss et al. 1998). The digested sludge will undergo solid-liquid separation process known as dewatering to form filter cake (biosolids). Both the anaerobic digestion and sludge dewatering operations are considered vital points for rheological investigation, as approximately 70% of the overall operating cost is from these processes (Seyssiecq et al. 2003, Abu-Jdayil et al. 2010, Markis et al. 2013, Markis et al. 2014, Yeneneh 2014). Sludge rheology (viscosity, yield stress and shearing behaviour) is dictated by many factors including total solid concentration, temperature, pH, dose of polymer or other agents, chemical composition especially concentration of biopolymers and organics (Eshtiaghi et al. 2013, Ratkovich et al. 2013, Markis et al. 2014, Hong et al. 2015a, Hong et al. 2015b, 2016, Yeneneh et al. 2016). According to Einstein law of viscosity, solids within a fluid is considered as a key factor that contributes to non-Newtonian flow behaviour (Sanin 2002). Different sludge types generally behave like a non-Newtonian and shear thinning material, which has been studied by many researchers (Sanin 2002, Tixier et al. 2003a, b, Mori et al. 2006, Pevere et al. 2006, Abu-Jdayil 2011, Eshtiaghi et al. 2013). Total solid content is a parameter that influences the rheological and flow behaviour of all sludge types. It was found that increasing viscosity of sludge due to increase of solid content will lead to stronger inter-particle interactions which are caused by the size increase of particles in suspension, resulting in higher apparent viscosity for different sludge types (Hong et al. 2015b, 2016, Yeneneh et al. 2016). Experimental studies have confirmed that solid content is an important parameter that influences the rheological behaviour. It helps to validate the dynamic and complex nature of different sludge types. Utilizing one parameter alone to describe the rheological behaviour of different sludge types is not adequate hence the use of multiple parameters are recommended to improve the understanding of sludge behaviour (Lotito et al. 1997, Show et al. 2007, Chong et al. 2012, Piani et al. 2014, Hong et al. 2015b, 2016, Yeneneh et al. 2016). Temperature is also a key parameter that has strong effect on the rheological properties of all types of sludge by affecting flocculated particle size, shape, and degree of dispersion within the different sludge types (Sanin 2002). Studies have shown that yield stress increases with increasing total solid content but decreases with increasing temperature, while viscosity shows lower values at higher temperature (Hasar et al. 2004, Chong et al. 2012, Baroutian et al. 2013, Eshtiaghi et al. 2013, Farno et al. 2013, Hong et al. 2015b, Farno et al. 2016, Hong et al. 2016, Yeneneh et al. 2016). Baudez (2008) also found that shear stress and shear rate increase with the increase of total solid content and are highly dependent on the fractal dimensions of the floc. pH is another parameter which highly influences the rheological behaviour of different sludge types. The floc network strength and surface charge of particles changes as with the system pH (Liao et al. 2002, Neyens et al. 2004). Furthermore, studies have shown that the organic component within the sludge undergoes chemical and microbiological aging process, where the degradation and synthesis of volatile fatty acids, are the causes behind the changes in viscosity and yield stress of the sludge (Baudez 2008). This has significant impact on the overall performance of the anaerobic digestion process as the overall storage time can significantly affect viscosity of the sludge and hence the overall mixing efficiency.

According to Farno et al. (2013), Markis et al. (2013), Markis et al. (2014), Hong et al. (2015a), Hong et al. (2015b), Farno et al. (2016), Hong et al. (2016), Markis et al. (2016), Yeneneh et al. (2016), studies on different sludge types are few, limited, and inconsistent. Furthermore, literature agrees that the sludge is unique to the source of origin, hence different sludge have different rheological properties; therefore, it requires further investigation to improve overall understanding. In addition, the majority of literature focus on rheological investigation of synthetic sludge system but not sludge from large wastewater treatment plants (Bhattacharya 1981, Moeller et al. 1997, Nguyen et al. 2001, Tixier et al. 2003a, Baudez et al. 2011, Baroutian et al. 2013, Markis et al. 2013).

1.2 Objectives

Rheology of wastewater treatment plant (WWTP) sludge depends highly on its origin, geographical location, and treatment types. The main goal of this project is to investigate and determine the rheological characteristics of different sludge types from different treatment stages of a Wastewater Treatment Plant (WWTP). This includes, raw primary sludge (RPS), excess activated sludge (EAS), thickened excess activated sludge (TEAS), mixed sludge (MS), and digested sludge (DS). Investigating the influence of pH, temperature, total solid concentration, raw primary and thickened excess activated sludge mixing ratio, aging process, and polymer dosing on rheological properties for each sludge type will be studied here. In addition, selection and performance study of alternate conditioning agents for the enhancement of sludge dewaterability will be studied and the optimum condition will be determined from the rheological study.

Specific objectives are as follows:

- Investigate rheological and physico-chemical characteristics of different sludge types from WWTP and the relationship between these properties and fit the rheological data to various rheological models.
- Develop a comprehensive rheological map of WWTP sludge including all primary, secondary and advanced treatment processes.
- Investigate the effects of temperature, pH, solids concentration, mixing, and polymer dose on rheological properties of yield stress, viscosity, shear modulus, flow consistency index for various type of sludge from WWTP.
- Determine the optimum operating conditions for anaerobic digester and dewatering unit to minimize polymer consumption and enhance digested sludge, biosolid and centrate rheology and quality using experimental and modelling techniques.
- Develop predictive rheological model by using historical data from WWTP and adaptive neuro-fuzzy inference system (ANFIS).

1.3 Scope

Rheological parameters can play a vital role in sludge management. It has been used as a designing parameter for transporting, storing, landfill and spreading operations but with improved understanding, it can be used as a controlling parameter for many treatments such as stabilization and dewatering. Despite their complexity, rheological behaviour of sludge is an important property which affects:

a) Pumping,
b) Bioreactor hydrodynamics or mixing,
c) Oxygen transfer,
d) Settling hydrodynamics,
e) Membrane filtration, and
f) Dewatering.

Therefore, knowledge of sludge rheology is very important for efficient management of activated sludge system such as in the calculation of pressure losses in pipes and pump selection and for the design of aeration system (Clauss et al. 1998, Tchobanoglous et al. 2003, Tixier et al. 2003a, Mori et al. 2006). Furthermore, Ratkovich et al. (2013) mentioned that sludge sedimentation, hydrodynamics in secondary settler is crucial for their performance. Hence sludge rheology study is highly associated with the treatment performance and operating cost as well as with the efficient treatment system design. The major scope of this work is as follows:

- A rational design of the sludge handling system requires detailed knowledge of the flow behaviour and rheological characteristics of activated sludge. This is accomplished by generating a flow curve plot (shear stress and viscosity as a function of shear rate) which is used to characterize the different sludge.
- Determination of rheological parameters such as yield stress, viscosity, zero-rate viscosity, etc. which would be used to further improve actual sludge treatment process.
- Understanding and utilizing rheological properties of sludge as a controlling tool for polymer dose assessment for sludge chemical conditioning.
- Generating new predictive model for sludge based on the sludge characteristics at source and the adopted treatment methods.

1.4 Significance

Significant improvement in monitoring, control and performance of wastewater treatment processes can be achieved by investigating flow and rheological behaviour of sludge. This research project is intended to improve the understanding of rheological property of sludge which will assist in:

a) Increasing the efficiency of the sludge treatment process by ensuring effective monitoring and control of stabilization and dewatering.
b) Reducing treatment cost through optimization of polymer dose/other conditioning agents and other process parameters.
c) Reducing energy consumption and lower emission of greenhouse gases.
d) Reducing the volume of digested sludge.
e) Improving sludge management such as mixing, pumping and transportation, storage, and land applications.

f) Developing various rheological models for wastewater treatment sludge, which is new to Australian wastewater treatment plant and its application on the development of model for evaluation and enhancement of digester performance.

1.5 Thesis organisation

This thesis has been organised into eight chapters that covers all the details of this research work. An overview of the thesis structure is shown in Figure 1.1 and the outline of each chapter are described below.

Chapter 1: Introduction

This chapter outlines a brief introduction to the research project which includes the aim and objectives of the project. It will also provide background understanding of rheology and the impact of physico-chemical properties on municipal sludge.

Chapter 2: Literature review

This chapter outlines a detailed review of existing literature on the topic of rheology of different types of municipal sludge. This includes the techniques used to measure rheological parameters, impact of different physico-chemical changes on the rheological properties of different sludge types and recommendation on using rheology as a monitoring tool.

Chapter 3: Methodology

This chapter outlines the method in which the research project have been undertaken. The method covers the techniques used to characterise the sludge samples, measuring the rheological properties of sludge, and attaining the rheological parameter from various rheological models.

Chapter 4: Rheological and physico-chemical characteristics of thickened excess activated sludge

This chapter outlines the research findings on the impact of physico-chemical characteristics such as total solid concentration, temperature, pH and chemical conditioning on the rheological properties of thickened excess activated sludge (TEAS).

Chapter 5: Rheological and physico-chemical characteristics of mixed digester feed sludge

This chapter outlines the research findings on the impact of physico-chemical characteristics such as total solid concentration, temperature, pH and mixing ratio on the rheological properties of mixed digester feed sludge (MS).

Chapter 6: Rheological and physico-chemical characteristics of digested sludge, biosolid and centrate

This chapter outlines the research findings on the impact of physico-chemical characteristics such as total solid concentration, temperature, pH and chemical conditioning on the rheological properties of digested sludge (DS), biosolid and centrate.

Chapter 7: Historical data analysis using ANFIS as a tool for dewatering performance monitoring and control

This chapter outlines the research findings on the application of Adaptive neuro-fuzzy logic inference system (ANFIS) as a tool to understand the relationship between biosolid capture rate and volatile solid and total solid content of digested sludge and polymer dose.

Chapter 8: Conclusion and recommendation

This chapter gives the major conclusions drawn from all chapters of within the thesis, based on research findings from the data obtained, along with suggestions and recommendations for future scientific work to be carried out.

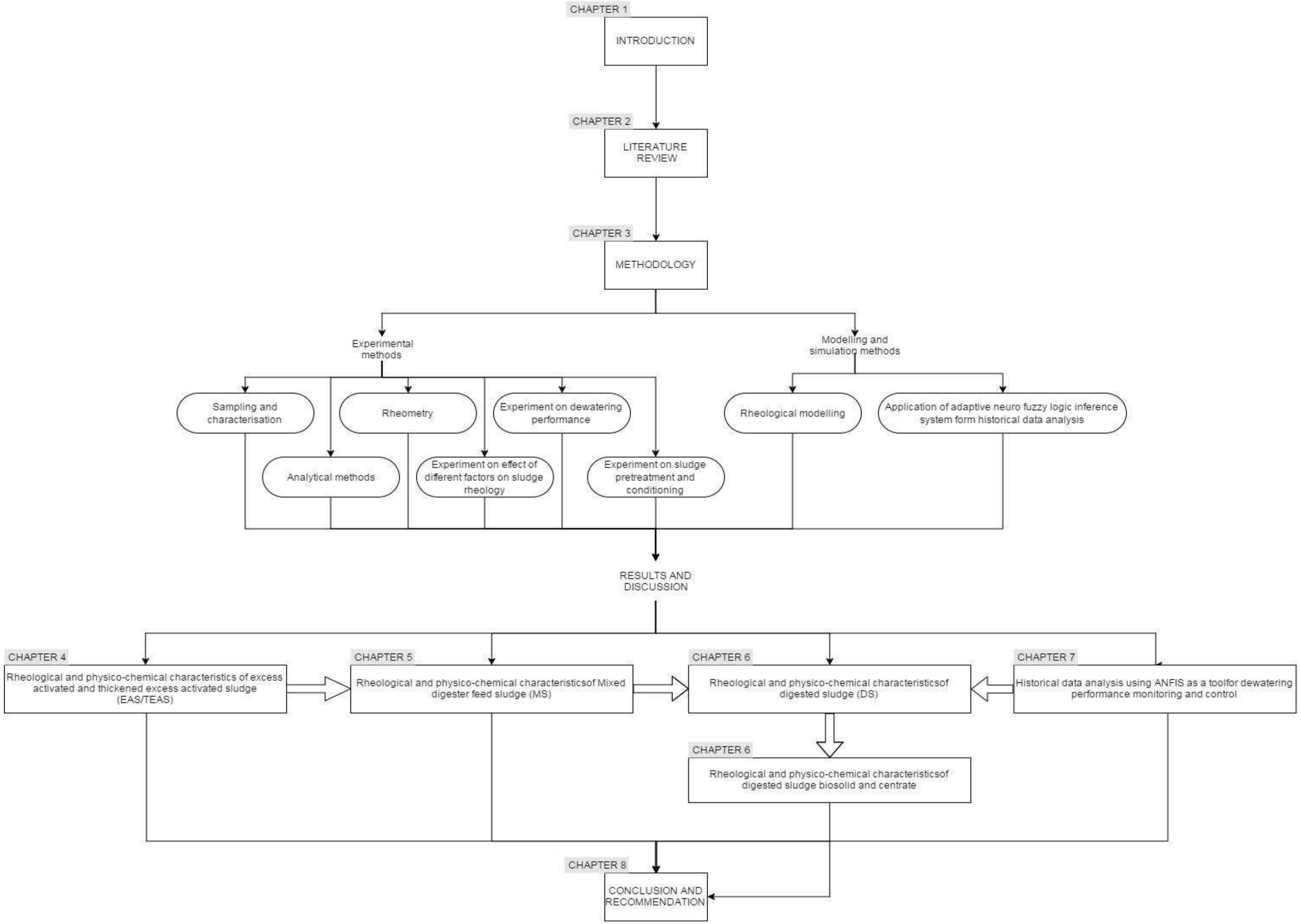

Fig. 1.1: Overview schematic diagram of research thesis chapter structure.

Reference

[1] Abu-Jdayil, Basim. 2011. "Rheology of sodium and calcium bentonite–water dispersions: Effect of electrolytes and aging time." *International Journal of Mineral Processing* no. 98 (3–4):208-213. doi: http://dx.doi.org/10.1016/j.minpro.2011.01.001.

[2] Abu-Jdayil, Basim, Fawzi Banat, and Mukheled Al-Sameraiy. 2010. "Steady Rheological Properties of Rotating Biological Contactor (RBC) Sludge." *Journal of Water Resource and Protection* no. 2 (1):1-7. doi: 10.4236/jwarp.2010.21001.

[3] Baroutian, Saeid, Nicky Eshtiaghi, and Daniel J. Gapes. 2013. "Rheology of a primary and secondary sewage sludge mixture: Dependency on temperature and solid concentration." *Bioresource Technology* no. 140 (0):227-233. doi: http://dx.doi.org/10.1016/j.biortech.2013.04.114.

[4] Baudez, J. C., F. Markis, N. Eshtiaghi, and P. Slatter. 2011. "The rheological behaviour of anaerobic digested sludge." *Water Research* no. 45 (17):5675-5680. doi: http://dx.doi.org/10.1016/j.watres.2011.08.035.

[5] Baudez, Jean-Christophe. 2008. "Physical aging and thixotropy in sludge rheology." *Applied Rheology* no. 18:1123-1139.

[6] Bhattacharya, SN. 1981. "Flow characteristics of primary and digested sewage sludge." *Rheologica Acta* no. 20 (3):288-298.

[7] Chong, Siewhui, Tushar Kanti Sen, Ahmet Kayaalp, and Ha Ming Ang. 2012. "The performance enhancements of upflow anaerobic sludge blanket (UASB) reactors for domestic sludge treatment–A State-of-the-art review." *Water research* no. 46 (11):3434-3470.

[8] Clauss, F., D. Helaine, C. Balavoine, and A. Bidault. 1998. "Improving activated sludge floc structure and aggregation for enhanced settling and thickening performances." *Water Science and Technology* no. 38 (8–9):35-44. doi: http://dx.doi.org/10.1016/S0273-1223(98)00675-1.

[9] Eshtiaghi, Nicky, Flora Markis, Shao Dong Yap, Jean-Christophe Baudez, and Paul Slatter. 2013. "Rheological characterisation of municipal sludge: A review." *Water Research* no. 47 (15):5493-5510. doi: http://dx.doi.org/10.1016/j.watres.2013.07.001.

[10] Farno, Ehsan, Jean Christophe Baudez, Rajarathinam Parthasarathy, and Nicky Eshtiaghi. 2016. "Impact of thermal treatment on the rheological properties and composition of waste activated sludge: COD solubilisation as a footprint of rheological changes." *Chemical Engineering Journal* no. 295:39-48. doi: http://dx.doi.org/10.1016/j.cej.2016.03.022.

[11] Farno, Ehsan, Rajarathinam Parthasarathy, Jean Christophe Baudez, and Nicky Eshtiaghi. 2013. Effect of Thermal History on Municipal Digested Sludge Rheology: Experimental and Modeling. In *Chemeca 2013*.

[12] Hasar, Halil, Cumali Kinaci, Ayhan Ünlü, Hasan Toğrul, and Ubeyde Ipek. 2004. "Rheological properties of activated sludge in a sMBR." *Biochemical Engineering Journal* no. 20 (1):1-6. doi: http://dx.doi.org/10.1016/j.bej.2004.02.011.

[13] Hong, Chen, Yanxiao Si, Yi Xing, ZhiQiang Wang, Qeng Qiao, and Min Liu. 2015a. "Effect of surfactant on bound water content and extracellular polymers substances distribution in sludge." *RSC Advances* no. 5 (30):23383-23390. doi: 10.1039/C4RA15370G.

[14] Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2015b. "Rheological characteristics of mixture of raw primary and thickened excess activated sludge: impact of mixing ratio, solid concentration, temperature and sludge age." *Desalination and Water Treatment*:1-12. doi: 10.1080/19443994.2015.1115374.

[15] Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016. "Rheological characteristics of municipal thickened excess activated sludge (TEAS): impacts of pH, temperature, solid concentration and polymer dose." *Research on Chemical Intermediates*:1-19. doi: 10.1007/s11164-016-2482-2.

[16] Liao, BQ, DG Allen, GG Leppard, IG Droppo, and SN Liss. 2002. "Interparticle interactions affecting the stability of sludge flocs." *Journal of colloid and interface science* no. 249 (2):372-380.

[17] Lotito, V., L. Spinosa, G. Mininni, and R. Antonacci. 1997. "The rheology of sewage sludge at different steps of treatment." *Water Science and Technology* no. 36 (11):79-85. doi: http://dx.doi.org/10.1016/S0273-1223(97)00672-0.

[18] Markis, Flora, Jean-Christophe Baudez, Rajarathinam Parthasarathy, Paul Slatter, and Nicky Eshtiaghi. 2014. "Rheological characterisation of primary and secondary sludge: Impact of solids concentration." *Chemical Engineering Journal* no. 253 (0):526-537. doi: http://dx.doi.org/10.1016/j.cej.2014.05.085.

[19] Markis, Flora, Jean-Christophe Baudez, Rajarathinam Parthasarathy, Paul Slatter, and Nicky Eshtiaghi. 2016. "Predicting the apparent viscosity and yield stress of mixtures of primary, secondary and anaerobically digested sewage sludge: Simulating anaerobic digesters." *Water Research* no. 100:568-579. doi: http://dx.doi.org/10.1016/j.watres.2016.05.045.

[20] Markis, Flora, Kevin Hii, Rajarathinam Parthasarathy, Jean-Christophe Baudez, Paul Slatter, and Nicky Eshtiaghi. 2013. Rheological Characterisation of blends of Primary and Secondary Sludge. In *Chemeca 2013*.

[21] Moeller, Gabriela, and Luis Gilberto Torres. 1997. "Rheological characterization of primary and secondary sludges treated by both aerobic and anaerobic digestion." *Bioresource Technology* no. 61 (3):207-211. doi: http://dx.doi.org/10.1016/S0960-8524(97)00061-8.

[22] Mori, M., I. Seyssiecq, and N. Roche. 2006. "Rheological measurements of sewage sludge for various solids concentrations and geometry." *Process Biochemistry* no. 41 (7):1656-1662. doi: http://dx.doi.org/10.1016/j.procbio.2006.03.021.

[23] Neyens, Elisabeth, Jan Baeyens, Raf Dewil, and Bart De heyder. 2004. "Advanced sludge treatment affects extracellular polymeric substances to improve activated sludge dewatering." *Journal of Hazardous Materials* no. 106 (2–3):83-92. doi: http://dx.doi.org/10.1016/j.jhazmat.2003.11.014.

[24] Nguyen, T., and A. Oloyede. 2001. "Predictive rheological models for the consolidation behaviour of articular cartilage under static loading." *Proc Inst Mech Eng H* no. 215 (6):565-77.

[25] Pevere, A., G. Guibaud, E. van Hullebusch, P. Lens, and M. Baudu. 2006. "Viscosity evolution of anaerobic granular sludge." *Biochemical Engineering Journal* no. 27 (3):315-322. doi: http://dx.doi.org/10.1016/j.bej.2005.08.008.

[26] Piani, Luciano, Claudia Bruna Rizzardini, Adriano Papo, and Daniele Goi. 2014. "Rheology Measurements for Online Monitoring of Solids in Activated Sludge Reactors of Municipal Wastewater Treatment Plant." *The Scientific World Journal* no. 2014:6. doi: 10.1155/2014/590961.

[27] Ratkovich, N., W. Horn, F. P. Helmus, S. Rosenberger, W. Naessens, I. Nopens, and T. R. Bentzen. 2013. "Activated sludge rheology: A critical review on data collection and modelling." *Water Research* no. 47 (2):463-482. doi: http://dx.doi.org/10.1016/j.watres.2012.11.021.

[28] Sanin, F. Dilek. 2002. "Effect of solution physical chemistry on the rheological properties of activated sludge." *Water SA* no. 28 (2):207-212.

[29] Seyssiecq, Isabelle, Jean-Henry Ferrasse, and Nicolas Roche. 2003. "State-of-the-art: rheological characterisation of wastewater treatment sludge." *Biochemical Engineering Journal* no. 16 (1):41-56. doi: http://dx.doi.org/10.1016/S1369-703X(03)00021-4.

[30] Show, Kuan-Yeow, Taohong Mao, and Duu-Jong Lee. 2007. "Optimisation of sludge disruption by sonication." *Water Research* no. 41 (20):4741-4747. doi: http://dx.doi.org/10.1016/j.watres.2007.07.017.

[31] Tchobanoglous, G., F.L. Burton, and H.D. Stensel. 2003. *Wastewater Engineering: Treatment and Reuse*: McGraw-Hill.

[32] Tixier, N., G. Guibaud, and M. Baudu. 2003a. "Determination of some rheological parameters for the characterization of activated sludge." *Bioresource Technology* no. 90 (2):215-220. doi: http://dx.doi.org/10.1016/S0960-8524(03)00109-3.

[33] Tixier, N., G. Guibaud, and M. Baudu. 2003b. "Effect of ph and ionic environment changes on interparticle interactions affecting activated sludge flocs: A rheological approach." *Environmental Technology* no. 24 (8):971-978. doi: 10.1080/09593330309385635.

[34] Yeneneh, Anteneh Mesfin. 2014. *Study on performance enhancement of anaerobic digestion of municipal sewage sludge*. PhD Thesis, Chemical Engineering Department, Curtin University, Perth, Australia.

[35] Yeneneh, Anteneh Mesfin, Eugene Hong, Tushar Kanti Sen, Ahmet Kayaalp, and Ha Ming Ang. 2016. "Effects of Temperature, Polymer Dose, and Solid Concentration on the Rheological Characteristics and Dewaterability of Digested Sludge of Wastewater Treatment Plant (WWTP)." *Water, Air, & Soil Pollution* no. 227 (4):1-14. doi: 10.1007/s11270-016-2820-4.

CHAPTER 2
LITERATURE REVIEW

Abstract

In this chapter, an up to date literature information on rheological behaviour of raw primary sludge, excess activated sludge, thickened excess activated sludge, mixture of raw primary and thickened excess activated sludge (mixed sludge), digested sludge, and biosolid under the influence of different operating parameters and their impacts on process performance are presented. Solid concentration, temperature, primary to thickened excess activated sludge mixing ratio, and sludge age were found to affect the viscosity, yield stress, flow index and flow consistency of mixed sludge. Viscosity also showed a decreasing trend with decreasing total solid concentration and percentage of thickened excess activated sludge in the mixture. In contrast, yield stress and viscosity generally showed reduction with increasing temperature. The effect of dose of conditioning agents on the rheological behaviour of sludge was also addressed in this review. Investigating the relationship between rheological and physico-chemical characteristics of sludge can also serve as a tool to optimize essential process parameters. The applicability and practical significance of various rheological models such as Bingham, Power Law (Ostwald), Herschel-Bulkley, Casson, Sisko, Careau, and Cross models to represent experimental rheological characteristic of different sludge types was also investigated in this review.

2.1 Rheological behaviour of sludge

Rheology is the study of flow and deformation of materials under applied forces. The rheology of Non-newtonian fluids like, polymers, detergents, pastes and wax, oil and biological materials like sludge is very complex and requires thorough investigation (Dentel 1997, Khalili Garakani et al. 2011, Dieudé-Fauvel et al. 2014, Hong et al. 2016b, a, Markis et al. 2016, Yeneneh et al. 2016). This particular research reviews the rheological flow behaviour of municipal sewage sludge. Published articles in recent years have reported different aspects of the rheological flow behaviour of sludge from different parts of municipal wastewater treatment process. Sustainable sludge and wastewater management is getting increasingly more difficult with the rapid growth of urban population and the demand for environmentally friendly methods for disposal. This in turn demands the development of present technologies and operation for wastewater treatment plants such as improving pumping, hydrodynamics, mass transfer rates, sludge settling, filtration and other related processes. Significant improvement in monitoring, control and performance of wastewater treatment processes can be achieved by investigating flow and rheological behaviour of sludge. A larger number of research work has been conducted in the area of sludge rheology (Lotito et al. 1997, Seyssiecq et al. 2003, Baudez et al. 2011, Eshtiaghi et al. 2013, Ratkovich et al. 2013, Markis et al. 2014, Hong et al. 2015, Hong et al. 2016a, b, Yeneneh et al. 2016). The rheological flow behaviour is highly influenced by wastewater treatment operating parameters such as source of sewage, total solid concentration of sludge, temperature, and sludge treatment methods (Seyssiecq et al. 2003, Abu-Jdayil et al. 2010, Markis et al. 2014, Hong et al. 2016a, b, Yeneneh et al. 2016). Studies show that sludge is highly complex in nature and needs detailed investigation to improve the understanding on the impacts of different operating parameters on the rheological and flow properties of different sludge type (Markis et al. 2014, Hong et al. 2016a, b, Yeneneh et al. 2016). A typical wastewater treatment plant generally consists of four stages, which are preliminary, primary, secondary, and advanced treatment stages. Different types of sludge are generated from these various treatment sections, such as raw primary sludge, excess activated sludge, and thickened excess activated sludge, mixed sludge, digested sludge and biosolid. Raw primary sludge that comes from the underflow stream of primary sedimentation tanks is transferred to secondary treatment units of aeration and sedimentation where nutrient removal and biomass accumulations takes place (Yeneneh 2014). The product of the secondary treatment process, activated sludge, is thickened in the dissolved air flotation thickener (DAFT) to form thickened excess activated sludge. Thickened excess activated sludge is a complicated colloidal material which is composed of organic and inorganic particles. Raw primary sludge and thickened excess activated sludge is then mixed to form mixed sludge which is fed to the anaerobic digesters for further degradation (Clauss et al. 1998). The product of the anaerobic digestion process, digested sludge, would be fed to the dewatering plant for further solid-liquid separation. Both the anaerobic digestion and sludge dewatering operations account for approximately 70% of the overall wastewater treatment plant operation cost, making it a vital process for rheological investigation (Seyssiecq et al. 2003, Abu-Jdayil et al. 2010, Markis et al. 2013, Markis et al. 2014, Yeneneh 2014).

Sludge rheology (viscosity, yield stress and shearing behaviour) is affected by many factors including total solid concentration, temperature, pH, dose of polymer or other agents, chemical composition especially concentration of biopolymers and organics (Eshtiaghi et al. 2013, Ratkovich et al. 2013, Markis et al. 2014, Hong et al. 2015, Hong et al. 2016a, b, Yeneneh et al. 2016). According to Einstein law of viscosity, solids existing within a fluid is considered as a key factor that contributes to non-Newtonian flow behaviour (Sanin 2002). Different sludge types generally behave like a non-Newtonian and shear thinning material, which has been reported in many literature (Sanin 2002, Tixier et al. 2003a, b, Mori et al. 2006, Pevere et al. 2006, Abu-Jdayil 2011, Eshtiaghi et al. 2013). Total solid content is a parameter that influences the rheological and flow behaviour of sludge types. It was found that increasing viscosity of sludge due to the increase of solid content will lead to stronger inter-particle interactions which are caused by the size increase of particles in suspension, resulting in higher apparent viscosity for different sludge types (Hong et al. 2016b, a, Yeneneh et al. 2016). Experimental studies have confirmed that solid content is a key parameter that highly influences the rheological behaviour. It helps to validate the dynamic and complex nature of different sludge types. Baudez (2008) also found that shear stress and shear rate increase with the increase of total solid content and are highly dependent on the fractal dimensions of the floc. Utilizing one parameter alone to describe the rheological behaviour of different sludge types is not adequate hence the use of multiple parameters is recommended to improve the understanding (Lotito et al. 1997, Piani et al. 2014, Hong et al. 2016a, b, Hong et al. 2016c, Yeneneh et al. 2016, Hong et al. 2017). Hence, other parameters need to be investigated as well. Temperature is also considered a key parameter that has strong effect on the rheological properties of all sludge types by affecting flocculated particle size, shape, and degree of dispersion within the different sludge types (Sanin 2002). Studies have shown that yield stress increases with increasing total solid content but decreases with increasing temperature, while viscosity shows lower values at higher temperature (Hasar et al. 2004, Baroutian et al. 2013b, Eshtiaghi et al. 2013, Farno et al. 2013, Hong et al. 2016b, a, Yeneneh et al. 2016). pH is another parameter which highly influences the rheological behaviour of different sludge types. The network strength and surface charge of particles change as the pH is increased or decreased (Liao et al. 2002, Neyens et al. 2004). Studies on the relationship between rheological characteristics of digested sludge and dewatering performance particularly on rheology as an indicator or monitoring tool of dewatering performance are only emerging very recently.

According to Markis et al. (2013), Hong et al. (2016b, 2016a), Yeneneh et al. (2016), Hong et al. (2017), studies on different sludge types are few, limited, and inconsistent. Furthermore, literature agrees that each type of sludge is unique to the source, hence different sludge types have different rheological properties; therefore, further research should continue to improve overall understanding on the various aspects of sludge rheology (Bhattacharya 1981, Moeller et al. 1997, Baudez et al. 2011, Markis et al. 2013). Furthermore, the effect of rheological behaviour of sludge from different parts of wastewater treatment plant on pumping cost, mixing and mass transfer are very scattered and limited. This review paper intends to show the findings of published literature on the rheological characteristics of sludge coming from different parts of wastewater treatment plant under the influence of key operating parameters. Rheological measurement techniques and standards for sludge systems have also been included in this review. The challenges and the research gaps were addressed accordingly.

2.2 Rheological modelling of Sludge

According to Björn et al. (2012), ideal fluids exhibits rheological behaviour, which is linear and are classified as Newtonian fluids, while non-Newtonian fluids exhibit a non-linear rheological behaviour as the fluid properties are usually complex in structure. Non-Newtonian fluids are characterised as pseudo-plastic, viscoplastic, dilatant and thixotropic fluids. Once rheological data have been collected, rheological models are used to determine the rheological parameters such as shear stress, yield stress, flow index, infinite, zero-rate viscosities, and flow consistency index, which depict the general flow behaviour of the fluid. In the case of sludge, several rheological models are used to determine its relevant rheological parameters (Khalili Garakani et al. 2011, Sokolov 2013). Bingham, Ostwald, Herschel-Bulkley, Sisko, Careau, and Cross models, as shown in Equations (2-1), (2-2), (2-3), (2-4), (2-5), and (2-6) respectively, are different shear stress and viscosity models used for all sludge types to determine and characterize their flow behaviour properties (Mori et al. 2006, Khalili Garakani et al. 2011, Ratkovich et al. 2013). Studies have shown that applying the six different rheological models to investigate the rheological behaviour of different sludge types are very limited and the applicability of each of the models is subjective and strongly depends on the condition of the sludge (Khalili Garakani et al. 2011, Eshtiaghi et al. 2013).

$$\tau = \tau_y + \eta_B \dot{\gamma}^n \qquad (2\text{-}1)$$

$$\tau = K\dot{\gamma}^n \qquad (2\text{-}2)$$

$$\tau = \tau_y + K\dot{\gamma}^n \qquad (2\text{-}3)$$

$$\mu = \mu_\infty + K\dot{\gamma}^{n-1} \qquad (2\text{-}4)$$

$$\frac{\mu-\mu_\infty}{\mu_0-\mu_\infty} = \left(1 + (\lambda\dot{\gamma})^2\right)^{\frac{n-1}{2}} \qquad (2\text{-}5)$$

$$\frac{\mu-\mu_\infty}{\mu_0-\mu_\infty} = \frac{1}{1+(\lambda\dot{\gamma})^m} \qquad (2\text{-}6)$$

where τ_y is yield stress (Pa), η_B is the high shear-limiting viscosity (Pa.s), $\dot{\Upsilon}$ is the shear rate (s^{-1}), n is the flow index, K is the consistency index (Pa.s^n), μ_∞ is the infinite-rate apparent viscosity (Pa.s), μ_0 is the zero-shear apparent viscosity (Pa.s), λ is the time constant (s), and m is the Cross rate constant. Equations (2-1) to (2-6) are commonly used to model the shear stress (τ is the shear stress in Pa) profile and viscosity (μ is the viscosity in Pa.s) profile.

The apparent viscosity of Newtonian fluids exhibits a linear and constant relationship between shear stress and shear rate. Yield stress, the force required to be applied to fluid system before it will flow, is not considered in the Newtonian equation. Hence, there is no yield stress to overcome with the increase of shear stress. This is not applicable for sludge system. This is because, yield stress and varying viscosity occurs in sludge systems. For sludge system, the models that are of greatest interest are the non-Newtonian model such as Bingham, Casson, and Herschel-Bulkley models (Baroutian et al. 2013a). In all three of these models the system behaves as a solid when the shear stress is less than the yield stress, however when the yield stress is exceeded the system acts as a fluid. The ratio between shear stress and shear rate in each of those models represents the apparent viscosity of the material can be seen as the gradient of the line. The Bingham and Casson models are robust, two parameter models. They are able to characterise non-settling fine particle slurries (Rao 2007). The Bingham model represents a linear relationship between shear stress and shear rate once the yield stress of the material has been exceeded. This model is time independent, which is acceptable when using diluted sludge as there are reversible thixotropic events that with stirring and measurement are negligible (Pignon et al. 1998, Khalili Garakani et al. 2011, Eshtiaghi et al. 2013). In the development of Casson model, Casson theoretically considered the magnitude of inter-particle forces, the model was originally used for the characterisation of printing inks (Rao 2007). The

Casson model like the Bingham model is also time independent. The total resistance to shear for both the Bingham and Casson models can be shown using the apparent viscosity. The apparent viscosities (μ_{app}) for Bingham and Casson models are shown in Equations 2-7 and 2-8 respectively.

$$\mu_{app} = \frac{\mu_p}{1-\frac{\tau_y}{\tau}} \qquad (2\text{-}7)$$

$$\mu_{app} = \frac{\mu_\infty}{\left(1-\sqrt{\frac{\tau_c}{\tau}}\right)^2} \qquad (2\text{-}8)$$

The Herschel-Bulkley model is a three parameter model which takes into account yield stress and the non-linear relationship between shear stress and shear rate (Mullineux 2008). The K and N values are found experimentally once the collected data is plotted on a curve. From rheological measurement, it is reliably possible to find the yield stress which enables a suitable model to be fitted. The Herschel-Bulkley model can take into account the effects of shear thinning and shear thickening, which makes it a very universally applicable model for the analysis of sludge rheology.

2.3 Sludge rheometry

There are many different methods of measuring the rheological properties of sludge with the different properties being measured using varying equipment and control techniques. Dapčević et al. (2008) looked into the methods of testing yield stress for various pseudo-plastic materials, the use of controlled shear rate, controlled shear stress and controlled deformation were discussed. It was found that the method of controlled shear stress was the preferred method due to its simplicity and reproducibility. In this study the vane geometry was discussed, suggesting that when the sample size is sufficient it is advantageous to use this method. This is due to the elimination of wall slip and the simple operation of the equipment with minimal sample destruction (Dapčević et al. 2008).

A rheometer is capable of operating at either constant shear stress or constant shear rate, which enables many different measurements to be performed (Seyssiecq et al. 2003, Stickland 2015, Stickland et al. 2015, Bobade et al. 2017). A viscometer can only measure using controlled shear rate which can give flow and viscosity curves, however a rheometer is capable of controlling the shear stress to be able to measure viscoelastic properties, creep and recovery measurements (Seyssiecq et al. 2003, Stickland 2015, Stickland et al. 2015, Bobade et al. 2017). From measurement of flow properties, the yield stress is able to be found as the point where the shear rate is equal to zero. This yield stress value can then be used in the application of a suitable model.

The geometry of the rheometer can be either parallel plate, cone and plate, concentric cylinder or vane. The nature of the slurry being researched rules out the possibility of using either parallel plate or cone and plate geometries. The remaining two systems of the concentric cylinder and vane could be possibly used as they are both immersed in a vessel while rotating and measuring the rheological properties. The concentric cylinder comes in many design. The double gap design is used to increase surface area for testing with very low viscosity materials, while the other two take into account end effects. Due to the smooth nature of the concentric cylinders slip effects may be present, as well as settling due to the heavy nature of the particles. Furthermore, the double gap geometry can limit settling during rheological measurements while enhancing the sensibility of the shear stress measurement for concentrated sludge system (Barnes et al. 1989, Schramm et al. 1994, Barnes et al. 2001, Seyssiecq et al. 2003). Vane geometry is ideal for sludge system, as it is simple, and eliminates slip effects. This geometry is frequently used to measure rheological properties due to being the simplest technique and the most consistent (Dentel 1997, Barnes et al. 2001, Baudez 2008, Knutsen et al. 2009, Wang et al. 2010b, Markis et al. 2014).

The complexity of sludge as well as a lack of uniformity associated with sludge rheometric techniques have highlighted that sludge is a highly difficult material to characterise in order to design and optimise wastewater treatment plants (Markis et al. 2016). Hence, a viable sludge rheological measurement technique that can ensure reproducibility of results and improve accuracy of measurement should be developed accounting for the challenges cited above.

2.4 Rheological characteristics of different sludge types from WWTPs

The conventional wastewater treatment process involves four major treatment steps. Preliminary, primary, secondary (biological) and tertiary (advanced) treatment steps. Municipal sewage sludge undergoes significant change in physio-chemical and rheological behaviour from the preliminary to the advanced treatment steps. Different types of sludge are generated from these treatment stages, raw primary sludge, excess activated sludge, and thickened excess activated sludge, mixed sludge, digested sludge and biosolid. Raw primary sludge that comes from the underflow stream of primary sedimentation tanks is transferred to secondary treatment units of aeration and sedimentation where nutrient removal and biomass accumulations takes place (Yeneneh 2014). Raw primary sludge shows complex, shear thinning, non-Newtonian rheological flow behaviour with higher yield stress and viscosity compared to the excess activated sludge from secondary sedimentation tanks. The thickening that occurs in the dissolved air floatation thickener increases the total solid concentration of the excess activated sludge and the rheological flow behaviour and the non-Newtonian character significantly increases. Activated sludge, a product of the secondary treatment, is thickened in the dissolved air flotation thickener (DAFT) to form thickened excess activated sludge. Thickened excess activated sludge is a complicated colloidal material which is composed of organic and inorganic particles. Raw primary sludge and thickened excess activated sludge is then mixed to form mixed sludge which is fed to the anaerobic digesters for further degradation (Clauss et al. 1998). The product of the anaerobic digestion process, digested sludge, would be fed to the dewatering plant for further solid-liquid separation. Both the anaerobic digestion and sludge dewatering operations account for approximately 70% of the overall wastewater treatment plant operation cost, making it a vital process for rheological investigation (Seyssiecq et al. 2003, Abu-Jdayil et al. 2010, Markis et al. 2013, Markis et al. 2014, Yeneneh 2014, Yeneneh et al. 2015, Markis et al. 2016). The various literature information of different sludge types are presented below.

2.4.1 Rheological characteristics of raw primary sludge

According to Bhattacharya (1981), raw primary sludge, product of the primary treatment, contains both organic and inorganic materials with trapped bubbles within the suspension. The flow behaviour and rheological properties of raw primary sludge is highly influenced by physico-chemical properties such as concentration, composition, temperature, pH and etc.

Few studies have focused on the rheological behaviour of primary sludge. The pioneering work of Bhattacharya (1981) and Moeller et al. (1997) are the only two studies to date that address the rheology of primary sludge. Bhattacharya (1981), reported that the rheological properties of raw primary sludge behaves like a shear thinning fluid for a total solid concentration range of 3.0% to 8.0%. In contrast, Moeller et al. (1997), reported that no yield stress could be detected for a total solid concentration range of 1% to 3%. It is reported that any inconsistency arising from experimental work could be due to the lack of uniform rheometric methods and techniques which were highlighted by Seyssiecq et al. (2003), Eshtiaghi et al. (2013), Ratkovich et al. (2013). Thus far, Markis et al. (2014), Hong et al. (2016a), Markis et al. (2016) are the only few recent rheological research studies that have some focus on raw primary sludge which also included work from our own research group.

2.4.2 Rheological characteristics of excess activated and thickened excess activated sludge

Current literature mainly focuses on the rheological characteristic of both excess activated and thickened excess activated sludge which is commonly known as activated sludge. Activated sludge is the product of the secondary treatment and contain mainly polysaccharide and protein rich bacteria and micro-organisms that form extracellular polymeric substances. Activated sludge is described as a complex non-Newtonian, viscoelastic and shear thinning fluid (Markis et al. 2014). According to Keiding et al. (2001), Sutherland (2001), Eshtiaghi et al. (2013), the gel like structure of activated sludge are held by both electrostatic and hydrogen bonds. Unno et al. (1985), Tixier et al. (2003a, 2003b), Markis et al. (2014) illustrated that activated sludge is thixotropic and undergoes aging as the solid structure is able to rebuild under shear. Our research group; Hong et al. (2016b), investigated the effect of change in total solid concentration on thickened excess activated sludge rheological flow behaviour for total solid concentrations of 0.9% to 3.7%. It was reported that, viscosity was observed to increase with the increase of total solid concentration due to the increase in solid content within the sludge sample. Furthermore, they used different rheological behaviour models to fit the shear stress-rate curve to determine important rheological model parameters. According to the Bingham pseudo-plastic model, the increase in total solid concentration resulted in the increase of yield stress, Baroutian et al. (2013b), Farno et al. (2013) also reported similar trend. This is also due to the change of flow consistency and the flocculated particle size of the thickened excess activated sludge where the energy of cohesion and inter-particle interaction increase with increasing solid concentration (Mori et al. 2006). Furthermore, this is due to stronger network of sludge floc structure with the increase of solid concentration where colloidal and hydrodynamic forces between sludge particles change (Baroutian et al. 2013b, Markis et al. 2014).

2.4.3 Rheological characteristics of mixed sludge

The mixture of both raw primary sludge and secondary sludge forms what is known as mixed sludge. The overall rheological behaviour of mixed sludge is partially similar to those of raw primary and thickened excess activated sludge (Hong et al. 2016a), where the yield stress, viscosity and, shear stress-shear rate profiles falls in between those of raw primary sludge and secondary sludge. It was reported that, the rheological properties of mixed sludge have significant implications on the performance of anaerobic digester. According to research, the yield stress and viscosity of mixed sludge have significant impact on the overall mixing hydrodynamics, mass transfer and the power requirement for anaerobic digester (O'Neil 1985, Wu et al. 2008, Abbassi-Guendouz et al. 2012, Ratkovich et al. 2013). Raw primary sludge exhibits lower yield stress and excess activated sludge directly coming from the activated sludge treatment process has extremely low yield and behaves like a Newtonian fluid as the total solid content is very low. The mixing ratio between raw primary sludge and thickened excess activated sludge is an essential process parameter that affects flow hydrodynamics and the biochemical methane production capacity, digestion kinetics, volatile solid removal, and overall performance of anaerobic digestion process and dewaterability of the digested sludge that comes out of this process which is also studied by our previous work (Yeneneh 2014, Yeneneh et al. 2015). Hong et al. (2016a) investigated the effect of varying mixing ratio for raw primary sludge to thickened excess activated sludge. The test range conducted were 80:20, 70:30, 60:40, 50:50, 40:60, and 20:80 of raw primary to thickened excess activated sludge respectively. Generally, typical mixing ratio ranges between 70:30 to 50:50 of raw primary to thickened excess activated sludge are used within industrial operations (Yeneneh 2014, Yeneneh et al. 2015). Based on the results of literature, it can be seen that with increasing percentage of secondary sludge, yield stress and viscosity significantly increased and the greater percentage of raw primary sludge in the mixed sludge enhances anaerobic digester performance. Furthermore, both raw primary and activated sludge behaved as shear thinning, yield stress fluids with primary sludge exhibiting highly thixotropic behaviour. The apparent viscosity, yield stress and fluid consistency of both raw primary and activated sludge increase with increasing total solids concentration and followed the Herschel–Bulkley model (Markis et al. 2014, Yeneneh 2014, Yeneneh et al. 2015, Hong et al. 2016a).

2.4.4 Rheological characteristics of digested sludge, biosolid and centrate

Studies on the rheological properties of digested sludge have been conducted by many researchers, including our own research work, such as Moeller et al. (1997), Lay et al. (1999), Forster (2002), Houghton et al. (2002), Paul et al. (2006), Wang et al. (2010b), Baudez et al. (2011), Eshtiaghi et al. (2012), Baudez et al. (2013), Farno et al. (2013), Noutsopoulos et al. (2013), Dieudé-Fauvel et al. (2014), Lau et al. (2014), Markis et al. (2014), Tian et al. (2015), Yeneneh et al. (2015), Farno et al. (2016), Markis et al. (2016), Yeneneh et al. (2016). In contrast, very limited research were undertaken on rheological properties of biosolid and centrate. Hence, we conducted detailed research work on the rheological behaviour of biosolid and centrate, Hong et al. (2017), which adds to the limited works of Neyens et al. (2004), Hamel et al. (2005), Higgins et al. (2005), Ayol et al. (2006), Dursun et al. (2007), Carrère et al. (2010). According to these researchers the rheological behaviour of digested sludge, centrate and biosolid were found to fit best to Herschel-Bulkley rheological model, which is mostly used to represent non-Newtonian viscoelastic shear thinning fluid flow behaviour which was supported by our previous study (Hong et al. 2017). The zero-rate and infinite rate viscosities determined using this model showed that biosolid was observed to have the highest initial rate viscosity, followed by digested sludge and centrate. The significant deviation in the yield stress, zero-rate and infinite-rate viscosities of biosolid compared to that of digested sludge and centrate is mainly due the increase in total solid concentration and flocculation colloidal effect of the polymer due to bridging effect and increase of the network strength between sludge flocs particles (Sun et al. 2014, Yeneneh et al. 2016). Baudez et al. (2011) and Farno et al. (2016) reported similar rheological behaviour of digested sludge but not on biosolid. The shear force requirement and torque of biosolid is also more than 100 times higher than that of digested sludge and centrate and the shear modulus showed a similar trend. The significant deviation in torque requirement and shear modulus of biosolid shows the network strength and strong non-Newtonian viscoelastic behaviour of the biosolid floc particles, which is responsible for higher pumping cost and centrifuge power requirement (Seyssiecq et al. 2003).

According to Baudez et al. (2011) and Monteiro (1997), at low temperature digested sludge exhibits a linear viscoelastic behaviour while at high temperature it behaves similar to Bingham fluid. In contrast to temperature, at varying total solid concentration the property of digested sludge tend to maintain its form and quality. Baudez et al. (2011) also mentioned that there are many factors which affects the quality and rheological properties of digested sludge, resulting in difficulties in maintaining consistent results implying that the particle interactions within the digested sludge are dominated by steric effect more than an electrostatic effect. Furthermore, Dentel (1997), Dursun et al. (2007) work on digested sludge concluded that rheological method are for more applicable for characterizing digested sludge dewatering properties when compared to traditional methods such as CST. They also concluded that the rheological method can improved by utilizing an immobilized cell, during the process of sludge concentration by dewatering.

2.5 Effect of various physico-chemical and other process parameters on rheological characteristics of sludge

2.5.1 Effect of pH

It is generally known that rheological properties of sludge are affected pH. Rheological parameters such as shear stress and viscosity follow a decreasing trend with increasing pH. This trend has been frequently reported in many research papers including articles previously published by us Hong et al. (2016b) and others like Pevere et al. (2007) Pevere et al. (2006) Tixier et al. (2003b) Sanin (2002) Ruiz-Hernando et al. (2014a) Sanin (2002). Sanin (2002) investigated the effect of change in pH on the rheological properties of activated sludge. He reported that apparent viscosity increased with increasing pH of the activated sludge. It was also reported at slightly acidic pH of 5-6, the surface of the sludge floc is only slightly negatively charged and the floc maintains its most compact structure. When the sludge flocs are more compact, the exposed cross-sectional area of solids is reduced, therefore the obstruction of fluid flow and deformation properties will be less resulting in lower viscosity and shear stress. As the pH of sludge increases beyond pH of 7, the effect of pH on viscosity and shear stress are increasingly intensified. This trend was also reported by Tixier et al. (2003b) and Tenney et al. (1965) where the sludge floc became increasingly negatively charged with increasing pH resulting in repulsion and expansion of the floc structure which leads to the increase in exposed cross-sectional area resulting in higher resistance to flow. Hence, higher viscosity and shear stress values are expected at higher pH and vice versa. Pevere et al. (2006) also reported the same trend, but added that pH has limited impact on the overall rheology of sludge but instead sludge rheology is highly dependent on the source of the sludge. Wang et al. (2017) reported that in the pH range of 2.6- 6.8 the viscosity and shear stress of sludge was observed to increase with increasing pH in the same way as the reports of previous researchers. It was also reported that sludge floc structure and surface properties are highly dependent on pH. Al-Dawery et al. (2017) confirmed that sludge particles formed larger floc sizes at higher alkalinity compared to more acidic sludge environment. As pH of sludge increases yield stress was found to increase in the same manner as the viscosity and shear stress. The pH dependence of rheology has been considered by Tombácz et al. (2006) on similar colloidal material particularly on kaolinite and montmorillonite. In the same way as the other findings reported above, they observed that the charge on the faces of the particles depended on the pH of the solution, with a high pH resulting in a net negative surface charge and a low pH a net positive surface charge. This surface charge has a bearing on the rheology of the material as it changes the way the particles interact, changing the strength of the interparticle forces. This change in interparticle forces directly affects the way the material reacts to shear rate and shear stress. The pH of the material can have a direct impact on the surface charge of the particles, hence affecting the inter-particle forces and the electrical double layer. The electrical double layer results from the ionic environment surrounding the particle developing to neutralise the net charge between the particle and the bulk medium. Due to the effect of interparticle forces. Table 2.1 shows the summary of the reports by different researchers on the effect of pH on sludge viscosity and shear stress for varying pH ranges.

Table 2.1: Impact of pH on rheological properties of different types of wastewater sludge.

Sludge type	**pH range**	**Shear rate (s^{-1})**	**Model**	**Results**	**Reference**
DS	2.6 – 6.8	0 – 1000	Herschel-Bulkley	Shear stress increases with increasing pH. Viscosity value increases with increasing pH value.	Wang et al. (2017)
DS	5.6 – 9.0	0 – 1000	Bingham	Yield stress increases with increasing pH.	Al-Dawery et al. (2017)
EAS/TEAS	3.6 – 10.0	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Shear stress increases with increasing pH. Viscosity value increases with increasing pH value.	Hong et al. (2016b)
EAS/TEAS	6 – 14	-	-	Viscosity value increases with increasing pH value.	Ruiz-Hernando et al. (2014b)
EAS/TEAS	6 – 14	0 – 300	-	Viscosity value increases with increasing pH value.	Ruiz-Hernando et al. (2013)

EAS/TEAS	6.8 – 7.2	600	-	Viscosity value increases with increasing pH value.	Pevere et al. (2007)
EAS/TEAS	2 – 11	200 – 1000	-	Viscosity value increases with increasing pH value.	Pevere et al. (2006)
EAS/TEAS	2 – 12	0 – 800	Bingham, Ostwald	Viscosity value increases with increasing pH value.	Tixier et al. (2003b)
EAS/TEAS	5.5 – 9.1	1.8 – 73.4	Ostwald	Viscosity value increases with increasing pH value.	Sanin (2002)

RPS: Raw primary sludge; EAS/TEAS: Excess activated sludge/thickened excess activated sludge; MS: Mixed sludge; DS: Digested sludge

2.5.2 Effect of temperature

Rheological properties as a function of temperature have been investigated by many researchers as shown in Table 2.2, including our own study, and generally it has been reported that yield stress and viscosity of different sludge types decrease with increasing of temperature (Manoliadis et al. 1984, Sozanski et al. 1997, Hasar et al. 2004, Paul et al. 2006, Abu-Jdayil et al. 2010, Baroutian et al. 2013b, Baudez et al. 2013, Eshtiaghi et al. 2013, Farno et al. 2013, Ruiz-Hernando et al. 2014a, Trávníček et al. 2014, Cao et al. 2016, Hong et al. 2016b, a, Yeneneh et al. 2016). Baroutian et al. (2013b) have conducted work on the rheological behaviour of mixed primary and thickened excess activated sludge and have reported that yield stress decreases with increasing temperature. This trend was also reported by Khalili Garakani et al. (2011), who also applied seven different models on activated sludge system in order to obtain a deeper understanding of the actual sludge behaviour. While Farno et al. (2015) studied the effect of temperature on both yield stress and viscosity. It was reported that increasing the temperature decreased the apparent viscosity of the sludge, however at high shear rates, viscosity has been reported to have an increasing trend instead. Bougrier et al. (2008) performed a similar study which involved determination of the effect of thermal treatment on the solubilisation, physical properties and anaerobic digestion of several activated sludge samples. In their study, treatment temperature ranged up to 180ºC, which is considered to be unreasonably high as it would lead to the boiling of the sludge solution. They reported that as temperature increases the viscosity decreases. As the temperature of the thermal treatment continues to rise the viscosity change begins to slow and eventually no change will be observed. Hence, this confirms that such high temperatures are both impractical and ineffective in terms of changing the sludge viscosity and shear stress. Furthermore, Hii et al. (2017) investigated the effects of thermal pre-treatment on sludge. It was found that, the rheology of the sludge changes when allowed to be cooled back to room temperature, suggesting that it is critical that rheological measurement are conducted immediately.

Table 2.2: Impact of temperature on rheological properties of different types of wastewater sludge.

Sludge type	**Temperature range** (˚C)	**Shear rate** (s^{-1})	**Model**	**Results**	**Reference**
EAS/TEAS	80 – 145	0 – 600	Herschel-Bulkley	Viscosity and yield stress decrease linearly with increasing temperature.	Hii et al. (2017)
DS	60 – 180	-	-	Viscosity increase with the decrease in temperature.	Zhang et al. (2017)
DS	20 – 45	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Increasing temperature from 20 to 50 °C resulted in decrease in viscosity from 0.0053 to 0.0011Pa. Digester operating temperature range of 35–36 °C enhanced rheological properties and also dewatering process.	Yeneneh et al. (2016)
EAS/TEAS	23 – 45	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress decreased by 2.5 times when the temperature was raised from 23 to 55°C. Viscosity decreased by 4.3times with an increase in temperature from 23 to 55°C.	Hong et al. (2016b)
EAS/TEAS	50 – 80	0 – 1000	Herschel-Bulkley	Yield stress and infinite viscosity decreases with increasing of temperature.	Farno et al. (2016)
DS	20 – 55	0 – 300	Bingham, Ostwald, Herschel-Bulkley	Viscosity decreased by 6 times with an increase in temperature from 20 to 55°C.	Cao et al. (2016)

MS	25 – 55	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Viscosity decreased by 50% with the increase of temperature from 25 – 55°C. Yield stress decreased by 33% with the increase of temperature from 25 – 55°C.	Hong et al. (2016a)
EAS/TEAS	70 – 80	5 – 300	Ostwald	Pre-treatment and post-treatment conditioning (low-temperature thermal) resulted in reduction of viscosity.	Ruiz-Hernando et al. (2014a)
DS	10 – 60	0 – 1000	Bingham	Increasing temperature resulted in decrease in yield stress and viscosity. Preheating and cooling sludge as a pre-treatment condition resulted in the decrease of initial yield stress.	Baudez et al. (2013)
MS	25 – 55	0 – 1000	Herschel-Bulkley	Yield stress decreases with increasing temperature.	Baroutian et al. (2013b)
EAS/TEAS	4 – 35	100	-	Increasing temperature resulted in decrease in yield stress and viscosity.	Dieudé-Fauvel et al. (2009)
EAS/TEAS	15 – 30	-	Bingham, Ostwald	Increasing temperature resulted in decrease in yield stress and viscosity.	Hasar et al. (2004)
EAS/TEAS	0 – 25	0 – 1000	Bingham	Temperature greatly affected the rheological properties of sludge at lower total solid content.	Sozanski et al. (1997)

				Increasing temperature resulted in decrease in yield stress and viscosity.	
RPS EAS/TEAS	10 – 25	-	Bingham	Yield stress has an exponential relationship with temperature. Flow behaviour index were found to be essentially independent of temperature. Temperature changes the overall sludge consistency resulting in significant energy loss	Manoliadis et al. (1984)
RPS: Raw primary sludge; EAS/TEAS: Excess activated sludge/thickened excess activated sludge; MS: Mixed sludge; DS: Digested sludge B: Bingham; O: Ostwald; HB: Herschel-Bulkley; S: Sisko; C: Carreau; Cr: Cross; Ca: Casson					

2.5.3 Effect of total and volatile solid concentration

Total suspended solids (TSS) concentration is one of the most important parameters affecting sludge rheology and therefore several studies have been performed on this topic. These studies as shown in Table 2.3, involve varying the TSS concentration and then observing the effects on various rheological properties, predominately apparent viscosity and/or yield stress, in order to improve the understanding of sewage sludge flow behaviour. Rheological properties under the influence of TSS concentration have been investigated by several researchers such as Yeneneh et al. (2016) Markis et al. (2016) Hong et al. (2016b) Cao et al. (2016) Hong et al. (2016a) Piani et al. (2014) Markis et al. (2014) Baroutian et al. (2013b) Khalili Garakani et al. (2011) Yang et al. (2009) Laera et al. (2007) Wu et al. (2008) Mori et al. (2006) Pevere et al. (2006) Hasar et al. (2004) Tixier et al. (2003a) Spinosa et al. (2003) Sanin (2002) Rosenberger et al. (2002) Forster (2002) Lotito et al. (1997). Several of these studies were discussed focusing on an overview of their relevant findings. The range of TSS concentrations chosen varies in great degree, the investigated range highly depends on the origin of sludge and the expected output conditions of the wastewater treatment plant being investigated. Although, different authors investigated different TSS conditions, this does not necessarily mean that their findings are less accurate.

Baroutian et al. (2013b) investigated the effect of total solid concentration on sludge rheology and reported that yield stress of digested sludge is directly related to total solid content of the system where yield stress increases with increasing total solid concentration. This is due to the existence of solids particle within the sludge system which resulted in an increase in viscosity within the sludge system. This trend was also reported by Farno et al. (2013) and Yang et al. (2009). Yang et al. (2009) reported that the apparent viscosity of sludge reflects the internal and external interactions and forces occurring within sludge flocs resulting in different flow curve behaviour for low and high solid concentration. Baudez et al. (2001) and Forster (1981) also reported that the rheological properties of sludge is governed by the synthesis of volatile fatty acids. Another similar study was performed by Markis et al. (2016) in which they looked at the impact of TSS concentration on the rheological properties of primary and secondary sludge (activated sludge). The results from experiments performed by Markis et al. (2016) show that as solid concentration increases the apparent viscosity of the activated sludge also increases, this agrees with the findings of Tixier et al. (2003a). Additionally, it shows that there is a linear relationship between the TSS concentration and apparent viscosity whereas Tixier et al. (2003a) found more of an exponential relationship and this difference could be due to the TSS concentration range used (i.e. At low concentrations the relationship may start off as exponential but then as it gets higher it becomes linear). The other study discussed is that of Sanin (2002) who examined the effect of different operational and other process parameters on the rheology of activated sludge with one of them being solids concentration (TSS). The findings from Sanin (2002) agrees with both Tixier et al. (2003a) and Markis et al. (2016) that as solids concentration increases so does apparent viscosity additionally it supports the idea that at low TSS concentration the relationship is exponential.

Table 2.3: Impact of total solid concentration on rheological properties of different types of wastewater sludge.

Sludge type	Total solid concentration range (g/L)	Shear rate (s^{-1})	Model	Results	Reference
DS	10 – 20	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress increased with the increase of total solid concentration. Viscosity increased with the increase of total solid concentration.	Hong et al. (2017)
DS	10 – 20	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress increased 6 times with the increase of total solid concentration from 10 – 20g/L. Viscosity increased 41 times with the increase of total solid concentration from 10 – 20g/L.	Yeneneh et al. (2016)
RPS EAS/TEAS	28 – 50 28 – 92	0 – 1000	Herschel-Bulkley	Rheological properties of mixed sludge changed dramatically with increasing TEAS concentration.	Markis et al. (2016)
EAS/TEAS	9 – 37	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress increased 6 times with the increase of total solid concentration from 9 – 37g/L. Viscosity increased 6 times with the increase of total solid concentration from 9 – 37g/L.	Hong et al. (2016b)
DS	40 – 100	0 – 300	Bingham, Ostwald, Herschel-Bulkley	Yield stress increased 78 times with the increase of total solid concentration from 40 – 100g/L.	Cao et al. (2016)

				Viscosity increased 42 times with the increase of total solid concentration from 40 – 100g/L.	
MS	20 – 30	0 – 1000	Bingham, Ostwald, Herschel-Bulkley, Sisko, Carreau, Cross	Yield stress decrease by 85% with the decrease of total solid concentration from 30 – 20g/L. Viscosity decrease by 15% with the decrease of total solid concentration from 30 – 20g/L	Hong et al. (2016a)
EAS/TEAS	0 – 1	0 – 240	Ostwald	Sludge sample show slightly thixotropic and shear-thinning behaviour with increasing total solid concentration.	Piani et al. (2014)
RPS EAS/TEAS	28 – 82 28 – 50	0 – 1000	Herschel-Bulkley	Both RPS and EAS/TEAS behave as shear thinning, yield stress fluids.	Markis et al. (2014)
MS	43 – 98	0 – 1000	Herschel-Bulkley	Concentration has a significant impact on the sludge yield stress and the model coefficients.	Baroutian et al. (2013b)
EAS/TEAS	2.74 – 16	25 – 1000	Bingham, Ostwald, Herschel-Bulkley, Carreau	Both yield stress and viscosity increases as total solid concentration of sludge increases.	Yang et al. (2009)
EAS/TEAS	3.7 – 22.9	3 – 1300	Bingham, Ostwald	Both yield stress and viscosity increase as total solid concentration of sludge increases. Model parameters shows strong correlation with total solid concentration.	Laera et al. (2007)
EAS/TEAS	4.2 – 25	940	-	Yield stress decrease by 38% with the decrease of total solid concentration from 4.2 – 25g/L.	Wu et al. (2008)

				Viscosity decrease by 38% with the decrease of total solid concentration from 4.2 – 25g/L	
EAS/TEAS	27 – 57	0 – 3000	Bingham, Ostwald, Herschel-Bulkley	Yield stress decrease by 90% with the decrease of total solid concentration from 27 – 57g/L for both dynamic and flow measurements.	Mori et al. (2006)
EAS/TEAS	8.3 – 22.6	200 – 1000	-	Increase in shear stress was observed with increasing total solid concentration. Viscosity increased with increasing total solid concentration.	Pevere et al. (2006)
EAS/TEAS	2.9 – 12.3	-	Bingham, Ostwald	Viscosity showed minimum change (<1%). Yield stress increased 2.5 to 4 times with the increase of total solid concentration from 2.9 – 12.3g/L.	Hasar et al. (2004)
EAS/TEAS	3.1 – 6.3	0 – 800	Bingham, Ostwald	Viscosity was greatly affected by total solid concentration. Viscosity of sludge with the same total solid content differ greatly due to source even when the treatment process is exactly the same.	Tixier et al. (2003a)
-	35.1 – 446.7	0.05 – 4.05	Bingham	Yield stress increase with the increase of total solid concentration.	Spinosa et al. (2003)

EAS/TEAS	2.0 – 18	1.8 – 73.4	Ostwald	Viscosity of sludge increased by 5 times with increase in total solids concentration for the range.	Sanin (2002)
EAS/TEAS	2.7 – 47	0 – 2200	Ostwald	Increase in viscosity of approx. 15% with increasing total solid concentration. Increase in shear stress with increasing total solid concentration.	Rosenberger et al. (2002)
EAS/TEAS	10.5 – 26.6	0 – 10	-	Increase in shear stress with increasing total solid concentration.	Forster (2002)
EAS/TEAS MS DS	3 – 47 11 – 82 12 – 67	0.015 – 4.05	Bingham, Ostwald	Rheological properties of sludge changes above 80-100g/L if total solid concentration.	Lotito et al. (1997)
RPS: Raw primary sludge; EAS/TEAS: Excess activated sludge/thickened excess activated sludge; MS: Mixed sludge; DS: Digested sludge					

2.5.4 Effect of conditioning agents

Better understanding of sludge dewatering processes helps to improve biosolid management and results in further economic and environmental benefits. Enhanced dewatering can lead to reduction in liquid volume within biosolid which would reduce the capital, transportation and operational costs (Neyens et al. 2004, Wang et al. 2010a, Mowla et al. 2013). Dewatering is typically achieved by use of filter presses or centrifuges. In order to enhance the dewatering process, condition agents such as polymers are used to flocculate the sewage sludge. These conditioning agents can modify the floc structure of the sludge resulting in the change of fluid properties and can impact the overall efficiency of the dewatering process (Dieudé-Fauvel et al. 2011). Dewatering of waste activated or digested sludge is a costly process in the operation of wastewater treatment plants. Expenses related to the dewatering process, including cost of conditioning agents, typically account for 30-50% of the annual operating cost of municipal treatment plants (Sorensen et al. 1995). Considering the huge cost related to the dewatering process it seems highly relevant to improve our understanding of the relation between suspension structure (rheology) and dewaterability, and in particular how to control suspension structure for optimisation of conditioning and dewatering (Mikkelsen et al. 2001, Hong et al. 2016a, b, Hong et al. 2017). Furthermore, there is lack of fundamental knowledge within the dewatering process, particularly on how flocs are structurally organized and how this may relate to their mechanical and dewatering properties (Dieudé-Fauvel et al. 2011). Many researchers have investigated the effectiveness of various conditioners on sludge dewatering and highlighted the importance of particle size and distribution and their impact on dewatering (Spicer et al. 1996, Mikkelsen et al. 2001, Houghton et al. 2002, Bache et al. 2003, Hou et al. 2003, Jin et al. 2004, Vlyssides et al. 2004, Bolto et al. 2007, Buyukkamaci et al. 2007, Shihab 2010, Dieudé-Fauvel et al. 2011, Qi et al. 2011, Mowla et al. 2013, Lau et al. 2014, Lau et al. 2015, Huang et al. 2017, Lau et al. 2017). All these published literature show that CST measurement has been used as a common indicator for dewatering performance and rheology was used to determine the flocs mechanical properties. In addition, polymer dose was found to be the main parameter which controls the floc structures, particle size and distribution hence rheology of the sludge system.

Forster (1982, 1983), Sanin et al. (1994) investigated the effects of different doses of conditioning agents on the rheological characteristics of sludge. The results showed that there is viscosity reduction due to floc breakup into smaller floc structure with the increase in polymer extracted. Dieudé-Fauvel et al. (2011) investigated the effects of particle size and distribution and their impact on dewatering with multiple polymers as the condition agents. The conditioning agents used in this work had varying molecular weight, cationic charges and cross-linkage. Dieudé-Fauvel et al. (2011) found that the rheological curves had the same trend and shape regardless of the type of conditioning agent used. Hence, the conditioning agent results in shifting of the rheograms only. It was noted that the key factors which resulted in shifting of the curves was the molecular weight and cationic charges of the conditioning agent and the dosage used. It was found that, the flocs size increases with increasing polymer dose which are supported by other researchers such as Spicer et al. (1996), Chu et al. (1999), Mikkelsen et al. (2001), Houghton et al. (2002), Qi et al. (2011), Al-Dawery et al. (2017). Based on rheological results, once optimum polymer dose has been reached, the sludge structures no longer undergo any changes but it does impact the liquid sludge properties. As a result of this, a relationship between rheological properties and polymer dosage can be established. The majority of current research work open the way for further investigation especially the development of rheological properties to optimize polymer dosage. Furthermore, Lee et al. (2000) suggested that using dual polyelectrolytes conditioning method significantly improves the performance of dewatering while decreasing the chance of overdosing.

2.5.5 Effect of chemical oxygen demand (COD)

Rheological properties of digested sludge also depend on total organic content or chemical oxygen demand (COD) of the feed to the anaerobic digesters and performance of the anaerobic biodegradation process (Farno et al. 2016). It was reported that the rheological behaviour of sludge from anaerobic digesters is governed by the synthesis of volatile fatty acids by extracting the main solid components (proteins, lipids and carbohydrates) (Baudez et al. 2001). Biosolid produced from digested sludge also showed poor dewaterability with the increase in volatile organic content of the digested sludge coming out of anaerobic digesters. This results in the increase of polymer consumption to compensate for the deterioration in dewaterability, which in turn incurs additional operational cost (Ayol et al. 2006). Not many work have been conducted to investigate the effect COD on rheology of sludge. Hii et al. (2017) have attempted to find a correlation between COD, yield stress and viscosity. It was reported that yield stress and viscosity were found to decrease with the increasing COD which could be attributed to cell wall breakdown of microorganism and release of soluble organics and breakdown of insoluble proteins into soluble amino acids. Similar trend was also reported by Farno et al. (2016), where the results confirmed that rheological parameter have a relationship with COD and a correlation can be developed to aid as monitoring tool. It is reported that the rate of change in COD when exposed to thermal treatment can be used to predict rheological parameters such as viscosity and yield stress. Similarly, Zhang et al. (2017), also observed some correlation between rheological measurement and COD. In this work, rheological measurement such as viscosity was used as a performance indicator to investigate the effects of COD change due to thermal pre-treatment, while the impact of COD on rheological properties were not investigated. Ciaciuch et al. (2017) also used a similar approach, where COD and rheological measurement were used as performance indicators to monitor the performance of two-stage anaerobic digestion process and no solid link between COD and rheological properties were made. The lack of detailed investigation between the relationship of rheological properties and COD was also highlighted by Oliveira et al. (2016a). It was reported that, rheological measurement coupled with COD should be explored further due to the potential it has to aid in monitoring conditioning requirements during plant operation.

2.6 Rheology as a tool for monitoring and control of important parameters in WWTPs

Rheological characteristics of sludge vary as a function of many factors such as source, environment and intrinsic properties of the sludge (Tang et al. 2014). Hence, Spinosa et al. (2003) and Markis et al. (2016) explained that rheology could potentially be used as a tool for monitoring and optimizing various wastewater treatment unit operations. This section investigates the applicability of rheology as a tool to monitor, control and optimize operational parameters.

2.6.1 Rheological parameter monitoring and control for anaerobic digester performance enhancement

The most common, preferred and cost effective process in the wastewater treatment plant to achieve significant sludge volume reduction is the anaerobic digestion process (Baudez et al. 2011, Evans et al. 2011, Li et al. 2011, Abelleira et al. 2012, Yeneneh 2014). The digestion process occurs in three stages, namely hydrolysis, acidogesis and methanogenesis. The digestion process starts with hydrolysis of the feed sludge which breaks down the insoluble organics. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and acetic acid. Finally, methanogenesis stage converts the remaining organics products into biogas. The remaining solids would have formed the digested sludge which would have organic matter removed when compared to activated sludge (Sólyom et al. 2011, Abbassi-Guendouz et al. 2012, Tang et al. 2014, Yeneneh 2014). Within the anaerobic digester, the composition of sludge is constantly changing and creating a scenario where it is difficult to understand and monitor the rheological behaviour of the sludge. Many researchers such as Bhattacharya (1981), Moeller et al. (1997), Lay et al. (1999), Mikkelsen et al. (2001), Forster (2002), Houghton et al. (2002), Ayol et al. (2006), Paul et al. (2006), Wang et al. (2010b), Baudez et al. (2011), Eshtiaghi et al. (2012), Baudez et al. (2013), Farno et al. (2013), Lau et al. (2013), Dieudé-Fauvel et al. (2014), Lau et al. (2014), Markis et al. (2014), Farno et al. (2015, 2016), Markis et al. (2016), Oliveira et al. (2016b), Yeneneh et al. (2016), Hong et al. (2017) have investigated the change in rheological behaviour of feed (activated sludge) and the product sludge (digested sludge) sludge of the anaerobic digester. Results from Tixier et al. (2003a) shows that viscosity greatly changes during the digestion process and settlability of the sludge also showed similar trend which indicates that sludge is sensitive to floc structure changes. They recommended that rheology can be used as a tool to determine sludge quality which potentially can be useful information for digester performance optimization. Monteiro (1997) reported that there is a relationship with sludge rheological behaviour changes with degree of digestion. Moreover, Monteiro (1997) explained that the total solids concentration changes is not sufficient to describe the change of rheological properties within the digester. Monteiro (1997) suggested that the rate of change of the rheological parameters follow the evolution of the biological process. For the range of solids concentration Monteiro et al studied it has been verified that the degree of digestion is the main factor affecting the rheological behaviour of the sludge and that sludge rheology is not significantly affected by the solids concentration of the sludge. In contrast, Moeller et al. (1997) showed that there is no viscosity changes for the sludge tested and suggested that using rheological properties as a tool for process control should be investigated carefully.

2.6.2 Rheology as a tool for monitoring and control of dewatering performance

Rheological characteristics of sludge were found to be efficient tools for monitoring, control and performance improvement of sludge treatment processes. Researches such as Lotito et al. (1997), Abu-Orf et al. (1999), Yen et al. (2002), Abu-Orf et al. (2005), Örmeci et al. (2005), Laera et al. (2007), Örmeci (2007), Tang et al. (2014), Stickland (2015), Yeneneh et al. (2016), Hong et al. (2017), have suggested that sludge rheological characteristic can be used as a tool for the optimization of polymer dose in the dewatering unit. Many of these researches were designed to identify key rheological parameter that can potentially be used as indicator for controlling the amount of conditioning agent used in wastewater treatment plants.

According to Kopp et al. (2001), dewaterability of digested sludge is highly dependent on the distribution of sludge-water in the sludge mass. There are four classes of sludge-water, free water, surface water, interstitial water, and intracellular water. Accurately measuring the amount of water within the digested sludge samples can be very difficult due to the complex nature, interaction and origin of these waters. For digested sludge, free water can easily be removed from solids particles using simple gravitational settling. Surface and interstitial waters exhibit some interaction with the solid particles which can be removed by chemical conditioning coupled with mechanical methods. Microbial extracellular polymeric substances (EPS) are major components of the sludge floc matrix. EPSs are regarded as one of the most important factors that influence the dewatering characteristic of sludge. Information regarding EPS is thus relatively favourable for understanding the exact roles of EPS in controlling dewaterability and for revealing the mechanisms enhancing dewatering (Neyens et al. 2004, Ouyang et al. 2009). According to Neyens et al. (2004), Ouyang et al. (2009) dewatering of sludge is more dependent on soluble EPS and not bound EPS. It was known that soluble EPS is responsible for water retention and the strong water binding capability of digested sludge, concluding that the higher the amount of soluble EPS in digested sludge results in poor dewatering performance.

According to Youcai et al. (2016), a key rheological parameter that highly impacts the dewatering performance is viscosity. Research work by Örmeci (2007), Tang et al. (2014), Yeneneh et al. (2016), Hong et al. (2017), supports that statement and found that CST value showed a significant correlation with viscosity. In the processes of traditional chemical conditioning and dewatering, capillary suction time (CST) tests are commonly-used indices for quantitative evaluation of the dewatering effect although it has been indicated that CST lacks reliable reproducibility (Stickland et al. 2009). The result of the work concluded that digested sludge samples with higher viscosity exhibits difficulties in dewatering. Furthermore, there is also a correlation between viscosity and soluble EPS. This is because, higher amount of soluble EPS have higher affinity for water which results in higher sludge viscosity value and ultimately, as mentioned above, resulting in poor dewatering performance. Abu-Orf et al. (2005), Örmeci et al. (2005), Örmeci (2007), (Wolny et al. 2008) have used rheological parameters to define the effects of conditioning agents on the physical characteristic of digested sludge. They were able to develop a simple protocol to determine the optimum polymer dosing conditioning using rheological parameter such as viscosity. Furthermore, they concluded that, comparing both traditional method and rheological parameters, rheology is more reliable as a control tool for optimizing conditioning agents for the dewatering process.

2.7 Conclusion

In this review chapter, the rheological and physico chemical characteristics of different types of wastewater treatment plant sludge were discussed at the beginning. In this chapter up-to-date developments, findings and compilations on rheological properties of sludge and the influence of different operational parameters on sludge rheology and the relationships were presented in fair depth. Based on detailed significant number of published articles the impacts of different operational parameters like solid concentration, temperature, pH, floc particle size, mixing ratio, dose of sludge conditioning agents on the rheological behaviour of sludge from different parts of WWTPs were analysed. Raw primary sludge, excess activated sludge, thickened excess activated sludge, mixture of raw primary and thickened excess activated sludge (mixed sludge), digested sludge, and biosolid rheological and flow behaviour under the influence of different operating parameters and the impacts on process performance were investigated and compared. Yield stress was found to increase with increasing solid concentration for all sludge types. Likewise, viscosity showed a decreasing trend with decreasing total solid concentration and percentage of thickened excess activated sludge in the mixture. Temperature showed an inverse relationship with yield stress and viscosity. This comprehensive review analysed and identified few research gaps for future studies. There are as follows:

- Lack of fundamental knowledge within the dewatering process, particularly with the way flocs are structurally organized and how this may relate to their mechanical and dewatering properties.
- Lack of uniform rheometric methods and techniques resulting inconstancy when comparing to other rheological studies.
- Studies on different sludge types are few, limited, and inconsistent. Too much studies have focused on activated sludge or digested sludge and very limited research were undertaken on rheological properties of biosolid and centrate.
- Not many work have been conducted to investigate the effect of COD on rheology of sludge.
- Further studies on the relationship between rheological characteristics of digested sludge and dewatering performance particularly on rheology as an indicator or monitoring tool of dewatering performance are required.

Reference

[1] Abbassi-Guendouz, Amel, Doris Brockmann, Eric Trably, Claire Dumas, Jean-Philippe Delgenès, Jean-Philippe Steyer, and Renaud Escudié. 2012. "Total solids content drives high solid anaerobic digestion via mass transfer limitation." *Bioresource Technology* no. 111:55-61. doi: http://dx.doi.org/10.1016/j.biortech.2012.01.174.

[2] Abelleira, J, SI Pérez-Elvira, J Sánchez-Oneto, JR Portela, and E Nebot. 2012. "Advanced thermal hydrolysis of secondary sewage sludge: a novel process combining thermal hydrolysis and hydrogen peroxide addition." *Resources, Conservation and Recycling* no. 59:52-57.

[3] Abu-Jdayil, Basim. 2011. "Rheology of sodium and calcium bentonite–water dispersions: Effect of electrolytes and aging time." *International Journal of Mineral Processing* no. 98 (3–4):208-213. doi: http://dx.doi.org/10.1016/j.minpro.2011.01.001.

[4] Abu-Jdayil, Basim, Fawzi Banat, and Mukheled Al-Sameraiy. 2010. "Steady Rheological Properties of Rotating Biological Contactor (RBC) Sludge." *Journal of Water Resource and Protection* no. 2 (1):1-7. doi: 10.4236/jwarp.2010.21001.

[5] Abu-Orf, M., and S. Dentel. 1999. "Rheology as Tool for Polymer Dose Assessment and Control." *Journal of Environmental Engineering* no. 125 (12):1133-1141. doi: doi:10.1061/(ASCE)0733-9372(1999)125:12(1133).

[6] Abu-Orf, Mohammad M., and Banu Örmeci. 2005. "Measuring Sludge Network Strength Using Rheology and Relation to Dewaterability, Filtration, and Thickening—Laboratory and Full-Scale Experiments." *Journal of Environmental Engineering* no. 131 (8):1139-1146. doi: 10.1061/(ASCE)0733-9372(2005)131:8(1139).

[7] Al-Dawery, Salam K, and Sajjala S Reddy. 2017. "An experimental study on the rheological properties of conditioned municipal activated sludge." *Journal of Engineering Science and Technology* no. 12 (1):138-154.

[8] Ayol, A., A. Filibeli, and S.K. Dentel. 2006. "Evaluation of conditioning responses of thermophilic-mesophilic anaerobically and mesophilic aerobically digested biosolids using rheological properties." *Water Science and Technology* no. 54 (5):23-31. doi: 10.2166/wst.2006.543.

[9] Bache, DH, EN Papavasilopoulos, E Rasool, YQ Zhao, and JF McGilligan. 2003. "Polymers in alum sludge dewatering: Developments and control." *Water and Environment Journal* no. 17 (2):106-110.

[10] Barnes, H.A., J.F. Hutton, and K. Walters. 1989. *An Introduction to Rheology*: Elsevier.

[11] Barnes, Howard Anthony, and Quoc Dzuy Nguyen. 2001. "Rotating vane rheometry — a review." *Journal of Non-Newtonian Fluid Mechanics* no. 98 (1):1-14. doi: https://doi.org/10.1016/S0377-0257(01)00095-7.

[12] Baroutian, S, N Eshtiagh, and D Gapes. 2013a. "Rheology of Primary and Secondary sweage sludge mixture: Dependency on temperature and solids concentration." *Bioresource Technology, vol.140*:227-223.

[13] Baroutian, Saeid, Nicky Eshtiaghi, and Daniel J. Gapes. 2013b. "Rheology of a primary and secondary sewage sludge mixture: Dependency on temperature and solid concentration." *Bioresource Technology* no. 140:227-233. doi: http://dx.doi.org/10.1016/j.biortech.2013.04.114.

[14] Baudez, J. C., F. Markis, N. Eshtiaghi, and P. Slatter. 2011. "The rheological behaviour of anaerobic digested sludge." *Water Research* no. 45 (17):5675-5680. doi: http://dx.doi.org/10.1016/j.watres.2011.08.035.

[15] Baudez, J. C., P. Slatter, and N. Eshtiaghi. 2013. "The impact of temperature on the rheological behaviour of anaerobic digested sludge." *Chemical Engineering Journal* no. 215–216:182-187. doi: http://dx.doi.org/10.1016/j.cej.2012.10.099.

[16] Baudez, Jean-Christophe. 2008. "Physical aging and thixotropy in sludge rheology." *Applied Rheology* no. 18:1123-1139.

[17] Baudez, Jean-Christophe, and Philippe Coussot. 2001. "Rheology of aging, concentrated, polymeric suspensions: Application to pasty sewage sludges." *Journal of Rheology* no. 45 (5):1123-1140. doi: 10.1122/1.1392298.

[18] Bhattacharya, SN. 1981. "Flow characteristics of primary and digested sewage sludge." *Rheologica Acta* no. 20 (3):288-298.

[19] Bobade, Veena, Jean Christophe Baudez, Geoffery Evans, and Nicky Eshtiaghi. 2017. "Impact of gas injection on the apparent viscosity and viscoelastic property of waste activated sewage sludge." *Water Research* no. 114:296-307.

[20] Bolto, Brian, and John Gregory. 2007. "Organic polyelectrolytes in water treatment." *Water research* no. 41 (11):2301-2324.

[21] Bougrier, Claire, Jean Philippe Delgenès, and Hélène Carrère. 2008. "Effects of thermal treatments on five different waste activated sludge samples solubilisation, physical properties and anaerobic digestion." *Chemical Engineering Journal* no. 139 (2):236-244. doi: http://dx.doi.org/10.1016/j.cej.2007.07.099.

[22] Buyukkamaci, Nurdan, and Emrah Kucukselek. 2007. "Improvement of dewatering capacity of a petrochemical sludge." *Journal of hazardous materials* no. 144 (1):323-327.

[23] Cao, Xiuqin, Zhuhe Jiang, Weisha Cui, Yuan Wang, and Ping Yang. 2016. "Rheological Properties of Municipal Sewage Sludge: Dependency on Solid Concentration and Temperature." *Procedia Environmental Sciences* no. 31:113-121. doi: http://dx.doi.org/10.1016/j.proenv.2016.02.016.

[24] Carrère, H., C. Dumas, A. Battimelli, D. J. Batstone, J. P. Delgenès, J. P. Steyer, and I. Ferrer. 2010. "Pretreatment methods to improve sludge anaerobic degradability: A review." *Journal of Hazardous Materials* no. 183 (1–3):1-15. doi: http://dx.doi.org/10.1016/j.jhazmat.2010.06.129.

[25] Chu, CP, and DJ Lee. 1999. "Moisture distribution in sludge: effects of polymer conditioning." *Journal of Environmental Engineering* no. 125 (4):340-345.

[26] Ciaciuch, Anna, Jerzy Gaca, and Karolina Lelewer. 2017. Effect of the two-stage thermal disintegration and anaerobic digestion of sewage sludge on the COD fractions. In *Polish Journal of Chemical Technology*.

[27] Clauss, F., D. Helaine, C. Balavoine, and A. Bidault. 1998. "Improving activated sludge floc structure and aggregation for enhanced settling and thickening performances." *Water Science and Technology* no. 38 (8–9):35-44. doi: http://dx.doi.org/10.1016/S0273-1223(98)00675-1.

[28] Dapčević, Tamara, Petar Dokić, Miroslav Hadnađev, and Milica Pojić. 2008. "Determining the yield stress of food products-importance and shortcomings." *Food Processing-Quality and Safety* no. 35 (3):143-149.

[29] Dentel, Steven K. 1997. "Evaluation and role of rheological properties in sludge management." *Water Science and Technology* no. 36 (11):1-8.

[30] Dieudé-Fauvel, E, and SK Dentel. 2011. "Sludge conditioning: Impact of Polymers on Floc structure." *Journal of Residuals Science & Technology* no. 8 (3).

[31] Dieudé-Fauvel, E., P. Héritier, M. Chanet, R. Girault, D. Pastorelli, E. Guibelin, and J. C. Baudez. 2014. "Modelling the rheological properties of sludge during anaerobic digestion in a batch reactor by using electrical measurements." *Water Research* no. 51 (0):104-112. doi: http://dx.doi.org/10.1016/j.watres.2013.12.018.

[32] Dieudé-Fauvel, E., H. Van Damme, and J. C. Baudez. 2009. "Improving rheological sludge characterization with electrical measurements." *Chemical Engineering Research and Design* no. 87 (7):982-986. doi: http://dx.doi.org/10.1016/j.cherd.2008.10.010.

[33] Dursun, D., and S. K. Dentel. 2007. "The importance of structural and gel fractions in determining shear sensitivity of sludge." *Water Science and Technology* no. 56 (9):75-86.

[34] Eshtiaghi, Nicky, Flora Markis, Shao Dong Yap, Jean-Christophe Baudez, and Paul Slatter. 2013. "Rheological characterisation of municipal sludge: A review." *Water Research* no. 47 (15):5493-5510. doi: http://dx.doi.org/10.1016/j.watres.2013.07.001.

[35] Eshtiaghi, Nicky, Shao Dong Yap, Flora Markis, Jean-Christophe Baudez, and Paul Slatter. 2012. "Clear model fluids to emulate the rheological properties of thickened digested sludge." *Water Research* no. 46 (9):3014-3022. doi: http://dx.doi.org/10.1016/j.watres.2012.03.003.

[36] Evans, Eric A, Kristin M Evans, Ania Ulrich, and Scott Ellsworth. 2011. "Anaerobic processes." *Water Environment Research* no. 83 (10):1285-1332.

[37] Farno, Ehsan, Jean Christophe Baudez, Rajarathinam Parthasarathy, and Nicky Eshtiaghi. 2015. "Impact of temperature and duration of thermal treatment on different concentrations of anaerobic digested sludge: Kinetic similarity of organic matter solubilisation and sludge rheology." *Chemical Engineering Journal* no. 273 (Supplement C):534-542. doi: https://doi.org/10.1016/j.cej.2015.03.097.

[38] Farno, Ehsan, Jean Christophe Baudez, Rajarathinam Parthasarathy, and Nicky Eshtiaghi. 2016. "Impact of thermal treatment on the rheological properties and composition of waste activated sludge: COD solubilisation as a footprint of rheological changes." *Chemical Engineering Journal* no. 295:39-48. doi: http://dx.doi.org/10.1016/j.cej.2016.03.022.

[39] Farno, Ehsan, Rajarathinam Parthasarathy, Jean Christophe Baudez, and Nicky Eshtiaghi. 2013. Effect of Thermal History on Municipal Digested Sludge Rheology: Experimental and Modeling. In *Chemeca 2013*.

[40] Forster, CF. 1981. "Preliminary studies on the relationship between sewage sludge viscosities and the nature of the surfaces of the component particles." *Biotechnology Letters* no. 3 (12):707-712.

[41] Forster, CF. 1982. "Sludge surfaces and their relation to the rheology of sewage sludge suspensions." *Journal of chemical technology and biotechnology* no. 32 (7-12):799-807.

[42] Forster, CF. 1983. "Bound water in sewage sludges and its relationship to sludge surfaces and sludge viscosities." *Journal of Chemical Technology and Biotechnology* no. 33 (1):76-84.

[43] Forster, Christopher F. 2002. "The rheological and physico-chemical characteristics of sewage sludges." *Enzyme and Microbial Technology* no. 30 (3):340-345. doi: http://dx.doi.org/10.1016/S0141-0229(01)00487-2.

[44] Hamel, Kathy, Matt Higgins, Yen-Chih Chen, Sudhir Murthy, Mike Travis, E. J. Barben, Alex Livadaros, and Nicholas Maas. 2005. "Part I of Field Research: Impact of Centrifuge Torque and Polymer Dose on Dewatering Performance from Anaerobically Digested Biosolids." *Proceedings of the Water Environment Federation* (2):1058-1067. doi: 10.2175/193864705783967872.

[45] Hasar, Halil, Cumali Kinaci, Ayhan Ünlü, Hasan Toğrul, and Ubeyde Ipek. 2004. "Rheological properties of activated sludge in a sMBR." *Biochemical Engineering Journal* no. 20 (1):1-6. doi: http://dx.doi.org/10.1016/j.bej.2004.02.011.

[46] Higgins, Matt, Kathy Hamel, Yen-Chih Chen, Sudhir Murthy, E. J. Barben, Alex Livadaros, Mike Travis, and Nicholas Maas. 2005. "Part II of Field Research: Impact of Centrifuge Torque and Polymer Dose on Odor Production from Anaerobically Digested Biosolids." *Proceedings of the Water Environment Federation* (2):1068-1083. doi: 10.2175/193864705783967665.

[47] Hii, Kevin, Raj Parthasarathy, Saeid Baroutian, Daniel J. Gapes, and Nicky Eshtiaghi. 2017. "Rheological measurements as a tool for monitoring the performance of high pressure and high temperature treatment of sewage sludge." *Water Research* no. 114 (Supplement C):254-263. doi: https://doi.org/10.1016/j.watres.2017.02.031.

[48] Hong, Chen, Yanxiao Si, Yi Xing, ZhiQiang Wang, Qeng Qiao, and Min Liu. 2015. "Effect of surfactant on bound water content and extracellular polymers substances distribution in sludge." *RSC Advances* no. 5 (30):23383-23390. doi: 10.1039/C4RA15370G.

[49] Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016a. "Rheological characteristics of mixture of raw primary and thickened excess activated sludge: impact of mixing ratio, solid concentration, temperature and sludge age." *Desalination and Water Treatment* no. 57 (44):20726-20737. doi: 10.1080/19443994.2015.1115374.

[50] Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016b. "Rheological characteristics of municipal thickened excess activated sludge (TEAS): impacts of pH, temperature, solid concentration and polymer dose." *Research on Chemical Intermediates* no. 42 (8):6567–6585. doi: 10.1007/s11164-016-2482-2.

[51] Hong, Eugene, Anteneh Mesfin Yeneneh, Tushar Kanti Sen, Ha Ming Ang, and Ahmet Kayaalp. 2017. "The relationship between physico-chemical and rheological characteristics of digested sludge, biosolid, centrate and the effects on dewatering performance (A case study)." *Journal of Water Process Engineering* no. 19:193-204. doi: https://doi.org/10.1016/j.jwpe.2017.07.022.

[52] Hong, Eugene, Anteneh Mesfin Yeneneh, Tushar Kanti Sen, Ha Ming Ang, Ahmet Kayaalp, and Mehlika Kayaalp. 2016c. "Rheological characteristics of mixture of raw primary and thickened excess activated sludge: impact of mixing ratio, solid concentration, temperature and sludge age." *Desalination and Water Treatment* no. 57 (44):20726-20737. doi: 10.1080/19443994.2015.1115374.

[53] Hou, Chia-Hung, and Kung-Cheh Li. 2003. "Assessment of sludge dewaterability using rheological properties." *Journal of the Chinese Institute of Engineers* no. 26 (2):221-226. doi: 10.1080/02533839.2003.9670772.

[54] Houghton, Jennifer I., and Tom Stephenson. 2002. "Effect of influent organic content on digested sludge extracellular polymer content and dewaterability." *Water Research* no. 36 (14):3620-3628. doi: http://dx.doi.org/10.1016/S0043-1354(02)00055-6.

[55] Huang, Ying, Leilei Yu, Ruihui Wang, Jian Wu, and Masaki Takaoka. 2017. "Pilot study of intense dewatering of urban sewage sludge." *Journal of Material Cycles and Waste Management* no. 19 (1):88-101. doi: 10.1007/s10163-015-0387-6.

[56] Jin, Bo, Britt-Marie Wilén, and Paul Lant. 2004. "Impacts of morphological, physical and chemical properties of sludge flocs on dewaterability of activated sludge." *Chemical Engineering Journal* no. 98 (1):115-126.

[57] Keiding, K., L. Wybrandt, and P. H. Nielsen. 2001. "Remember the water - A comment on EPS colligative properties." *Water Science & Technology* no. 43:17-23.

[58] Khalili Garakani, A. H., N. Mostoufi, F. Sadeghi, M. Hosseinzadeh, H. Fatourechi, M. H. Sarrafzadeh, and M. R. Mehrnia. 2011. "Comparison Between Different Models for Rheological Characterization of Activated Sludge." *Iranian Journal of Environmental Health Science & Engineering* no. 8 (3):255-264.

[59] Knutsen, Jeffrey S., and Matthew W. Liberatore. 2009. "Rheology of high-solids biomass slurries for biorefinery applications." *Journal of Rheology* no. 53 (4):877-892. doi: 10.1122/1.3143878.

[60] Kopp, J., and N. Dichtl. 2001. "Influence of the free water content on the dewaterability of sewage sludges." *Water Sci Technol* no. 44 (10):177-83.

[61] Laera, G., C. Giordano, A. Pollice, D. Saturno, and G. Mininni. 2007. "Membrane bioreactor sludge rheology at different solid retention times." *Water Research* no. 41 (18):4197-4203. doi: http://dx.doi.org/10.1016/j.watres.2007.05.032.

[62] Lau, S. W., S. H. Chong, H. M. Ang, T. K. Sen, and H. B. Chua. 2013. *Dewaterability of Anaerobic Digested Sludge with Cations and Chitosan as Dual Conditioners*. Edited by Ravindra Pogaku, Awang Bono and Christopher Chu, *Developments in Sustainable Chemical and Bioprocess Technology*. Boston, MA: Springer US.

[63] Lau, Shiew Wei, Ha Ming Ang, Tushar Sen, and Han Bing Chua. 2014. Assessment of chitosan conditioning in a synthetic anaerobic digested sludge system. In *Chemeca 2014: Processing excellence; Powering our future*. Barton, ACT: Engineers Australia.

[64] Lau, Shiew Wei, Tushar Sen, Han Bing Chua, and Ming Ang Ha. 2015. "Conditioning Aids and Their Applications for Sludge Dewatering." In *Physical, Chemical and Biological Treatment Processes for Water and Wastewater*, edited by Tushar Sen. USA: Nova Publishers.

[65] Lau, Shiew Wei, Tushar Kanti Sen, Han Bing Chua, and Ha Ming Ang. 2017. "Conditioning of Synthetic Sludge and Anaerobically Digested Sludge Using Chitosan, Organic Polyelectrolytes and Inorganic Metal Cations to Enhance Sludge Dewaterability." *Water, Air, & Soil Pollution* no. 228 (9):358. doi: 10.1007/s11270-017-3545-8.

[66] Lay, Jiunn-Jyi, Young-Joon Lee, and Tatsuya Noike. 1999. "Feasibility of biological hydrogen production from organic fraction of municipal solid waste." *Water Research* no. 33 (11):2579-2586. doi: http://dx.doi.org/10.1016/S0043-1354(98)00483-7.

[67] Lee, CH, and JC Liu. 2000. "Enhanced sludge dewatering by dual polyelectrolytes conditioning." *Water Research* no. 34 (18):4430-4436.

[68] Li, Wen-Wei, and Han-Qing Yu. 2011. "Physicochemical characteristics of anaerobic H 2-producing granular sludge." *Bioresource Technology* no. 102 (18):8653-8660.

[69] Liao, BQ, DG Allen, GG Leppard, IG Droppo, and SN Liss. 2002. "Interparticle interactions affecting the stability of sludge flocs." *Journal of colloid and interface science* no. 249 (2):372-380.

[70] Lotito, V., L. Spinosa, G. Mininni, and R. Antonacci. 1997. "The rheology of sewage sludge at different steps of treatment." *Water Science and Technology* no. 36 (11):79-85. doi: http://dx.doi.org/10.1016/S0273-1223(97)00672-0.

[71] Manoliadis, Odysseys, and Paul L Bishop. 1984. "Temperature effect on rheology of sludges." *Journal of environmental engineering* no. 110 (1):286-290.

[72] Markis, Flora, Jean-Christophe Baudez, Rajarathinam Parthasarathy, Paul Slatter, and Nicky Eshtiaghi. 2014. "Rheological characterisation of primary and secondary sludge: Impact of solids concentration." *Chemical Engineering Journal* no. 253 (0):526-537. doi: http://dx.doi.org/10.1016/j.cej.2014.05.085.

[73] Markis, Flora, Jean-Christophe Baudez, Rajarathinam Parthasarathy, Paul Slatter, and Nicky Eshtiaghi. 2016. "Predicting the apparent viscosity and yield stress of mixtures of primary, secondary and anaerobically digested sewage sludge: Simulating anaerobic digesters." *Water Research* no. 100:568-579. doi: http://dx.doi.org/10.1016/j.watres.2016.05.045.

[74] Markis, Flora, Kevin Hii, Rajarathinam Parthasarathy, Jean-Christophe Baudez, Paul Slatter, and Nicky Eshtiaghi. 2013. Rheological Characterisation of blends of Primary and Secondary Sludge. In *Chemeca 2013*.

[75] Mikkelsen, L. H., and K. Keiding. 2001. "Effects of solids concentration on activated sludge deflocculation, conditioning and dewatering." *Water Science and Technology* no. 44 (2-3):417-425.

[76] Moeller, Gabriela, and Luis Gilberto Torres. 1997. "Rheological characterization of primary and secondary sludges treated by both aerobic and anaerobic digestion." *Bioresource Technology* no. 61 (3):207-211. doi: http://dx.doi.org/10.1016/S0960-8524(97)00061-8.

[77] Monteiro, Paulo Santos. 1997. "The influence of the anaerobic digestion process on the sewage sludges rheological behaviour." *Water Science and Technology* no. 36 (11):61-67.

[78] Mori, M., I. Seyssiecq, and N. Roche. 2006. "Rheological measurements of sewage sludge for various solids concentrations and geometry." *Process Biochemistry* no. 41 (7):1656-1662. doi: http://dx.doi.org/10.1016/j.procbio.2006.03.021.

[79] Mowla, D., H. N. Tran, and D. Grant Allen. 2013. "A review of the properties of biosludge and its relevance to enhanced dewatering processes." *Biomass and bioenergy* no. 58:365-378.

[80] Mullineux, Glen. 2008. "Non-linear least squares fitting of coefficients in the Herschel–Bulkley model." *Applied Mathematical Modelling, Vol. 32*:2538-2551.

[81] Neyens, Elisabeth, Jan Baeyens, Raf Dewil, and Bart De heyder. 2004. "Advanced sludge treatment affects extracellular polymeric substances to improve activated sludge dewatering." *Journal of Hazardous Materials* no. 106 (2–3):83-92. doi: http://dx.doi.org/10.1016/j.jhazmat.2003.11.014.

[82] Noutsopoulos, C., D. Mamais, K. Antoniou, C. Avramides, P. Oikonomopoulos, and I. Fountoulakis. 2013. "Anaerobic co-digestion of grease sludge and sewage sludge: The effect of organic loading and grease sludge content." *Bioresource Technology* no. 131:452-459. doi: http://dx.doi.org/10.1016/j.biortech.2012.12.193.

[83] O'Neil, Daniel J. 1985. "Rheology and mass/heat transfer aspects of anaerobic reactor design." *Biomass* no. 8 (3):205-216. doi: http://dx.doi.org/10.1016/0144-4565(85)90048-4.

[84] Oliveira, I., J. P. Reed, M. Abu-Orf, V. Wilson, D. Jones, and S. R. Esteves. 2016a. "The potential use of shear viscosity to monitor polymer conditioning of sewage sludge digestates." *Water Research* no. 105 (Supplement C):320-330. doi: https://doi.org/10.1016/j.watres.2016.08.007.

[85] Oliveira, I., J. P. Reed, M. Abu-Orf, V. Wilson, D. Jones, and S. R. Esteves. 2016b. "The potential use of shear viscosity to monitor polymer conditioning of sewage sludge digestates." *Water Research* no. 105:320-330. doi: http://dx.doi.org/10.1016/j.watres.2016.08.007.

[86] Örmeci, Banu. 2007. "Optimization of a full-scale dewatering operation based on the rheological characteristics of wastewater sludge." *Water Research* no. 41 (6):1243-1252. doi: http://dx.doi.org/10.1016/j.watres.2006.12.043.

[87] Örmeci, Banu, and Mohammad M. Abu-Orf. 2005. "Protocol to Measure Network Strength of Sludges and Its Implications for Dewatering." *Journal of Environmental Engineering* no. 131 (1):80-85. doi: doi:10.1061/(ASCE)0733-9372(2005)131:1(80).

[88] Ouyang, E. M., W. Wang, N. Long, and H. Li. 2009. "Three-dimensional excitation emission matrix fluorescence spectroscopic characterization of loosely bound and tightly bound extracellular polymeric substances of sludge." *Spectroscopy and Spectral Analysis* no. 29 (5):1313-8.

[89] Paul, E., P. Camacho, D. Lefebvre, and P. Ginestet. 2006. "Organic matter release in low temperature thermal treatment of biological sludge for reduction of excess sludge production." *Water Sci Technol* no. 54 (5):59-68.

[90] Pevere, A., G. Guibaud, E. D. van Hullebusch, W. Boughzala, and P. N. L. Lens. 2007. "Effect of Na+ and Ca2+ on the aggregation properties of sieved anaerobic granular sludge." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* no. 306 (1–3):142-149. doi: http://dx.doi.org/10.1016/j.colsurfa.2007.04.033.

[91] Pevere, A., G. Guibaud, E. van Hullebusch, P. Lens, and M. Baudu. 2006. "Viscosity evolution of anaerobic granular sludge." *Biochemical Engineering Journal* no. 27 (3):315-322. doi: http://dx.doi.org/10.1016/j.bej.2005.08.008.

[92] Piani, Luciano, Claudia Bruna Rizzardini, Adriano Papo, and Daniele Goi. 2014. "Rheology Measurements for Online Monitoring of Solids in Activated Sludge Reactors of Municipal Wastewater Treatment Plant." *The Scientific World Journal* no. 2014:6. doi: 10.1155/2014/590961.

[93] Pignon, Frederic, Albert Magnin, and Jean-Michael Piau. 1998. "Thixotropic behavior of clay dispersions: Combinations of scattering and rheometric techniques." *Journal of Rheology. Vol 42*:1349.

[94] Qi, Ying, Khagendra B. Thapa, and Andrew F. A. Hoadley. 2011. "Application of filtration aids for improving sludge dewatering properties – A review." *Chemical Engineering Journal* no. 171 (2):373-384. doi: http://dx.doi.org/10.1016/j.cej.2011.04.060.

[95] Rao, M A. 2007. *Rheology of Fluid and Semisolid Foods*. New York: Springer Science.

[96] Ratkovich, N., W. Horn, F. P. Helmus, S. Rosenberger, W. Naessens, I. Nopens, and T. R. Bentzen. 2013. "Activated sludge rheology: A critical review on data collection and modelling." *Water Research* no. 47 (2):463-482. doi: http://dx.doi.org/10.1016/j.watres.2012.11.021.

[97] Rosenberger, S., K. Kubin, and M. Kraume. 2002. "Rheology of Activated Sludge in Membrane Bioreactors." *Engineering in Life Sciences* no. 2 (9):269-275. doi: 10.1002/1618-2863(20020910)2:9<269::AID-ELSC269>3.0.CO;2-V.

[98] Ruiz-Hernando, M., J. Martín-Díaz, J. Labanda, J. Mata-Alvarez, J. Llorens, F. Lucena, and S. Astals. 2014a. "Effect of ultrasound, low-temperature thermal and alkali pre-treatments on waste activated sludge rheology, hygienization and methane potential." *Water Research* no. 61 (0):119-129. doi: http://dx.doi.org/10.1016/j.watres.2014.05.012.

[99] Ruiz-Hernando, Maria, Guillermo Martinez-Elorza, Jordi Labanda, and Joan Llorens. 2013. "Dewaterability of sewage sludge by ultrasonic, thermal and chemical treatments." *Chemical Engineering Journal* no. 230 (Supplement C):102-110. doi: https://doi.org/10.1016/j.cej.2013.06.046.

[100] Ruiz-Hernando, Maria, Francesc-Xavier Simón, Jordi Labanda, and Joan Llorens. 2014b. "Effect of ultrasound, thermal and alkali treatments on the rheological profile and water distribution of waste activated sludge." *Chemical Engineering Journal* no. 255 (Supplement C):14-22. doi: https://doi.org/10.1016/j.cej.2014.06.036.

[101] Sanin, F Dilek, and P Aarne Vesilind. 1994. "Effect of centrifugation on the removal of extracellular polymers and physical properties of activated sludge." *Water Science and Technology* no. 30 (8):117-127.

[102] Sanin, F. Dilek. 2002. "Effect of solution physical chemistry on the rheological properties of activated sludge." *Water SA* no. 28 (2):207-212.

[103] Schramm, G.A., and Gebrueder Haake. 1994. *A Practical Approach to Rheology and Rheometry*: Haake.

[104] Seyssiecq, Isabelle, Jean-Henry Ferrasse, and Nicolas Roche. 2003. "State-of-the-art: rheological characterisation of wastewater treatment sludge." *Biochemical Engineering Journal* no. 16 (1):41-56. doi: http://dx.doi.org/10.1016/S1369-703X(03)00021-4.

[105] Shihab, MS. 2010. "Assessment of using chemical coagulants and Effective Microorganisms in sludge dewaterability process improvement." *Journal of Environmental Science and Technology* no. 3 (1):35-46.

[106] Sólyom, Katalin, Rafael B Mato, Sara Isabel Pérez-Elvira, and María José Cocero. 2011. "The influence of the energy absorbed from microwave pretreatment on biogas production from secondary wastewater sludge." *Bioresource Technology* no. 102 (23):10849-10854.

[107] Sorensen, Peter B., Jimmy R. Christensen, and Jacob H. Bruus. 1995. "Effect of Small Scale Solids Migration in Filter Cakes during Filtration of Wastewater Solids Suspensions." *Water Environment Research* no. 67 (1):25-32.

[108] Sozanski, Marek M., Edward S. Kempa, Krzysztof Grocholski, and January Bien. 1997. "The rheological experiment in sludge properties research." *Water Science and Technology* no. 36 (11):69-78. doi: http://dx.doi.org/10.1016/S0273-1223(97)00671-9.

[109] Spicer, Patrick T., and Sotiris E. Pratsinis. 1996. "Shear-induced flocculation: The evolution of floc structure and the shape of the size distribution at steady state." *Water Research* no. 30 (5):1049-1056. doi: http://dx.doi.org/10.1016/0043-1354(95)00253-7.

[110] Spinosa, L., and V. Lotito. 2003. "A simple method for evaluating sludge yield stress." *Advances in Environmental Research* no. 7 (3):655-659. doi: http://dx.doi.org/10.1016/S1093-0191(02)00041-2.

[111] Stickland, Anthony D. 2015. "Compressional rheology: A tool for understanding compressibility effects in sludge dewatering." *Water research* no. 82:37-46.

[112] Stickland, Anthony D, Ashish Kumar, Tiara E Kusuma, Peter J Scales, Amy Tindley, Simon Biggs, and Richard Buscall. 2015. "The effect of premature wall yield on creep testing of strongly flocculated suspensions." *Rheologica Acta* no. 54 (5):337-352.

[113] Stickland, Anthony D., and Richard Buscall. 2009. "Whither compressional rheology?" *Journal of Non-Newtonian Fluid Mechanics* no. 157 (3):151-157. doi: https://doi.org/10.1016/j.jnnfm.2008.11.006.

[114] Sun, Yongjun, Huaili Zheng, Jun Zhai, Houkai Teng, Chun Zhao, Chuanliang Zhao, and Yong Liao. 2014. "Effects of Surfactants on the Improvement of Sludge Dewaterability Using Cationic Flocculants." *PLoS ONE* no. 9 (10):1 - 10. doi: 10.1371/journal.pone.0111036.

[115] Sutherland, I. W. 2001. "Exopolysaccharides in biofilms, flocs and related structures." *Water Science & Technology* no. 43:77-86.

[116] Tang, Bing, and Zi Zhang. 2014. "Essence of disposing the excess sludge and optimizing the operation of wastewater treatment: Rheological behavior and microbial ecosystem." *Chemosphere* no. 105 (Supplement C):1-13. doi: https://doi.org/10.1016/j.chemosphere.2013.12.067.

[117] Tenney, Mark W., and Werner Stumm. 1965. "Chemical Flocculation of Microorganisms in Biological Waste Treatment." *Journal Water Pollution Control Federation* no. 37 (10):1370-1388. doi: 10.2307/25035388.

[118] Tian, Zhe, Yu Zhang, Yuyou Li, Yongzhi Chi, and Min Yang. 2015. "Rapid establishment of thermophilic anaerobic microbial community during the one-step startup of thermophilic anaerobic digestion from a mesophilic digester." *Water Research* no. 69 (0):9-19. doi: http://dx.doi.org/10.1016/j.watres.2014.11.001.

[119] Tixier, N., G. Guibaud, and M. Baudu. 2003a. "Determination of some rheological parameters for the characterization of activated sludge." *Bioresource Technology* no. 90 (2):215-220. doi: http://dx.doi.org/10.1016/S0960-8524(03)00109-3.

[120] Tixier, N., G. Guibaud, and M. Baudu. 2003b. "Effect of ph and ionic environment changes on interparticle interactions affecting activated sludge flocs: A rheological approach." *Environmental Technology* no. 24 (8):971-978. doi: 10.1080/09593330309385635.

[121] Tombácz, Etelka, and Márta Szekeres. 2006. "Surface charge heterogeneity of kaolinite in aqueous suspension in comparison with montmorillonite." *Applied*

Clay Science no. 34 (1–4):105-124. doi: http://dx.doi.org/10.1016/j.clay.2006.05.009.

[122] Trávníček, Petr, and Petr Junga. 2014. "Thixotropic behaviour of thickened sewage sludge." *Journal of Environmental Health Science & Engineering* no. 12:72-72. doi: 10.1186/2052-336X-12-72.

[123] Unno, Hajime, and Takashi Akehata. 1985. "Some rheological features of concentrated excess activated sludge of thixotropic nature." *Journal of chemical engineering of Japan* no. 18 (6):533-538.

[124] Vlyssides, AG, and PK Karlis. 2004. "Thermal-alkaline solubilization of waste activated sludge as a pre-treatment stage for anaerobic digestion." *Bioresource Technology* no. 91 (2):201-206.

[125] Wang, Hou-Feng, Yun-Jie Ma, Hua-Jie Wang, Hao Hu, Hai-Yang Yang, and Raymond J. Zeng. 2017. "Applying rheological analysis to better understand the mechanism of acid conditioning on activated sludge dewatering." *Water Research* no. 122 (Supplement C):398-406. doi: https://doi.org/10.1016/j.watres.2017.05.002.

[126] Wang, Wei, Yuxiang Luo, and Wei Qiao. 2010a. "Possible solutions for sludge dewatering in China." *Frontiers of Environmental Science & Engineering in China* no. 4 (1):102-107.

[127] Wang, YL, and SK Dentel. 2010b. "The effect of high speed mixing and polymer dosing rates on the geometric and rheological characteristics of conditioned anaerobic digested sludge (ADS)." *Water research* no. 44 (20):6041-6052.

[128] Wolny, Lidia, Paweł Wolski, and Iwona Zawieja. 2008. "Rheological parameters of dewatered sewage sludge after conditioning." *Desalination* no. 222 (1-3):382-387.

[129] Wu, Binxin, and Shulin Chen. 2008. "CFD simulation of non-Newtonian fluid flow in anaerobic digesters." *Biotechnology and Bioengineering* no. 99 (3):700-711. doi: 10.1002/bit.21613.

[130] Yang, Fei, Amos Bick, Semion Shandalov, Asher Brenner, and Gideon Oron. 2009. "Yield stress and rheological characteristics of activated sludge in an airlift membrane bioreactor." *Journal of Membrane Science* no. 334 (1–2):83-90. doi: http://dx.doi.org/10.1016/j.memsci.2009.02.022.

[131] Yen, Pei-Shan, L. C. Chen, C. Y. Chien, Rome-Ming Wu, and D. J. Lee. 2002. "Network strength and dewaterability of flocculated activated sludge." *Water Research* no. 36 (3):539-550. doi: http://dx.doi.org/10.1016/S0043-1354(01)00260-3.

[132] Yeneneh, Anteneh Mesfin. 2014. *Study on performance enhancement of anaerobic digestion of municipal sewage sludge*. PhD Thesis, Chemical Engineering Department, Curtin University, Perth, Australia.

[133] Yeneneh, Anteneh Mesfin, Eugene Hong, Tushar Kanti Sen, Ahmet Kayaalp, and Ha Ming Ang. 2016. "Effects of Temperature, Polymer Dose, and Solid Concentration on the Rheological Characteristics and Dewaterability of Digested Sludge of Wastewater Treatment Plant (WWTP)." *Water, Air, & Soil Pollution* no. 227 (4):119. doi: 10.1007/s11270-016-2820-4.

[134] Yeneneh, Anteneh Mesfin, Ahmet Kayaalp, Tushar Kanti Sen, and Ha Ming Ang. 2015. "Effect of Combined Microwave-Ultrasonic Pretreatment of Real Mixed Sludge on the Enhancement of Anaerobic Digester Performance." *Water, Air, & Soil Pollution* no. 226 (9):1-14. doi: 10.1007/s11270-015-2586-0.

[135] Youcai, Zhao, and Zhen Guangyin. 2016. *Pollution Control and Resource Recovery: Sewage Sludge*: Butterworth-Heinemann.

[136] Zhang, Jingsi, Yonggang Xue, Nicky Eshtiaghi, Xiaohu Dai, Wenquan Tao, and Zhuo Li. 2017. "Evaluation of thermal hydrolysis efficiency of mechanically dewatered sewage sludge via rheological measurement." *Water Research* no. 116 (Supplement C):34-43. doi: https://doi.org/10.1016/j.watres.2017.03.020.

CHAPTER 3
METHODOLODY

3.1 Introduction

This research work combines both experimental and modelling techniques. The experimental work was conducted on real sewage sludge from Beenyup wastewater treatment plant (WWTP). The different sludge type samples used throughout the research were collected from varying section of the WWTP and intensive characterization was conducted on each of the collected samples. The different sludge type collected were raw primary sludge, excess activated sludge, thickened excess activated sludge, mixed sludge, and digested sludge (DS). This chapter comprises the brief experimental procedures and methods used to determine the rheological properties and the characterization of sludge samples. The detailed experimental methods are discussed in the respective chapters. This chapter also includes a brief discussion on the modelling method and technique used.

3.2 Background and history of Beenyup wastewater treatment plant

One out of four major wastewater treatment facilities in Perth, Western Australia, Beenyup WWTP has a treatment capacity of 135 million litre/day with a projected capacity of 180 million litre/day by 2050. Beenyup WWTP currently serves about 660 000 people in the rapidly developing northern suburbs of Perth. Beenyup WWTP mainly processes sewage waste from household kitchens, bathrooms, toilets and laundries. The makeup of the waste if approximately 99% water and mostly discharged into the ocean and recharged into the local groundwater supplies after treatment.

Historically, Beenyup WWTP was established in 1970 to allow the consolidation and centralization of sewage sludge treatment for the northern suburbs. During the initial stage, the plant started operating at 3.6 million litre/day capacity. In 1978, the plant was then upgraded to support the conventional activated sludge process from its initial extended aeration process which resulted in a 27 million litre/day capacity. In addition, the plant also commissioned a gravity outfall system which allowed the plant to discharge treated effluent into the ocean while incineration technology was employed to handle the disposal of sludge. In 1984, the plant was further upgraded to accommodate a capacity of 54 million litre/day. The digestion process was then introduced and commissioned to replace the incineration process in 1990. In 1996, the secondary treatment was commissioned and resulted in the plant capacity reaching 112 million litre/day. In 2005, the plant received multiple enhancement such as the instalment of the odour control process, which increased the capacity of the plant to 120 million litre/day and was furthered increased to 135 million litre/day in 2007. In 2017, the plant commissioned an advanced water recycling facility resulting in the first wastewater treatment plant in Australia to support the groundwater replenishment scheme.

Beenyup WWTP receive raw sewage waste from three different sources which are combined at the inlet channel to form the feed. The feed flows into the screening process which is encompasses five screening steps with 6mm openings. The screening steps aims to remove large materials from the inflow such as plastics. The materials removed is later washed and compacted and disposed at an approved landfill. After screening, the organic materials would stay suspended while the inorganic materials would settle to the bottom and is removed by the grit removal tanks. The removed inorganic materials will then be disposed of at an approved landfill while the liquid waste is drained from the grit removal tanks by screw conveyor. The liquid waste then enters the primary treatment which consists of six sedimentation tanks with a sludge pumping system. The liquid waste will remain in the tank till 90% of the remaining solids settles to the bottom of the tanks and mechanical scrappers are used to transfer the settled solids to a hopper. The collected solids, forming the raw primary sludge, is then pumped to the sludge treatment area. Oil and grease that floats to the top of the tanks are collected and sent back to the head of the plant where it is removed. The sludge treatment area, which is mainly known as secondary treatment, is designed to remove biological content from the remaining sludge waste. Raw primary sludge is then mixed with thickened excess activated sludge and is transported to a two-stage anaerobic digestion process. Digested sludge is form after the digestion process and it is then pumped to the dewatering plant where centrifugation takes place. The digested sludge is converted to biosolid (solid waste) and centrate (liquid waste). The biosolid is then collected and transported by trucks to agricultural industry where it is use as soil improver

3.3 Sludge collection and sampling

Different sludge samples such as raw primary sludge (PRS), excess activated sludge (EAS), thickened excess activated sludge (TEAS), a mixture of RPS and TEAS also known as mixed sludge (MS), and digested sludge (DS) were collected from various sampling locations as shown in Table 3.1 within Beenyup WWTP. In addition to sludge samples, polymer used during the thickening of EAS (DAFT unit), polymer used during dewatering (centrifuge), centrate, and biosolids were also collected, and their impact on process optimization were investigated.

Table 3.1 Collection location at BWWTP for different sludge types and polymer.

Sludge type	**Collection location**
RPS	Primary gallery.
EAS and TEAS	Overflow collection tank and underflow of dissolve air flotation unit.
MS	At the mixing point after the break tanks before the anaerobic digesters.
DS	At the feed of centrifuge located after the anaerobic digester.
Centrate and bio-solids	The product line of the centrifuge and at the bio-solid collection tank downstream of the conveyor belt.
Polymer	Polymer mixing tank after primary dilution has taken place.

RPS is collected from the primary sedimentation gallery. It mainly contains all the settleable matter from the WWTP. EAS and TEAS samples were collected from the overflow and underflow of a dissolved air floatation unit. While a mixture of both RPS and TEAS, mixed sludge was collected from the sampling point before the anaerobic digesters. DS sample was collected from centrifuge in the dewatering plant, while the centate and biosolids were collected at the collection tank and outlet of the dewatering plant. During collection, the sludge samples were sealed and stored in the refrigeration unit. Fresh sludge samples were used in all experimental investigations to prevent changes in the rheological properties, due to the fermentation and other microbial activities. In addition, polymer used for the sludge treatment process is collected from the polymer mixing tank which is located next to the dewatering plant.

3.4 Sludge characterisation

Wastewater sludge types are generally complex in nature with varying characteristics, which are vital to their unpredictable behaviour. However, all sludge types can be identified and characterised based on their physico-chemical and biological parameters. The parameters studied are solid content, such as total solids (TS) and total volatile solids (VS) concentration, chemical oxygen demand (COD), conductivity, temperature, and pH. Standard Methods for Examination of Water and were used to determine these parameters (Sanin 2002, American Public Health Association et al. 2005, Li et al. 2008, Lotito et al. 2014, Yeneneh et al. 2015).

All characterisation are conducted on site at Beenyup WWTP. TS and VS were determined by employing the standard method (gravimetric method). COD was determined by using oxidation method with HACH COD reagent and colorimetric analysis on ORION UV/Vis spectrometer. pH was measured with WP-90 and WP-81 conductivity/TDS-pH/temperature meter equipped with a glass electrode. Temperature of mixed sludge was measured during collection and again at the beginning of each experiment and is expressed in degree centigrade (˚C) and obtained by using a standard thermometer.

3.4.1 Measurement of solid content

Solids content is a measurement of both suspended solids (total solid, TS) and dissolved solids (volatile solid, VS) is widely used to determine solid contents of sludge and is expressed as a percentage in relation to the sludge sample weight.

A list of key apparatus would be required to determine the solid content of sludge. These apparatuses are evaporating dish of 100ml in capacity, furnace, oven, desiccator, balance (capable of weighing to 0.1mg), magnetic stirrer/heating plate with temperature control, glass-fibre disks without organic binder (Whatman grade 934AJ etc), and filtration apparatus.

The procedure itself simply involves drying and igniting of sludge sample. To prepare the sludge for analysis, ignite a 100ml clean evaporating dish at 550±50˚C for an hour in a furnace. Then, place the heated evaporating dish on to ‘heating rack’ to allow heat to dissipate before cooling the evaporating dish in desiccator for an hour and finally weighing the cooled evaporating dish, Weight (B), and storing it in the desiccator until it is ready for use.

Once the sludge sample is collected and ready for total solid content measurement, take 50ml of sludge sample volume and place it in a beaker, which will yield a residue between 2.5mg and 200mg, and stir it using a magnetic stirrer with a stirrer bar. Pour the sample to the evaporating dish and weigh it, Weight (C). Next, place the sample into an oven and allow it to evaporate to dryness at 98˚C for an hour. Continue the drying process at 103 – 105˚C for another hour. Once completed, place the heated sample on to 'heating rack' to allow heat to dissipate before cooling the sample to balance temperature in an individual desiccator containing fresh desiccant, and weigh the sample, Weight (A). Repeat the drying, cooling, desiccating, and weighing cycle until a constant weight is obtained or until weight loss is < 4% of previous weight or 0.5mg, whichever is less. This residue is known as Residue A.

Pre-heat the furnace to 550±50˚C for 15 – 20 minutes while the sludge sample undergoes the drying process. Once both Residue A and furnace is ready, transfer Residue A from desiccator to the furnace for an hour to allow ignition of sample. After an hour of igniting, remove the sample and allow it to cool partially in air at room temperature till most of the heat has been dissipated. Finally, allow the sample to cool in a desiccator and weight it after cooling, Weigh (D). Repeat the cycle of igniting, cooling, desiccating, and weighing until weight loss < 4% or previous weight.

Once the measurement has been recorded, the next step would be to calculate and determine the total and volatile solid content. The formula to calculate both total and volatile solid content are shown in Equation 3-1 and 3-2 respectively.

$$\%\,Total\ Solids = \frac{(A-B)}{C-B} \times 100 \tag{3-1}$$

$$\%\,Volatile\ Solids = \frac{(A-D)}{A-B} \times 100 \tag{3-2}$$

where:

A = weight of dried residue + dish, mg
B = weight of dish
C = weight of wet sample + dish, mg

D = weight of residue + dish after ignition, mg

3.4.2 Measurement of chemical oxygen demand

Chemical oxygen demand (COD) method determines the quantity of oxygen required to oxidize the organic matter in a sludge sample, under specific conditions of oxidizing agent, temperature, and time. Organic and oxidisable inorganic substances in the sample are oxidized by potassium dichromate in 50% sulfuric acid solution at reflux temperature. Silver sulphate is used as a catalyst and mercuric sulphate is added to remove chloride interference. The excess dichromate is titrated with standard ferrous ammonium sulphate, using orthophenanthroline ferrous complex as an indicator. Apparatus required to determine the COD of sludge sample are COD digester, colorimeter and micro-pipette.

As mention above, an oxidizing reagent is required to measure the quantity of oxygen required to oxidize the organic matter within the sludge sample. Therefore, preparation of the oxidizing reagent is required before the sample can be measured. For this research work, HACH-COD reagent and colorimetric analysis on ORION UV/Vis colorimeter from Cole Parmer was purchased and used to reduce the time required to prepare the oxidizing reagent. 1ml of sludge sample was measure with a micro-pipette and diluted with 50ml of distilled water. 2ml of diluted samples is then pipetted to one HACH-COD reagent vial. The mixture of sample and reagent is allowed to homogenize and is placed within the COD digester. The sample is to be heated to 150˚C for 2 hours and allowed to be cooled to room temperature. Once cooled, the sample is placed into the colorimeter where COD is measured.

3.4.3 Measurement of temperature

Temperature measurement was conducted using a standard temperature meter. Temperature was measured immediately for each sample during the collection period and before and after every experimental work. During sample collection, the temperature is measure during and after filling of the collection bottles. During experimental work, the sample is heated to desired temperature with the in-built Peltier heating and cooling system equipped on the rheometer. The temperature of the samples are measured by using a temperature meter and verify on the rheometer display.

3.4.4 Measurement of pH

pH was measured with WP-81 pH meter equipped with a glass electrode. pH was measured immediately for each sample during the collection period and before and after every experimental work. During sample collection, the pH is measure after filling of the collection bottles. During experimental work, the pH of the sample is measured on a regular basis to ensure that no change occurred during storing of the sludge. The glass electrode was also washed with distilled water to ensure no sludge residue remains on it.

3.4.5 Organic and inorganic analysis

Fourier-transform infrared analysis was used to identify the organic, polymeric, and inorganic component within the sludge samples. For this analysis, FTIR – 100 (Universal ATR Sampling Accessory with MIR detector) was used. The analysis for organic and inorganic is fully computerized and the general procedure was taken from the user manual of the FTIR – 100. Generally, the sample pan and compress bar needs to be clear from any residue. To do so, cotton buds soaked in ethanol and deionised water is to be used to wipe the surface of both the pan and compress bar. Once the surface is confirmed to be clean, a background spectra analysis is conducted to ensure the actual sample is all that is analysed. Next, the sludge sample is loaded to the sample pan and is analysed by the FTIR – 100 software which generates the absorbance spectra and compared it to the in-built reference library which identify the best match.

3.4.6 Particle size analysis

The particle size distribution of sludge samples were determined using a laser diffraction method. For this method, Malvern Mastersizer 2000 with Hydro 2000S Accessory equipped was selected as it is fully computerized. The general procedure was taken from the user manual of the Malvern Mastersizer. Firstly, the sample needs to be dried before the sample can be analysed in the mastersizer. The sludge sample is dried by using an oven at 100˚C for 8-12 hours. Once, the sludge sample is dried, 5g of sample is loaded into sample holder and analysed by the mastersizer. The results are then displayed within the software attached to the mastersizer.

3.4.7 Dewaterability

In the processes of traditional chemical conditioning and dewatering, capillary suction time (CST) tests are commonly-used indices for quantitative evaluation of the dewatering effect (Stickland et al. 2009). The CST measurement was conducted using a Type 304 CST meter. The procedure briefly involves the time required for the sludge sample to be absorbed by a filter paper. To do so, firstly ensure that the sensor and sample tray on the CST meter is clean and dry. Once there is no residue, a test filter paper is placed on top of the sensor tray and the sensor is then placed onto of the filter paper. Next, the sample funnel is placed into the insert of the sensor and 5ml to 10ml of sludge sample is introduced into the funnel. The time required for sludge to be absorbed by the filter paper determines CST value in seconds.

3.5 Rheology measurement

Discovery Hybrid Rheometer G-2 (DHR-2) equipped with TRIOS analysis tool was used for the measurement of rheology. The rheometer was fitted with a standard Vane concentric cylinder with a 30mm diameter Peltier Steel Geometry with 4000 µm gap size. The rheometer is also equipped with a Peltier heating and cooling system which is used to control the temperature of the sample. For most of the rheology analysis, a shear rate range of $0s^{-1}$ to $1000s^{-1}$ was instigated. The rheological measurement cycle consists of four major steps. The first step is to place 35ml of sludge sample into the concentric cylinder (sample holder). The second step, is the conditioning step, where the sludge sample is placed into the concentric cylinder, allowed to be heated or cooled to the desired temperature and sheared at $5s^{-1}$ for 60s. Next, the sample undergoes an equilibration phase where the sludge sits still for 30s. The final step then applies a linear increase in shear force (linear flow sweep test) from $0s^{-1}$ to $1000s^{-1}$ with a total of 40 data points. Each data point recorded are based on five equilibrium points to reduce error and increase accuracy and repeatability of the test. The recorded data is then analysed using the TRIOS analysis tool to determine the rheological parameters of the sludge sample. The analysis tool will generate shear stress-rate and viscosity versus shear rate curves as a function of different operating parameters such as temperature, pH, total solid content and many more. A total of seven rheological models is then applied to each curves and model with the best fit and practical significance was selected to determine the apparent yield stress, apparent viscosity and flow index of each sludge sample. To further understand the rheological property, hysteresis tests were conducted on some sludge sample. In a hysteresis test cycle the sludge sample was homogenised before each test similar to the conditioning step described above. Next, the shear rate was first increased from 0 – 1000s^{-1} and then decreased from 1000 – 0s^{-1} at a desired temperature. This will allow the rheometer to record a closed loop curve and investigate the thixotropic behaviour of the sludge sample. The test cycle described was used for all sludge types investigated in this study and any differing method and technique used are described in the specific chapters.

3.6 Rheological ANFIS modelling

In this work, adaptive neural fuzzy inference systems (ANFIS) prediction tool in MATLAB was used in conjunction with Four years historical data from Beenyup WWTP. Several researchers have shown that this method can be employed successfully to predict and control product quality upstream and downstream of WWTPs. They also proposed that the performance of the dewatering unit and the quality of biosolid and conditioning agent dose (polymer) can be well predicted and optimized using the ANFIS modelling (Tay et al. 1999, Mjalli et al. 2007, Wu et al. 2008, Heddam et al. 2012, Atasoy et al. 2013, Ay et al. 2014). ANFIS would interpret the input vector and assign an output value utilizing fuzzy If-Then rule. This process involves a method which is based on hybrid learning or back propagation algorithm commonly known as a first-order Sugeno-fuzzy model which has the adaptive capabilities similar to neural network integrated into its qualitative logic (Perendeci et al. 2008). Furthermore, ANFIS method can be applied to different parameter of nonlinear relationship with different inputs and outputs in various areas while producing good predictive results. ANFIS model is also simpler to construct when compared to other modelling techniques used for similar applications. ANFIS can be trained with new data with varying changes allowing flexibility and adaptability in a manner that the model can be continuously updated (Turkdogan-Aydınol et al. 2010). In this section, a brief description on the ANFIS method and technique used are discussed.

3.6.1 Fuzzy logic and fuzzy inference system

The fuzzy system consists of four stages, which are fuzzification, fuzzy rule base, fuzzy output engine, and defuzzification as shown in Fig. 3.1 (Akkurt et al. 2004, Turkdogan-Aydınol et al. 2010). The input unit contains the input variables or any information related to the input variables which will have an impact on the investigated scenario. The term database is commonly used here as the information in relation to the input variables. The input variables can be in numerical and/or text form (Erdirencelebi et al. 2011). Fuzzification is a process that assigns numerical values to linguistic adjectives and determines the number of membership functions within the fuzzy system sets. The fuzzy rule base consists of all logical rules that connect the input to the output variables, which includes all possible intermediate connections between them. Fuzzy output engine takes the input variables and converts them to their corresponding outputs. This is done by considering the multiple relationships defined in the fuzzy rule base. Finally, defuzzification is the stage where the linguistic outputs from the fuzzy system are translated back into numerical values. The output unit produces variables at the end of the information and fuzzy rule base interaction.

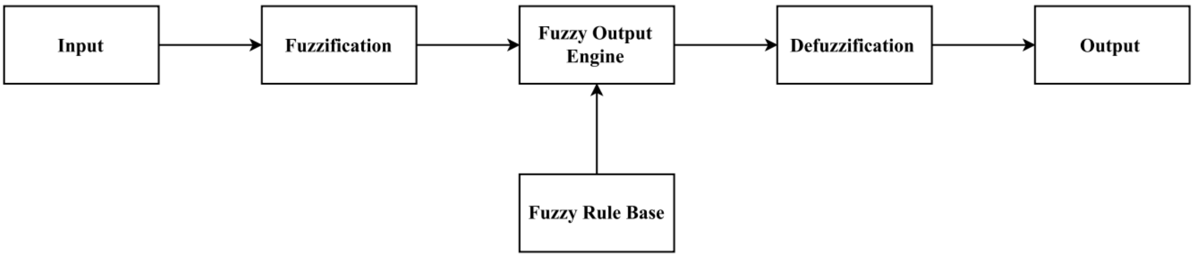

Fig. 3.1 Block diagram for fuzzy system controller.

The general ANFIS methodology to be used to develop the ANFIS prediction model is as shown in Fig. 3.2. The model was applied to determine the relationship between sludge rheological properties and key operating parameters.

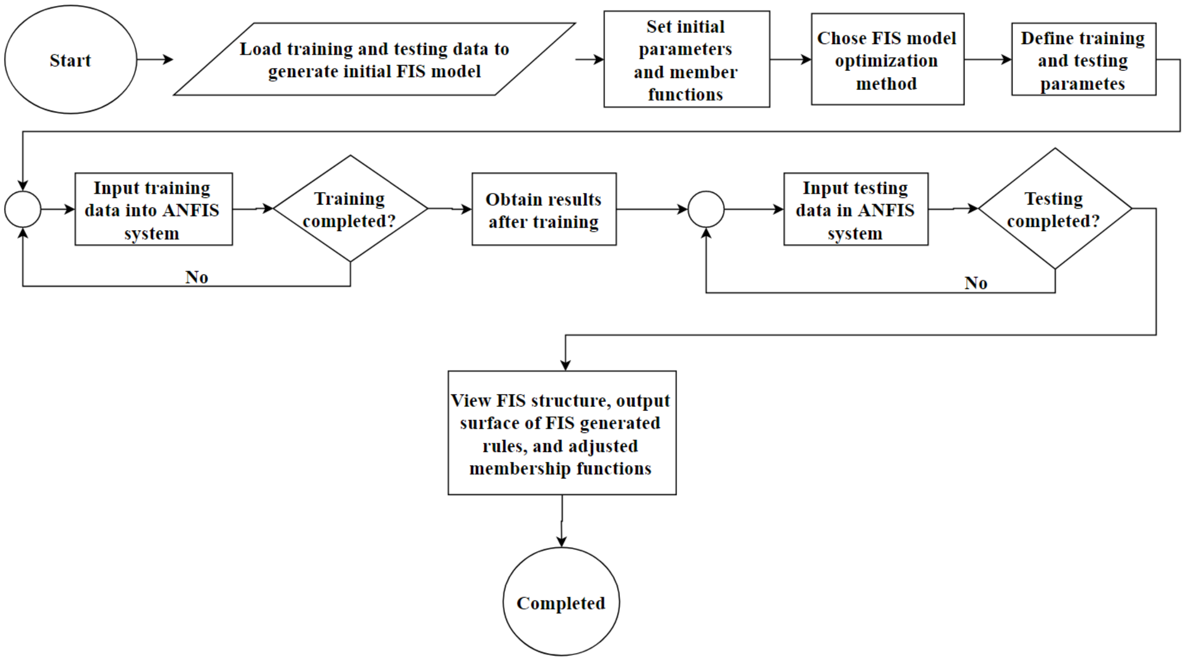

Fig. 3.2 Flow chart of ANFIS test step.

3.6.2 Model architecture and components

Similar to the Takagi–Sugeno fuzzy inference system, ANFIS is an adaptive network which adopted a function which utilizes supervised learning on learning algorithm (Takagi et al. 1985, Sugeno et al. 1986). The conceptual architecture of the neural fuzzy model is shown in Fig. 3.3. The model contains five key components, which are inputs and outputs, database and pre-processor, a fuzzy system generator, a fuzzy inference system, and an adaptive neural network (Jang 1993, Perendeci et al. 2008, Yeneneh 2014). The input and output parameters are commonly selected or generated from parameters used for system description. While the database and pre-processor is a prerequisite for model development and contains the system performance information. This information is usually developed by frequently collecting parameters data which are monitored by the system. For this study, MATLAB is considered to be a suitable tool and are used to develop the system performance information (Tay et al. 2000, Perendeci et al. 2008, Yeneneh 2014).

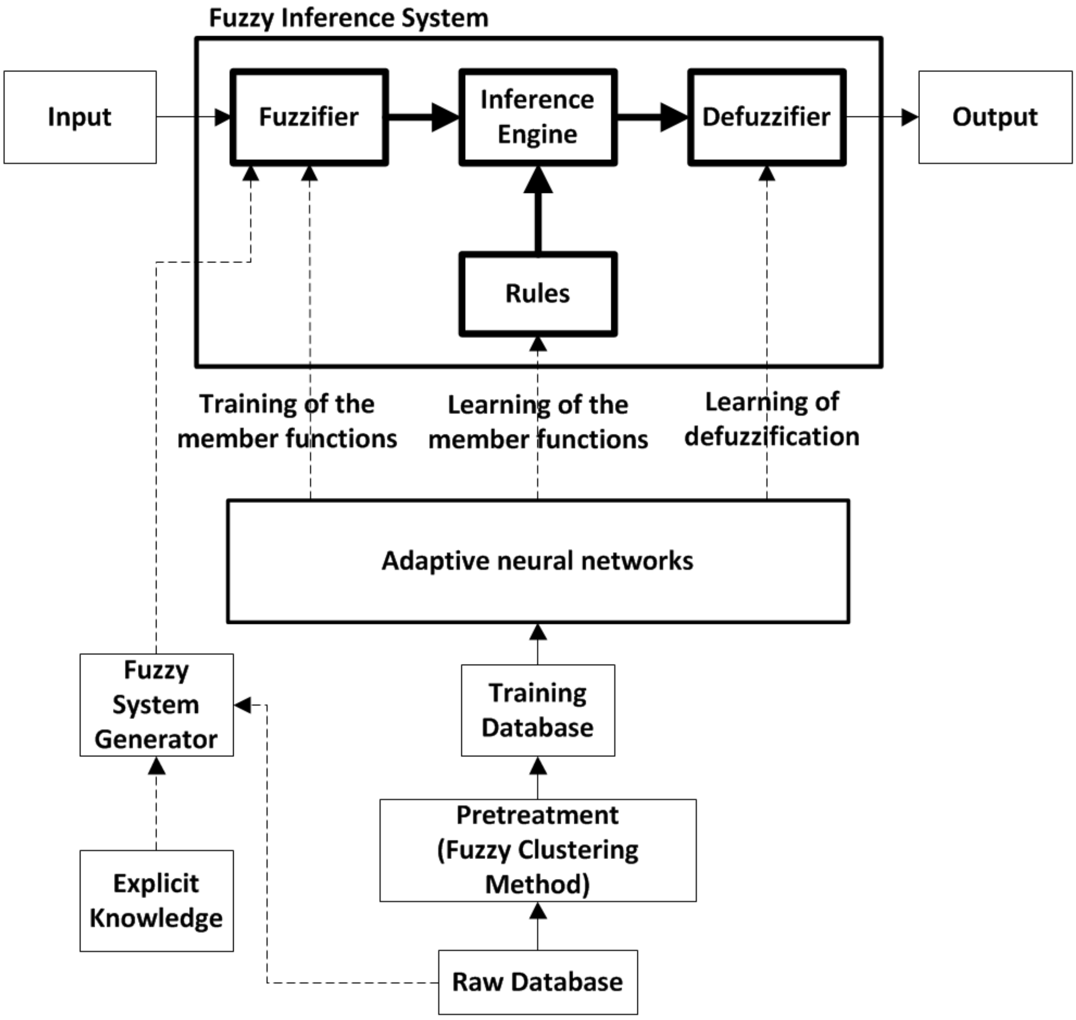

Fig. 3.3 Conceptual schematic architecture of adaptive neural fuzzy model for wastewater treatment system

Reference

[1] Akkurt, Sedat, Gokmen Tayfur, and Sever Can. 2004. "Fuzzy logic model for the prediction of cement compressive strength." *Cement and Concrete Research* no. 34 (8):1429-1433. doi: http://dx.doi.org/10.1016/j.cemconres.2004.01.020.

[2] American Public Health Association, American Water Works Association, Water Pollution Control Federation, and Water Environment Federation. 2005. *Standard Methods for the Examination of Water and Wastewater*: American Public Health Association.

[3] Erdirencelebi, Dilek, and Sukran Yalpir. 2011. "Adaptive network fuzzy inference system modeling for the input selection and prediction of anaerobic digestion effluent quality." *Applied Mathematical Modelling* no. 35 (8):3821-3832.

[4] Eshtiaghi, Nicky, Flora Markis, Shao Dong Yap, Jean-Christophe Baudez, and Paul Slatter. 2013. "Rheological characterisation of municipal sludge: A review." *Water Research* no. 47 (15):5493-5510. doi: http://dx.doi.org/10.1016/j.watres.2013.07.001.

[5] Jang, J-SR. 1993. "ANFIS: adaptive-network-based fuzzy inference system." *Systems, Man and Cybernetics, IEEE Transactions on* no. 23 (3):665-685.

[6] Li, Huan, Yiying Jin, RasoolBux Mahar, Zhiyu Wang, and Yongfeng Nie. 2008. "Effects and model of alkaline waste activated sludge treatment." *Bioresource Technology* no. 99 (11):5140-5144. doi: http://dx.doi.org/10.1016/j.biortech.2007.09.019.

[7] Lotito, Vincenzo, and Adriana Maria Lotito. 2014. "Rheological measurements on different types of sewage sludge for pumping design." *Journal of Environmental Management* no. 137 (0):189-196. doi: http://dx.doi.org/10.1016/j.jenvman.2014.02.005.

[8] Perendeci, Altunay, Sever Arslan, Serdar S Çelebi, and Abdurrahman Tanyolaç. 2008. "Prediction of effluent quality of an anaerobic treatment plant under unsteady state through ANFIS modeling with on-line input variables." *Chemical Engineering Journal* no. 145 (1):78-85.

[9] Piani, Luciano, Claudia Bruna Rizzardini, Adriano Papo, and Daniele Goi. 2014. "Rheology Measurements for Online Monitoring of Solids in Activated Sludge Reactors of Municipal Wastewater Treatment Plant." *The Scientific World Journal* no. 2014:6. doi: 10.1155/2014/590961.

[10] Ratkovich, N., W. Horn, F. P. Helmus, S. Rosenberger, W. Naessens, I. Nopens, and T. R. Bentzen. 2013. "Activated sludge rheology: A critical review on data collection and modelling." *Water Research* no. 47 (2):463-482. doi: http://dx.doi.org/10.1016/j.watres.2012.11.021.

[11] Sanin, F. Dilek. 2002. "Effect of solution physical chemistry on the rheological properties of activated sludge." *Water SA* no. 28 (2):207-212.

[12] Stickland, Anthony D., and Richard Buscall. 2009. "Whither compressional rheology?" *Journal of Non-Newtonian Fluid Mechanics* no. 157 (3):151-157. doi: https://doi.org/10.1016/j.jnnfm.2008.11.006.

[13] Sugeno, Michio, and GT Kang. 1986. "Fuzzy modelling and control of multilayer incinerator." *Fuzzy sets and systems* no. 18 (3):329-345.

[14] Takagi, Tomohiro, and Michio Sugeno. 1985. "Fuzzy identification of systems and its applications to modeling and control." *Systems, Man and Cybernetics, IEEE Transactions on* (1):116-132.

[15] Tay, Joo-Hwa, and Xiyue Zhang. 2000. "A fast predicting neural fuzzy model for high-rate anaerobic wastewater treatment systems." *Water Research* no. 34 (11):2849-2860.

[16] Turkdogan-Aydınol, F. Ilter, and Kaan Yetilmezsoy. 2010. "A fuzzy-logic-based model to predict biogas and methane production rates in a pilot-scale mesophilic UASB reactor treating molasses wastewater." *Journal of Hazardous Materials* no. 182 (1–3):460-471. doi: http://dx.doi.org/10.1016/j.jhazmat.2010.06.054.

[17] Yeneneh, Anteneh Mesfin. 2014. *Study on performance enhancement of anaerobic digestion of municipal sewage sludge*. PhD Thesis, Chemical Engineering Department, Curtin University, Perth, Australia.

[18] Yeneneh, Anteneh Mesfin, Ahmet Kayaalp, Tushar Kanti Sen, and Ha Ming Ang. 2015. "Effect of Combined Microwave-Ultrasonic Pretreatment of Real Mixed Sludge on the Enhancement of Anaerobic Digester Performance." *Water, Air, & Soil Pollution* no. 226 (9):1-14. doi: 10.1007/s11270-015-2586-0.

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CHAPTER 4

RHEOLOGICAL AND PHYSICO-CHEMICAL CHARACTERISTIC OF THICKENED EXCESS ACTIVATED SLUDGE

Abstract

This chapter deals with the characterization of thickened excess activated sludge in comparison to raw primary sludge and excess activated sludge. The effects of key parameters (total solid concentration, temperature, and pH) on the rheology and flow behaviour of thickened excess activated sludge were also studied. The rheological investigations were carried out for total solid concentration range of 0.9%w/w – 3.7%w/w, temperature range of 23°C – 55°C, and pH range of 3.6 – 10.0. Different rheological model equations were fitted to the experimental data. The model equations with better fitting were used to calculate the yield stress, apparent, zero-rate, infinite-rate viscosities, flow consistency index, and flow index. The decrease in concentration from 3.7%w/w to 3.1%w/w resulted in drastic reduction of yield stress from 27.6Pa to 11.0Pa, and further reduction of yield stress to 1.3Pa was observed as solid concentration was reduced to 1.3%w/w. The viscosity at higher shear rate (>600s^{-1}) decreased from 0.05Pa.s down to 0.008Pa.s when the total solid concentration was reduced from 3.7% to 0.9%. Yield stress decreased from 20.1Pa down to 8.3Pa for Bingham plastic model when temperature was raised from 25˚C to 55˚C. Activation energy and viscosity also showed decreasing trend with increasing temperature. Yield stress of thickened excess activated sludge increased from a value of 6.0Pa to 8.3Pa when pH was increased from 3.6 to 10.0. The effect of polymer dose on the rheological behaviour of thickening of excess activated sludge was also investigated, and the optimum polymer dosage for enhanced thickener performance was determined to be 1.3kg/ton DS.

Ref: Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016. "Rheological characteristics of municipal thickened excess activated sludge (TEAS): impacts of pH, temperature, solid concentration and polymer dose." Research on Chemical Intermediates:1-19.doi:10.1007/s11164-016-2482-2

4.1 Introduction

Chapter 4 outlines the research findings on the impact of physico-chemical characteristics such as total solid concentration, temperature, pH and chemical conditioning on the rheological properties of thickened excess activated sludge (TEAS). Primary sewage sludge that flows into Beenyup WWTP is usually subjected to primary treatment of sedimentation and thickening followed by secondary biological treatment involving aeration and sedimentation. This process produces activated sludge which is mainly composed of microbial populations in flocculated form. The activated sludge has to be thickened in dissolved air flotation thickener before it is introduced to anaerobic digestion process for further degradation and stabilization of the sludge. This process highly relies on good solid and liquid separation within the thickener (Clauss et al. 1998). Thickened activated sludge, a product of the thickening process, is a very complicated colloidal material which is composed of organic and inorganic particles. The organic part of thickened sludge we studied consists of bacteria such as *Pseudomonas*, *Flavobacterium*, *Acinetobacter*, *Achromobacter*, *Actinobacteria*, but also *protozoa* and *micromycetes*, while the organic matter consists mainly of solid particles of sand (Trávníček et al. 2014). The rheological and flow behaviour during the thickening of this complicated non-Newtonian pseudo-plastic fluid needs to be intensively investigated so as to optimize the performance of the thickening process, minimize the cost of polymer consumption and achieve maximum possible increase in total solid concentration of thickened activated sludge for efficient performance of the anaerobic digesters. This chapter investigates different factors affecting the rheology of thickened excess activated sludge, namely source, total solid concentration, pH, temperature, and sludge treatment methods (Seyssiecq et al. 2003, Abu-Jdayil et al. 2010, Markis et al. 2014).

Total solid concentration is a factor that influences the rheology and flow behaviour of thickened excess activated sludge significantly. Baroutian et al. (2013) and Farno et al. (2013) investigated the effect of total solid concentration and temperature on sludge rheology and found that yield stress increased with increasing solid concentration and decreased with increasing temperature. The increase in shear stress with solid concentration was observed to be more noticeable at higher shear rates. According to Einstein's Law of Viscosity, the existence of solids suspended in a fluid increases its viscosity (Sanin 2002). Sludge characteristic curve for low solid concentrations differs from that for high solid concentration where there is a strong interaction between solid particles. Depending on the solid concentration, activated sludge shows a slightly thixotropic and shear-thinning behaviour (Piani et al. 2014).

Temperature is another factor that influences the rheological properties of thickened excess activated sludge. Thermal energy results in a change of the shape, size and strength of flocculated particles, and the degree of their dispersion. These changes directly influence the rheological properties of sludge (Sanin 2002). Viscosity is generally lower with higher temperature and shear rate (Hasar et al. 2004, Eshtiaghi et al. 2013, Farno et al. 2013).

pH is another parameter that influences the network strength of flocs particularly for colloidal systems such as thickened excess activated sludge. pH of solution affects the surface charge of particles which in turn determines the strength of inter-particle forces and hence changes the rheological properties of the thickened excess activated sludge (Liao et al. 2002, Neyens et al. 2004).

In Beenyup WWTP, the thickening of excess activated sludge is achieved with the help of a polymer based flocculation agent in dissolved air flotation thickeners. These polymer or chemical additives can alter the floc size-density-structure relationship and affect the settling performance and phase separation of activated sludge system. Hence, determination of the optimum dose of polymer for enhanced settling performance is essential (Clauss et al. 1998). Therefore, established rheological data is required for the optimization of polymer consumption and enhancement of the cost effectiveness of the process (Örmeci 2007).

Rheological measurement are conducted by using rheometers which establishes a relationship between shear stress-shear rate and viscosity-shear rate (Ratkovich et al. 2013). It is considered to be difficult to obtain reliable rheological measurement due to great variability within the sludge sample, measuring method and devices used. Hence, a uniform measurement protocol is required to improve the reliability and repeatability of the data. Furthermore, rheological measurements are valuable data for system analysis by translating the data into mathematical equation which describes the system (Seyssiecq et al. 2003, Ratkovich et al. 2013). According to Ratkovich et al. (2013) and Eshtiaghi et al. (2013), there are no model which fit perfectly with any sludge samples and there are no clear indication that yield stress exist within sludge samples but it is widely accepted that rheological model which includes a yield stress term can be used to represent flow behaviour within a limited shear rate range. Many researchers focus on investigating the rheological behaviour of different types of sludge. However, due to the colloidal and complex nature of sludge, the parameters measured may show high variability. Particularly for activated sludge, results may not be consistent and replicable. The rheology of thickened excess activated sludge is different for each wastewater treatment plant. Very few researchers report the rheological behaviour of thickened excess activated sludge in their studies. There is also a need to optimize the polymer dose required for thickening of excess activated sludge to make the process more cost effective. Hence, this chapter focuses on investigating the rheological behaviour of thickened excess activated sludge and the impacts of different factors such as temperature, pH, solid concentration, and polymer dose on the rheological behaviour and other physico-chemical characteristics that are required for efficient operation in wastewater treatment processes.

4.2 Material and Method

The detailed material and method on rheometry and rheological modelling has been discussed in Chapter 3. The section below details the materials and methods that are specific and unique to Thickened excess activated sludge (TEAS) samples.

4.2.1 Collection of sludge

As shown in Fig. 4.1, thickened excess activated sludge (TEAS) samples were collected from the underflow of a dissolved air floatation unit at Beenyup Wastewater Treatment Plant of Water Corporation, Perth, Western Australia. Excess activated sludge (EAS), and raw primary sludge (RPS) were also collected from the same wastewater treatment plant as shown in Fig. 4.1 and Fig. 4.2.

Fig. 4.1 Excess activated sludge and thickened excess activated sludge sampling point at Beenyup WWTP

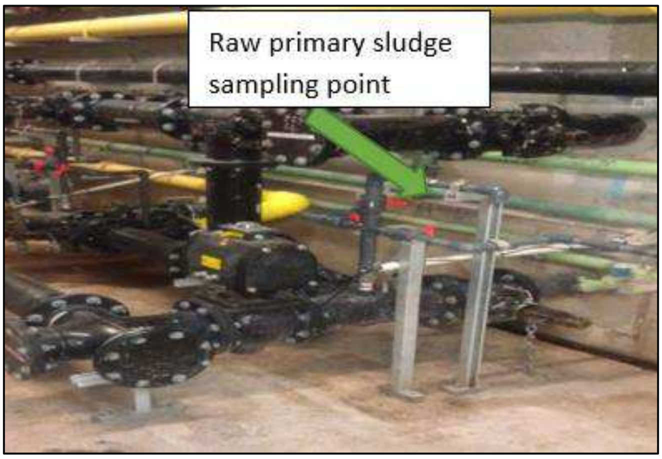

Fig. 4.2 Raw primary sludge sampling point at Beenyup WWTP

4.2.2 Characterization of sludge

Detailed characterization was conducted on each of the collected samples. The characterization of sludge involved determination of physico-chemical and biological parameters such as total solids content (TS), total volatile solids (VS), chemical oxygen demand (COD), temperature, and pH. Standard Methods for Examination of Water and Wastewater provided by the American Public Health Association et al. (2005) were used for the study as depicted in Chapter 3 (Sanin 2002, Li et al. 2008, Lotito et al. 2014).

4.2.3 Activation energy-shear rate relationship of sludge

The common definition for activation energy is defined as the minimum energy needed for a reaction to occur. For this particular study, higher activation energy is commonly associated with increasing flow resistance before the normal flow is achieved. The Arrhenius relationship obtained from the Ostwald law model is the most common method used to describe the relationship between activation energy and flow resistance. Equation 4-1 shows the effect of temperature on apparent viscosity at a specified shear rate of fluid, which is derived from the Arrhenius relationship to form the Arrhenius type model equation (Rao 2010).

$$\mu(T) = \mu_0 e^{\left(\frac{E}{RT}\right)} \quad 4\text{-}1$$

where T is temperature (K), μ_0 is a coefficient usually termed as frequency factor (pre-exponent coefficient), E is the activation energy (J.mol^{-1}) and R is the universal gas constant (8.314J.mol^{-1}K^{-1}).

4.3 Results and Discussion

4.3.1 Sludge characterization

The samples of raw primary sludge, excess activated sludge and thickened excess activated sludge are characterized in Table 4.1. The total solid content were 2.7% and 0.8% for raw primary, and excess activated sludge respectively. The sludge thickening process in the dissolved air flotation thickening unit resulted in an increase of the total solid content of the excess activated sludge from 0.8% to 3.7% solid for thickened excess activated sludge. pH, total and volatile solid content, and chemical oxygen demand measured for raw primary sludge, excess activated sludge and thickened excess activated sludge samples are also given in Table 4.1.

Table 4.1 Characterization of raw primary sludge, excess activated sludge and thickened excess activated sludge

Sludge sample	Raw primary sludge (RPS)	Excess activated sludge (EAS)	Thickened excess activated sludge (TEAS)
Total solid content (%)	2.7	0.8	3.7
Volatile solid content (%)	2.4	0.6	3.0
Chemical oxygen demand (ppm)	20100	1800	27500
pH	6	7	7
Temperature (°C)	25	25	25

4.3.2 Comparison of rheological behaviour between raw primary, excess activated, and thickened excess activated sludge.

The rheological behaviours of different sludge types such as raw primary sludge (RPS), excess activated sludge (EAS), and thickened excess activated sludge (TEAS) are presented in Fig. 4.3. The shear stress-shear rate plot for thickened excess activated sludge ranges from 28.2Pa for zero shear rate to 65.56Pa for 1000s^{-1} shear rate. The shear force requirement of TEAS to achieve normal flow is much higher than RPS and EAS. This is associated with the presence of significant amount of bio-polymeric material that shown colloidal property and greater total solid concentration. Moreover, the shear stress shows a sudden jump from 43.2Pa to 66.6Pa between shear rate ranges of 680s^{-1} to 740s^{-1} due to change in floc structure and size because of special shearing effect (Spicer et al. 1996). Rheological model parameters were generated from the shear stress-shear rate curves as shown in Table 4.2. Yield stress for thickened excess activated sludge was calculated to be 30.1Pa, 33.0Pa and 25.1Pa as per Power, Bingham, and Herschel-Bulkley models respectively as shown in Table 4.2. Raw primary sludge showed lower yield stress of 2.6Pa and excess activated sludge directly coming from the activated sludge treatment process has extremely low yield stress of 0.2Pa and behaves like a Newtonian fluid (Fig. 4.3) as the total solid content is very low (0.8%). This observation is also supported by the results for flow index as shown in Table 4.2.

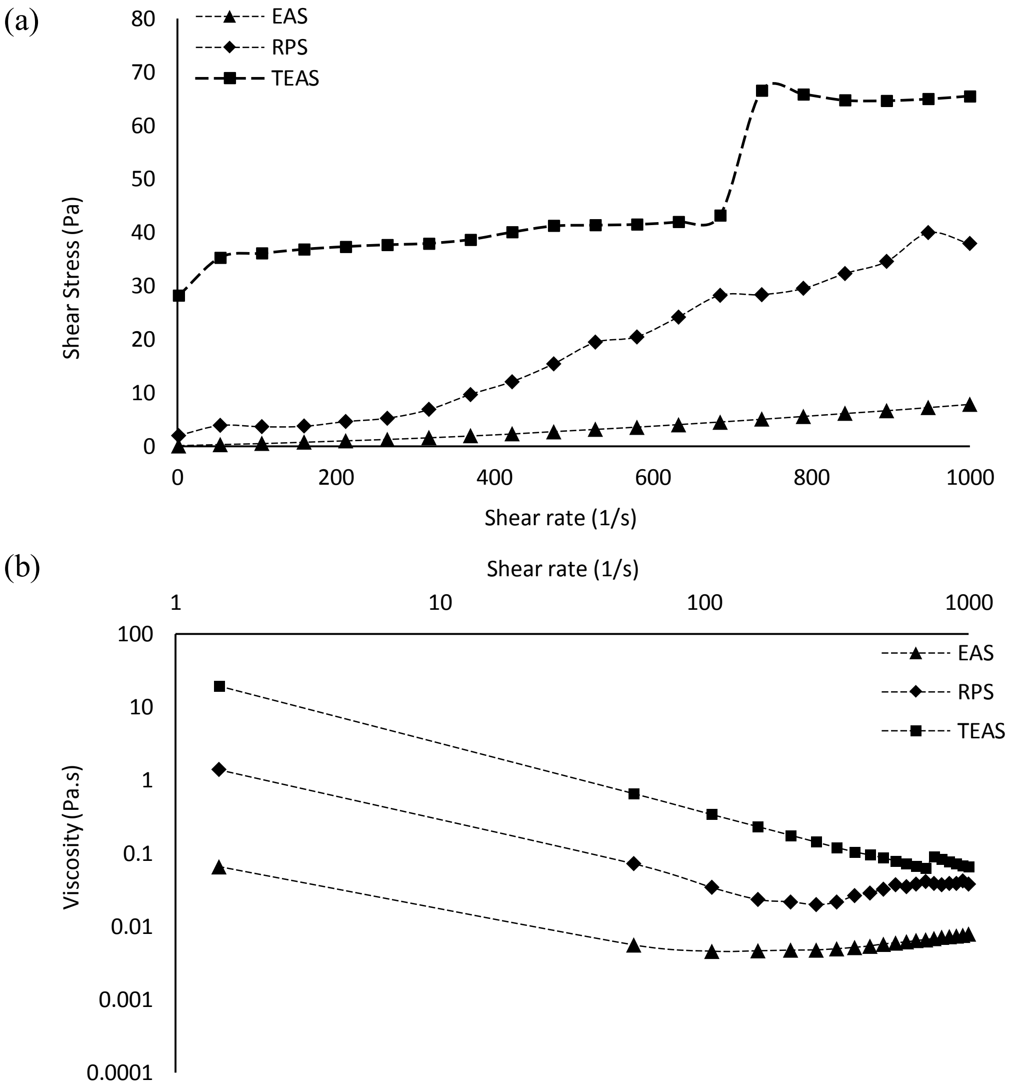

Fig. 4.3 (a) Shear stress-shear rate curves and (b) Viscosity-shear rate curves for different sludge types, EAS: TS=0.8%w/w, T=25°C & pH=7, RPS: TS=2.7%w/w, T=25°C & pH=6, TEAS: TS=3.7%w/w, T=25°C & pH=7, and MS: TS=3.0%w/w, T=25°C & pH=7

Table 4.2 Yield stress, viscosity and flow index based on different rheological models for different sludge types

Sludge Sample	Rheological Model	Yield Stress (Pa)	Viscosity (Pa.s)	Flow Index	R^2
Raw Primary Sludge	Bingham	-	0.04	-	0.91
	Power	-	7.5E-04	1.6	0.97
	Herschel-Bulkley	2.6	3.5E-05	2.1	0.99
Excess Activated Sludge	Bingham	0	6.5E-03	-	0.98
	Power	-	8.1E-03	1.3	0.99
	Herschel-Bulkley	0.2	3.4E-04	1.4	0.99
Thickened Excess Activated Sludge	Bingham	33	0.02	-	0.82
	Power	-	26.6	0.1	0.94
	Herschel-Bulkley	25.1	3.2	0.3	0.96

4.3.3 Effect of total solid concentration on thickened excess activated sludge rheology

In this section, the effect of change in total solid concentration on thickened excess activated sludge rheological flow behaviour will be discussed. Total solid concentrations of 3.7%, 3.1%, 2.6%, 2.1%, 1.3%, and 0.9% were investigated for this study. The desired solid concentrations were achieved by using vacuum filtration technique and by dilution method using deionized water (Baroutian et al. 2013, Lotito et al. 2014, Markis et al. 2014). The rheological behaviour of thickened excess activated sludge at the indicated solid concentrations was investigated by plotting shear stress-shear rate and viscosity-shear rate curves as shown in Fig. 4.4(a) and Fig. 4.4(b) respectively. The initial shear stress at zero shear-rate in the shear stress-shear rate plot was observed to increase with increasing total solid concentration as shown in Fig. 4.4(a). Similarly, viscosity was observed to increase with the increase of total solid concentration from 0.9% to 3.7% as shown in Fig. 4.4(b), due to the increase in solid content within the sludge sample. Furthermore, different rheological behaviour models were fitted to the shear stress-shear rate curve to obtain different rheological model parameters that are presented in Table 4.3. According to the Bingham pseudo-plastic model, the increase in total solid concentration resulted in the increase of yield stress as shown in Fig. 4.5(a). Similar trends were reported by Baroutian et al. (2013), Farno et al. (2013) and Spinosa et al. (2003). According to Bingham pseudo-plastic model, the decrease in concentration from 3.7% to 3.1% resulted in drastic reduction of yield stress from 27.6Pa to 11.0Pa, further reduction to 1.3Pa was observed as solid content decreased to 1.3% as shown in Fig. 4.5(a). The viscosity-shear rate curves were also fitted to various rheological models, and the results are shown in Table 4.4. According to the Cross model, the zero-rate viscosity increased from 0.008Pa.s to 26.4Pa.s as total solid concentration increased from 0.9% to 3.7% as shown in Fig. 4.5(b). Similarly, the infinite-rate viscosity increased from 0.008Pa.s to 0.05Pa.s as the total solid content was reduced from 3.7% to 0.9% as shown Fig. 4.5(c). The flow index decreased from 1.38 to 0.25 with the increase in total solid concentration as shown in Fig. 4.5(d), indicating a change from dilatant flow behaviour to non-Newtonian nature. The increase in total solid concentration resulted in the increase of energy of cohesion and inter-particle interaction which lead to the change of flow consistency (Mori et al. 2006). This is due to stronger network of sludge floc structure with the increase of solid concentration where colloidal, and hydrodynamic forces between sludge particles change (Baroutian et al. 2013, Markis et al. 2014).

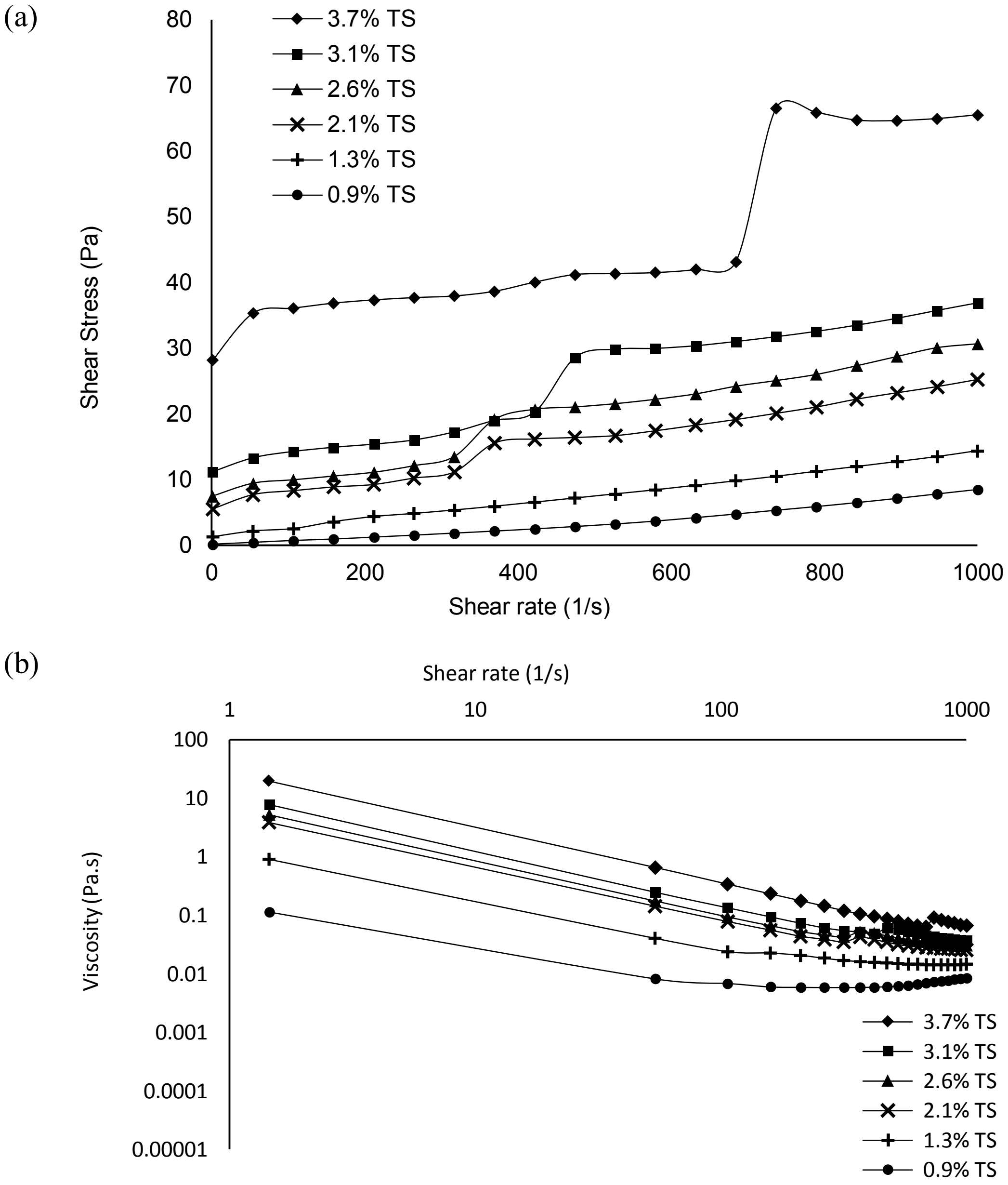

Fig. 4.4 (a) Shear stress-shear rate curves and (b) Viscosity-shear rate curves for different solid concentrations of thickened excess activated sludge at T = 23˚C and pH = 7.0

Table 4.3 Various rheological model parameters for varying total solid concentration of thickened excess activated sludge for different shear stress based rheological models

Total Solid Concentration	Rheological Model	Yield Stress (Pa)	Viscosity (Pa.s)	Flow Index	R^2
3.7%	Bingham	27.6	0.04	-	0.90
	Power	-	10.44	0.25	0.56
	Herschel-Bulkley	33.4	0.0001	1.93	0.85
3.1%	Bingham	11.0	0.03	-	0.94
	Power	-	1.42	0.47	0.87
	Herschel-Bulkley	10.2	0.05	0.91	0.94
2.6%	Bingham	7.7	0.02	-	0.97
	Power	-	0.78	0.53	0.93
	Herschel-Bulkley	6.7	0.06	0.87	0.97
2.1%	Bingham	6.2	0.02	-	0.98
	Power	-	0.64	0.52	0.93
	Herschel-Bulkley	5.5	0.04	0.89	0.98
1.3%	Bingham	1.3	0.01	-	0.99
	Power	-	0.05	0.81	0.99
	Herschel-Bulkley	1.6	0.01	1.06	0.99
0.9%	Bingham	-	0.01	-	0.97
	Power	-	-	1.38	0.99
	Herschel-Bulkley	0.4	-	1.58	0.99

Table 4.4 Various rheological model parameters for varying total solid concentration of thickened excess activated sludge for different viscosity based rheological models

Total Solid Concentration	Rheological Model	Zero-rate Viscosity (Pa.s)	Infinite-rate Viscosity (Pa.s)	Consistency Index (s)	Flow Index	R^2
3.7%	Cross	26.4	0.051	0.32	1.29	0.99
	Carreau	21.4	0.051	0.28	-	0.99
	Sisko	-	0.034	29.99	-	0.99
3.1%	Cross	15.7	0.033	0.71	1.18	0.99
	Carreau	9.8	0.033	0.49	-	0.99
	Sisko	-	0.029	11.44	-	0.99
2.6%	Cross	16.0	0.027	1.36	1.10	0.99
	Carreau	7.6	0.027	0.70	-	0.99
	Sisko	-	0.025	7.55	-	0.99
2.1%	Cross	10.5	0.021	1.16	1.08	0.99
	Carreau	5.3	0.021	0.63	-	0.99
	Sisko	-	0.019	5.52	0.02	0.99
1.3%	Cross	4.8	0.013	2.95	1.02	0.99
	Carreau	1.6	0.012	1.03	-	0.99
	Sisko	-	0.012	1.27	0.03	0.99
0.9%	Cross	0.008	0.008	0.00	-	0.00
	Carreau	0.007	0.007	0.00	-	0.00
	Sisko	-	0.007	0.18	-	0.96

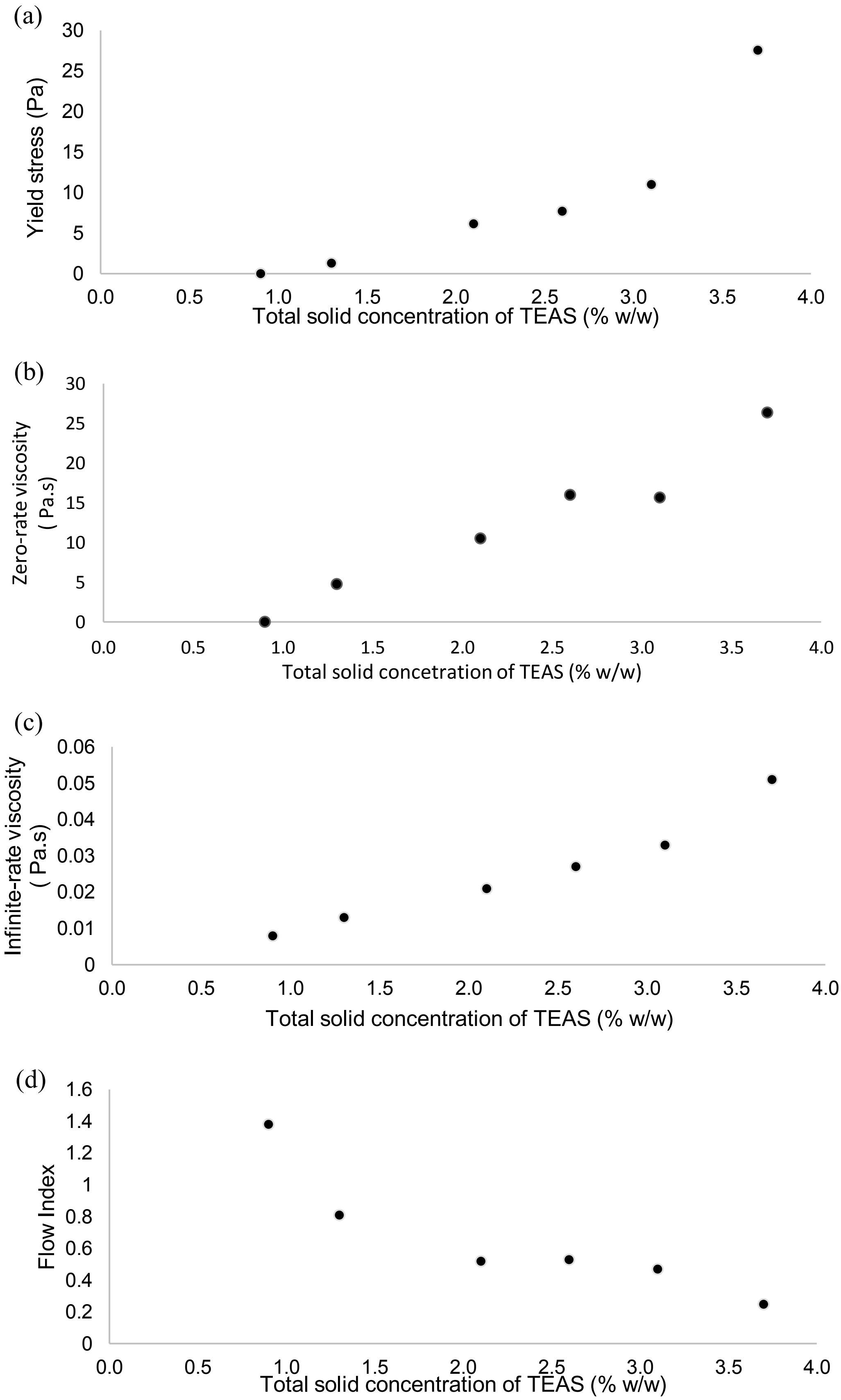

Fig. 4.5 Rheological model based parameters for varying total solid concentrations of thickened excess activated sludge (a) yield stress (Bingham), (b) zero-rate viscosity (Cross), (c) infinite-rate viscosity (Cross), and (d) flow index (Power)

4.3.4 Effect of temperature on thickened excess activated sludge rheology

In this section, the effect of temperature on rheological behaviour of thickened excess activated sludge was studied for different temperatures of 23˚C, 25˚C, 30˚C, 35˚C, 45˚C, 50˚C, and 55˚C respectively. The desired temperature conditions were achieved by using Peltier Concentric Cylinder Temperature Control System, which is attached to the Discovery Hybrid Rheometer at typical heating rate of 10˚C/min (Baroutian et al. 2013). The rheological behaviour of thickened excess activated sludge at different temperatures is presented as shear stress-shear rate curves and viscosity-shear rate curves as shown in Fig. 4.6(a) and Fig. 4.6(b) respectively. The shear stress at zero or infinite rates in the shear stress-shear rate plot was observed to decrease with increasing temperature as shown in Fig. 4.6(a). Similarly, viscosity was observed to decrease with increase in temperature as shown in Fig. 4.6(b), due to the weakening of inter-molecular cohesive forces within the activated sludge sample (Manoliadis et al. 1984, Paul et al. 2006, Appels et al. 2010). The experimental results show that there is a critical shear rate (685s^{-1} at 23˚C, 317s^{-1} at 25˚C, 264s^{-1} at 30˚C, 369s^{-1} at 35˚C and 422s^{-1} at 50˚C) where shear stress increases suddenly to a much higher level for a given temperature due to changes in the floc-size-density-structure of the thickened activated sludge samples subjected to shearing. This critical shear rate shifted back to lower values between temperatures of 23˚C and 30˚C and increased again between temperatures of 35˚C and 50˚C as shown in Fig. 4.6(a). This critical region helps to decide the shear rate that pumps, fluid movers and agitators should deliver to thickened excess activated sludge at a given temperature to minimize power consumption and achieve smooth flow of the sludge. Furthermore, different rheological models were fitted to the shear stress-shear rate curves and the rheological model parameters obtained from the model fitting are tabulated in Table 4.5. According to the Bingham pseudo-plastic model, the increase in temperature resulted in decrease of yield stress as shown in Fig. 4.7(a). Similar trends were reported by many authors such as Eshtiaghi et al. (2013), Farno et al. (2013), Appels et al. (2010), Paul et al. (2006), Hasar et al. (2004), and Manoliadis et al. (1984) for other sludge systems. Bingham pseudo-plastic model fitting resulted in the reduction of yield stress from 20.1Pa to 8.3Pa for the increase in temperature from 25˚C to 55˚C as shown in Fig. 4.7 (a). The viscosity shear rate curves were also fitted to various rheological models and model parameters are reported in Table 4.6. According to the Cross model, the zero-rate viscosity showed a decreasing trend from 33kPa.s to 4.4Pa.s for temperature increasing from 25°C to 55°C as shown in Fig. 4.7(b). In contrast, the infinite-rate viscosity showed an increasing trend from 0.021Pa.s to 0.031Pa.s as the temperature was increased from 25°C to 50°C and it decreased to 0.024Pa.s for 55˚C as shown Fig. 4.7(c). The decrease in infinite-rate viscosity is due to some restructuring in the floc network which resulted in the weakening of the network strength and a corresponding decrease in infinite rate viscosity. The flow index was observed to increase from 0.27 to 0.43 with the increase of temperature from 25˚C to 55˚C as shown in Fig. 4.7(d), indicating thickened excess activated sludge showed strictly non-Newtonian pseudo-plastic behaviour in the temperature range investigated in this study.

(a)

(b)

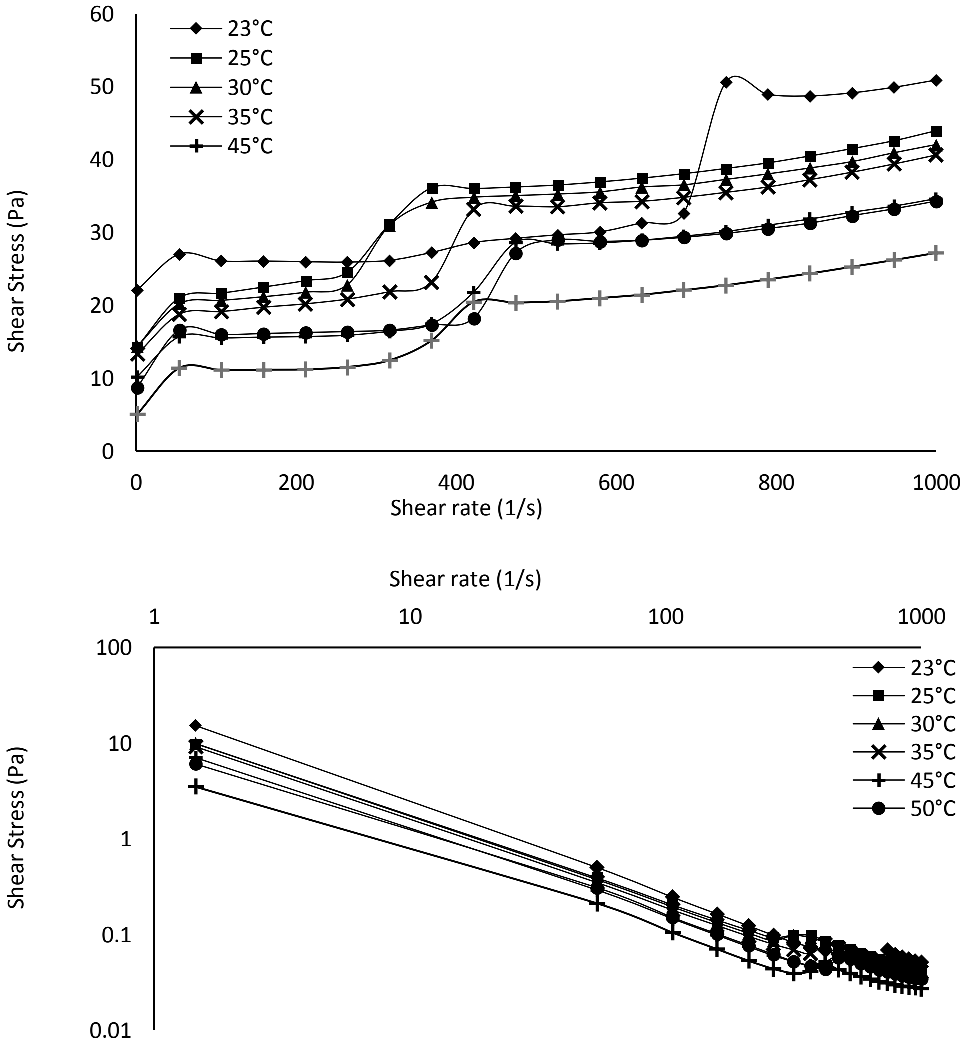

Fig. 4.6 (a) Shear stress-shear rate curves and (b) Viscosity-shear rate curves for different temperatures of thickened excess activated sludge with TS = 3.5% w/w and pH = 7.0

Table 4.5 Various rheological model parameters for varying thickened excess activated sludge temperature for different shear stress based rheological models

Temperature (°C)	Rheological Model	Yield Stress (Pa)	Viscosity (Pa.s)	Flow Index	R^2
25	Bingham	20.1	0.03	-	0.88
	Power	-	6.6	0.27	0.90
	Herschel-Bulkley	12.5	0.9374	0.51	0.94
30	Bingham	19.3	0.03	-	0.88
	Power	-	6.36	0.27	0.88
	Herschel-Bulkley	12.6	0.77	0.53	0.93
35	Bingham	16.2	0.03	-	0.91
	Power	-	4.17	0.32	0.85
	Herschel-Bulkley	13.0	0.21	0.71	0.93
45	Bingham	11.9	0.02	-	0.92
	Power	-	2.21	0.39	0.84
	Herschel-Bulkley	10.8	0.06	0.86	0.92
50	Bingham	11.9	0.02	-	0.90
	Power	-	2.37	0.38	0.83
	Herschel-Bulkley	10.6	0.07	0.84	0.90
55	Bingham	8.3	0.02	-	0.93
	Power	-	1.31	0.43	0.91
	Herschel-Bulkley	5.9	0.15	0.72	0.94

Table 4.6 Various rheological model parameters for varying thickened excess activated sludge temperature for different viscosity based rheological models

Temperature (°C)	Rheological Model	Zero-rate Viscosity (Pa.s)	Infinite-rate Viscosity (Pa.s)	Consistency Index (s)	Flow Index	R^2
25	Cross	33.4×10^3	0.021	52.7×10^3	0.91	0.96
	Carreau	660.0	0.020	70.92	-	0.96
	Sisko	-	0.020	13.59	0.09	0.99
30	Cross	46.0×10^3	0.021	6.5×10^3	0.92	0.99
	Carreau	809.3	0.021	82.39	-	0.99
	Sisko	-	0.021	13.69	0.08	0.99
35	Cross	32.8	0.028	1.72	1.03	0.99
	Carreau	13.7	0.028	0.75	-	0.99
	Sisko	-	0.024	13.22	0.04	0.99
45	Cross	9.8	0.032	0.31	1.28	0.99
	Carreau	7.7	0.031	0.27	-	0.99
	Sisko	-	0.023	10.51	0.03	0.99
50	Cross	7.3	0.031	0.21	1.34	0.99
	Carreau	5.7	0.031	0.20	-	0.99
	Sisko	-	0.020	9.06	0.07	0.99
55	Cross	4.4	0.024	23.1×10^3	1.25	0.99
	Carreau	3.7	0.024	0.22	-	0.99
	Sisko	-	0.016	5.06	0.12	0.99

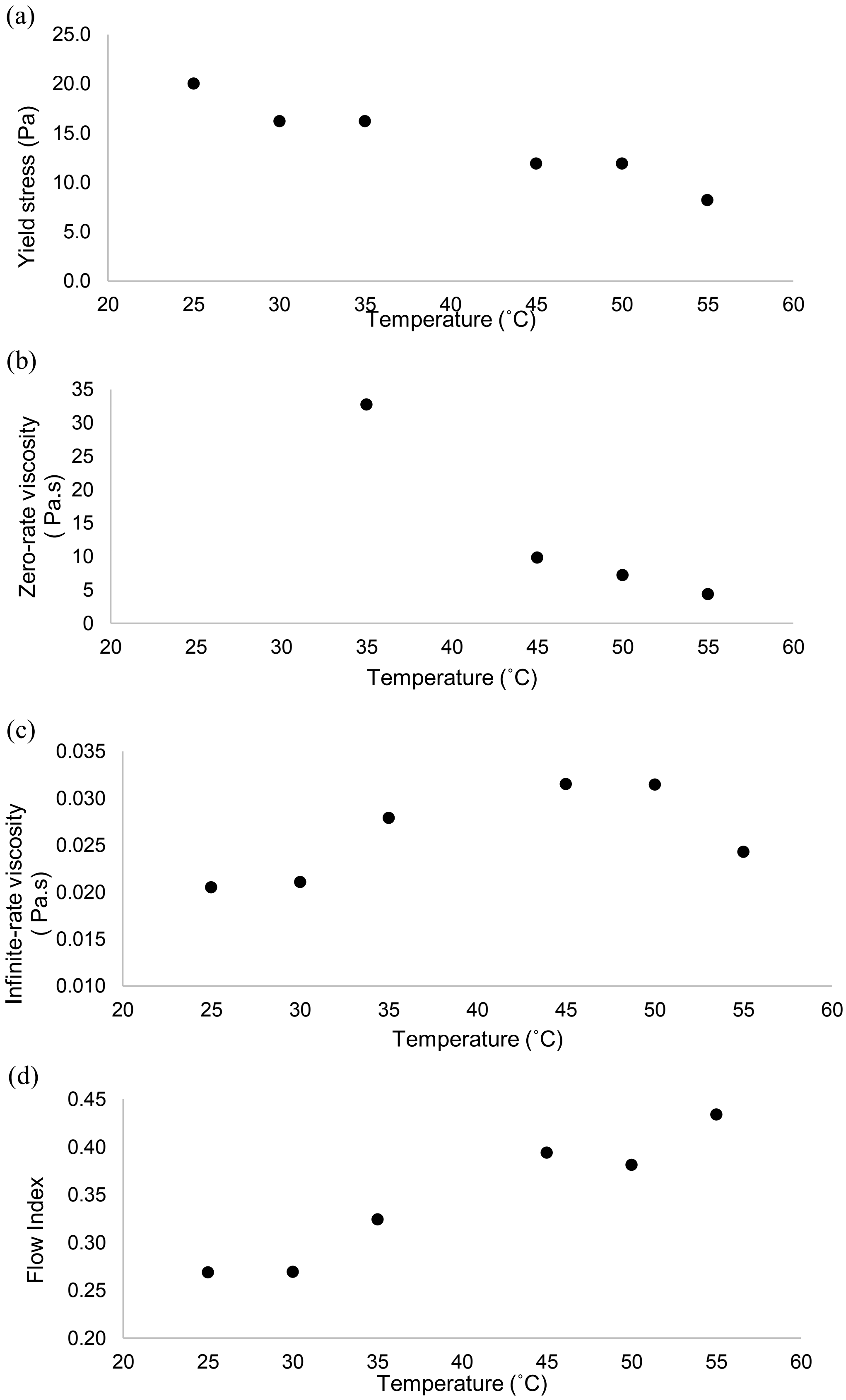

Fig. 4.7 Rheological model based parameters for varying temperature of thickened excess activated sludge (a) yield stress (Bingham), (b) zero-rate viscosity (Cross), (c) infinite-rate viscosity (Cross), and (d) flow index (Power)

4.3.5 The relationship between activation energy and apparent viscosity of TEAS due to change in temperature

Activation energy-shear rate relationship for thickened excess activated sludge for a temperature range of 25˚C to 55˚C and shear rate range of $1s^{-1}$ to $1000s^{-1}$ was developed by using Arrhenius type of equation (Equation 4-1). The experimental work conducted on the effect of temperature on the rheological behaviour of thickened excess activated sludge was used for the development of Arrhenius type relationship. The plot of the natural logarithm of the apparent viscosity in Pascal seconds (η) (ordinate) versus inverse of temperature in Kelvin (1/T) (abscissa) at a particular shear rate as shown in Fig. 4.8 was used to determine the activation energy (slope) and frequency factor (intercept). The activation energy and the frequency factor show a consistent relationship for varying shear rate as shown in Fig. 4.9. Higher activation energy is associated with increased resistance to flow before the normal flow is achieved and the molecular (floc particle) activity for such a condition is low as it can be observed from the plot of frequency factor. Higher activation energy value corresponds to lower frequency or pre-exponent factor as presented in Fig. 4.9. The activation energy required at lower shear rate ($1.45s^{-1}$) is very high, $25.1KJ.mol^{-1}$ and it drastically decreased to a relatively lower value of $13.8KJ.mol^{-1}$ at shear rate of $54s^{-1}$. It increased to a higher value of $24.8KJ.mol^{-1}$ between shear rates of $54s^{-1}$ to $369s^{-1}$; however, further increase in shear rate to $527s^{-1}$ resulted is a rapid decrease of the activation energy down to $13.1KJ.mol^{-1}$. The activation energy was observed to decrease very slightly down to $11.3KJ.mol^{-1}$ in the shear rate range of $527s^{-1}$ to $1000s^{-1}$. In general, in the rheological investigation of thickened excess activated sludge, the activation energy indirectly shows the strength of the inter-particle forces that keep the floc network together. Increase in activation energy shows higher resistance to flow or greater floc network strength. On the other hand, the frequency factor shows the distribution of the flocs, hence higher activation energy resulting in restricted flow relates to low frequency factor and vice versa. The trend in the frequency factor corresponds well to the described activation energy profile (Fig. 4.9).

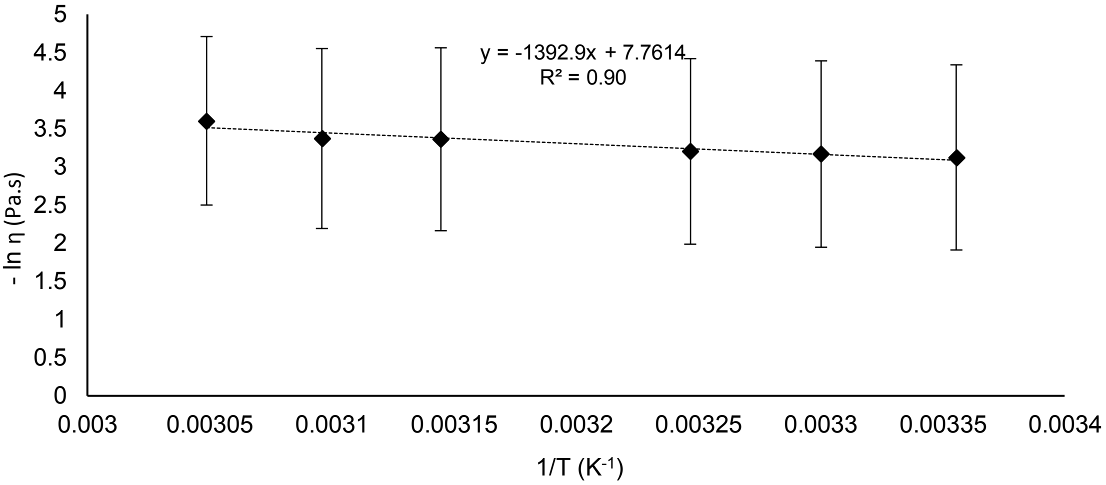

Fig. 4.8 Apparent viscosity of thickened excess activated sludge versus (1/T) plot for the determination of activation energy

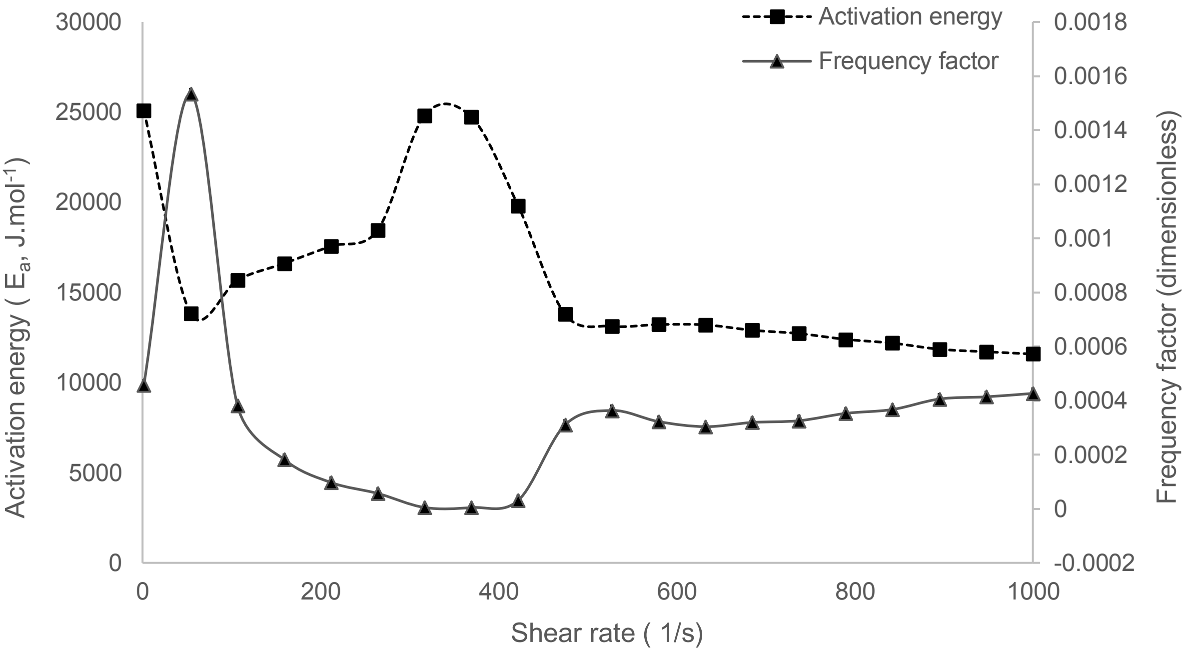

Fig. 4.9 Activation energy (Ea, J/mol) and frequency factor (dimensionless) versus shear rate plot for temperature range of (23˚C - 55˚C)

4.3.6 Effect of pH on thickened excess activated sludge rheology

In this section, the effect of pH range was investigated for the range of 3.6 to 10.0 so that the rheological properties of thickened excess activated sludge can be established in both acidic and alkaline regions. The pH of thickened excess activated sludge was adjusted by the addition of hydrochloric acid and sodium hydroxide (Sanin 2002). Experimental results show that pH significantly affects the shear stress-shear rate and viscosity shear rate profile of thickened excess activated sludge as shown in Fig. 4.10(a) and Fig. 4.10(b) respectively. The shear stress requirement at a given shear rate was observed to increase with increasing pH as shown in Fig. 4.10(a). The trend observed in the shear stress-shear rate profile is due to the flocculation effect and formation of stronger floc networks with the change in the charge and colloidal chemistry of the sludge floc particles (Neyens et al. 2004). Viscosity, on the other hand, showed a different trend from that shown in Fig. 4.10(b). Sludge particle surfaces tend to become more negatively charged when the pH increases above the isoelectric point. Hence, the isoelectric point of bacteria being between pH of 2.0 and 4.0 (Tenney et al. 1965), pH of 3.6, in this study, falls within the isoelectric range; Therefore, at a higher pH values, the particle surfaces of thickened excess activated sludge will be more negatively charged resulting in repulsion and expansion effects. This condition is important as the extent of compaction of particle structure plays a role in the fluid flow and deformation properties of the sludge and will have an effect on resistance to flow due to the size of exposed cross-sectional area of solids (Sanin 2002). Different rheological models were also fitted to the shear stress-shear rate and viscosity-shear rate curves the same way as the other parameters discussed in the above sections as shown in Table 4.7 and Table 4.8. Based on the Bingham model, yield stress was observed to increase from 6.0Pa to 8.3Pa for pH of 3.6 to 5.4, and it further increased from 6.6Pa to 8.3Pa for a pH change from 7.0 to 10.0 as shown in Fig. 4.11 (a). According to the Cross model, the zero-rate viscosity was mostly constant around 3.9Pa.s to 4.9Pa.s for all the pH conditions considered in this study as shown in Fig. 4.11 (b). Furthermore, the infinite-rate viscosity decreased from 0.02Pa.s to 0.016Pa.s as shown in Fig. 4.11 (c) and the flow index showed non-Newtonian behaviour for the whole pH range of 3.6 to 10.0 in Fig. 4.11 (d). The number of negative surface charges were observed to decrease under acid condition because of the neutralization effect on the negative functional groups located on the surface of extracellular polymeric substances of the sludge particle.

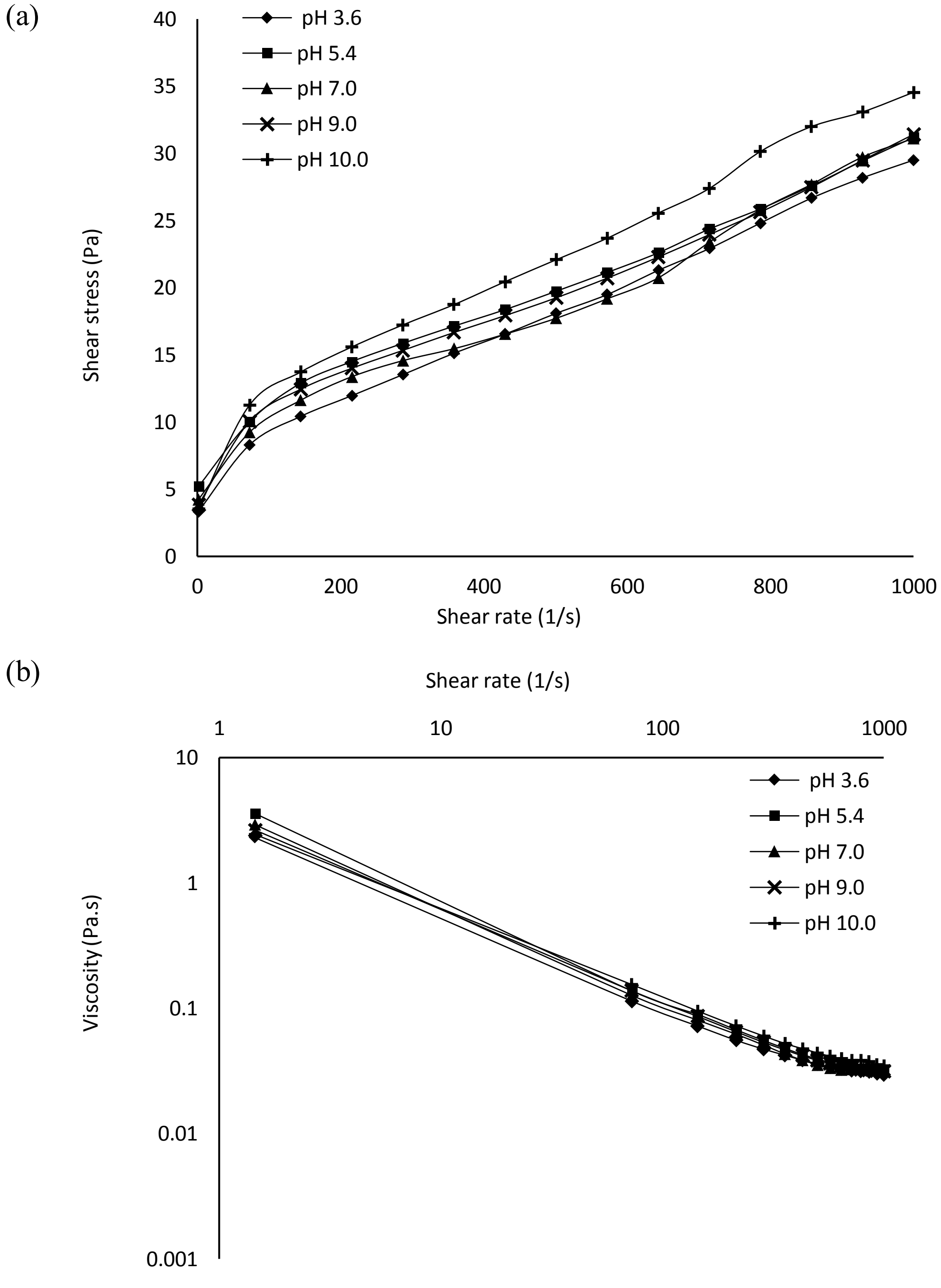

Fig. 4.10 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for thickened excess activated sludge at different pH condition at T = 23˚C and TS = 3.5% w/w

Table 4.7 Various rheological model parameters for varying pH of thickened excess activated sludge for different shear stress based rheological models

pH	Model	Yield Stress (Pa)	Viscosity (Pa.s)	Flow Index	R^2
3.6	Bingham	6.0	0.024	-	0.99
	Power	-	0.6	0.57	0.98
	Herschel-Bulkley	4.2	0.107	0.79	0.99
5.4	Bingham	8.3	0.023	-	0.98
	Power	-	1.19	0.46	0.96
	Herschel-Bulkley	5.9	0.15	0.74	0.99
7.0	Bingham	6.6	0.024	-	0.98
	Power	-	0.63	0.55	0.94
	Herschel-Bulkley	6.1	0.04	0.93	0.98
9.0	Bingham	7.5	0.024	-	0.97
	Power	-	0.97	0.49	0.96
	Herschel-Bulkley	5.0	0.17	0.72	0.99
10.0	Bingham	8.3	0.027	-	0.97
	Power	-	1.03	0.50	0.98
	Herschel-Bulkley	4.4	0.29	0.67	0.99

Table 4.8 Various rheological model parameters for varying pH of thickened excess activated sludge for different viscosity based rheological models

pH	Model	Zero-rate Viscosity (Pa.s)	Infinite-rate Viscosity (Pa.s)	Consistency Index (s)	Flow Index	R^2
3.6	Cross	4.9	0.022	0.79	0.97	1.00
	Carreau	660.0	0.020	70.92	-	0.96
	Sisko	-	0.020	13.59	0.09	1.00
5.4	Cross	22.4	0.018	4.94	0.90	1.00
	Carreau	6.6	0.018	1.19	-	1.00
	Sisko	-	0.017	4.92	0.14	1.00
7.0	Cross	4.9	0.023	0.49	1.06	1.00
	Carreau	3.3	0.023	0.36	-	1.00
	Sisko	-	0.018	4.04	0.15	1.00
9.0	Cross	4.8	0.021	0.55	0.99	0.99
	Carreau	3.0	0.021	0.38	-	1.00
	Sisko	-	0.015	3.59	0.20	1.00
10.0	Cross	3.9	0.024	0.41	0.98	1.00
	Carreau	2.7	0.024	0.31	-	1.00
	Sisko	-	0.016	3.26	0.25	1.00

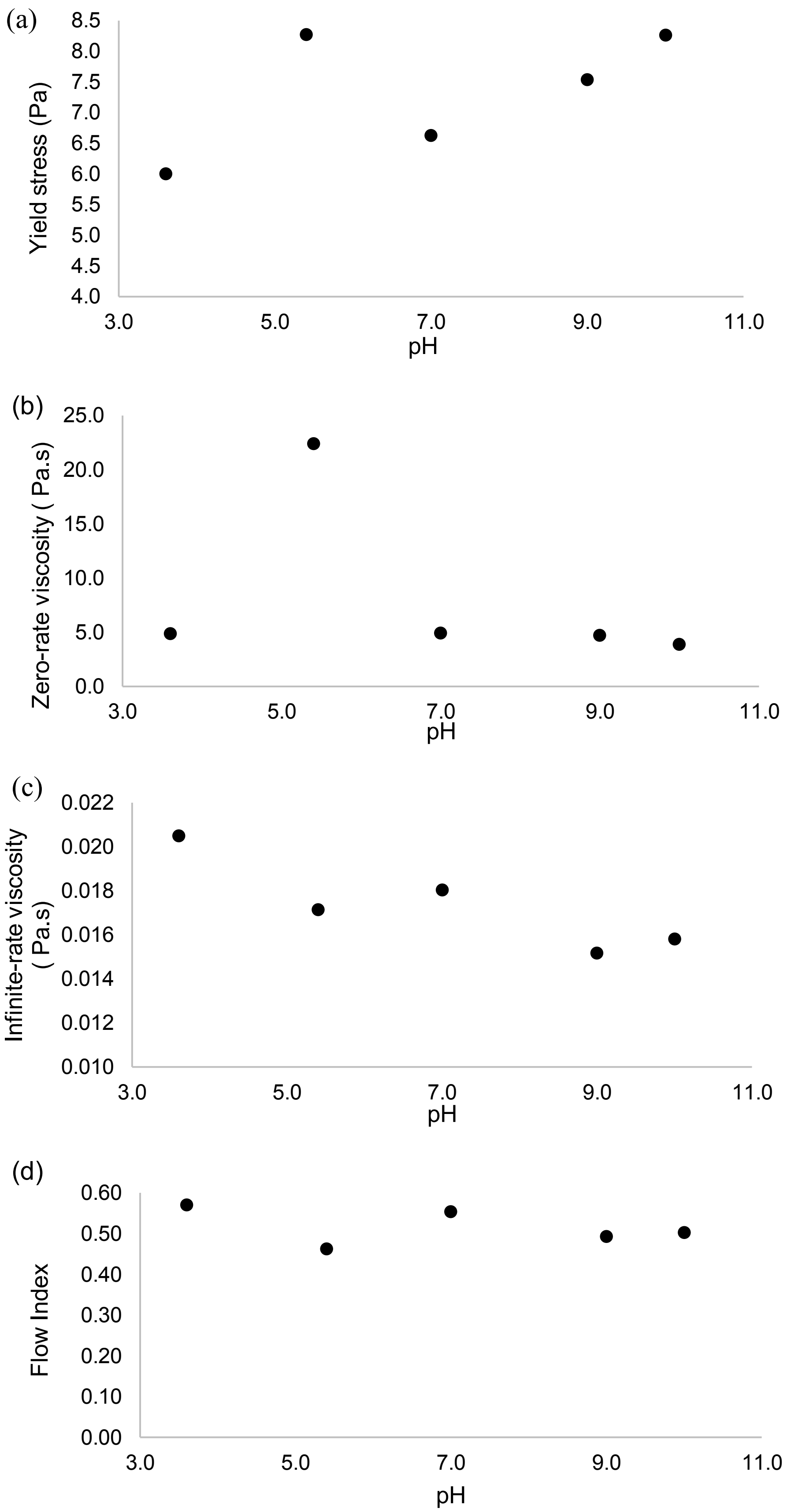

Fig. 4.11 Rheological model based parameters for varying pH of thickened excess activated sludge (a) yield stress (Bingham), (b) zero-rate viscosity (Cross), (c) infinite-rate viscosity (Sisko), and (d) flow index (Power)

4.3.7 Polymer dose optimization and effects on excess activated sludge thickening

Polymer consumption optimization in dissolved air flotation thickeners is crucial to minimize operational cost of wastewater treatment plants. Experimental polymer consumption optimization was conducted in this study using a combination of jar test and rheological flow investigation for different polymer doses (expressed in kilogram of polymer per ton of dried solids) of 1.0kg/ton DS, 1.3kg/ton DS, 1.5kg/ton DS, 2.0kg/ton DS and 2.3kg/ton DS. Polymer doses considered in the experimental study were selected based on the polymer consumption trend in Beenyup Wastewater Treatment Plant of Water Corporation, Perth, WA. The polymer used in the study has total solid concentration of 0.48 % and pH of 7.0. Shear stress and viscosity profiles were found to increase with increasing polymer dose from 1.0kg/ton DS to 2.3kg/ton DS due to the increase in average floc size and network of polymer-sludge colloids making the solid phase more compact and dense as shown in Fig. 4.12(a) and (b). The growth of flocs is in favour of solid-liquid separation; however, the significant increase in power consumption due to very high apparent viscosity and shear force requirement during thickening and hindered settling due to very large and loosely held floc particles at high polymer dose of 2.3kg/ton DS makes high polymer consumption unfavourable (an overdose condition). Polymer dose of 2.0kg/ton DS resulted in faster settling; however, the settling rate was much faster at lower polymer doses of 1.5kg/ton DS and 1.3kg/ton DS with significantly reduced shear stress requirement and viscosity as shown in Fig. 4.12. The rate of settling decreased at poly dose of 1.0kg/ton DS due to insufficient flocculation and smaller floc sizes. Hence, polymer dose of 1.3kg/ton DS was found to be the optimum for enhanced thickening and lesser cost of operation of the thickening unit due to reduced shear force, viscosity and polymer consumption.

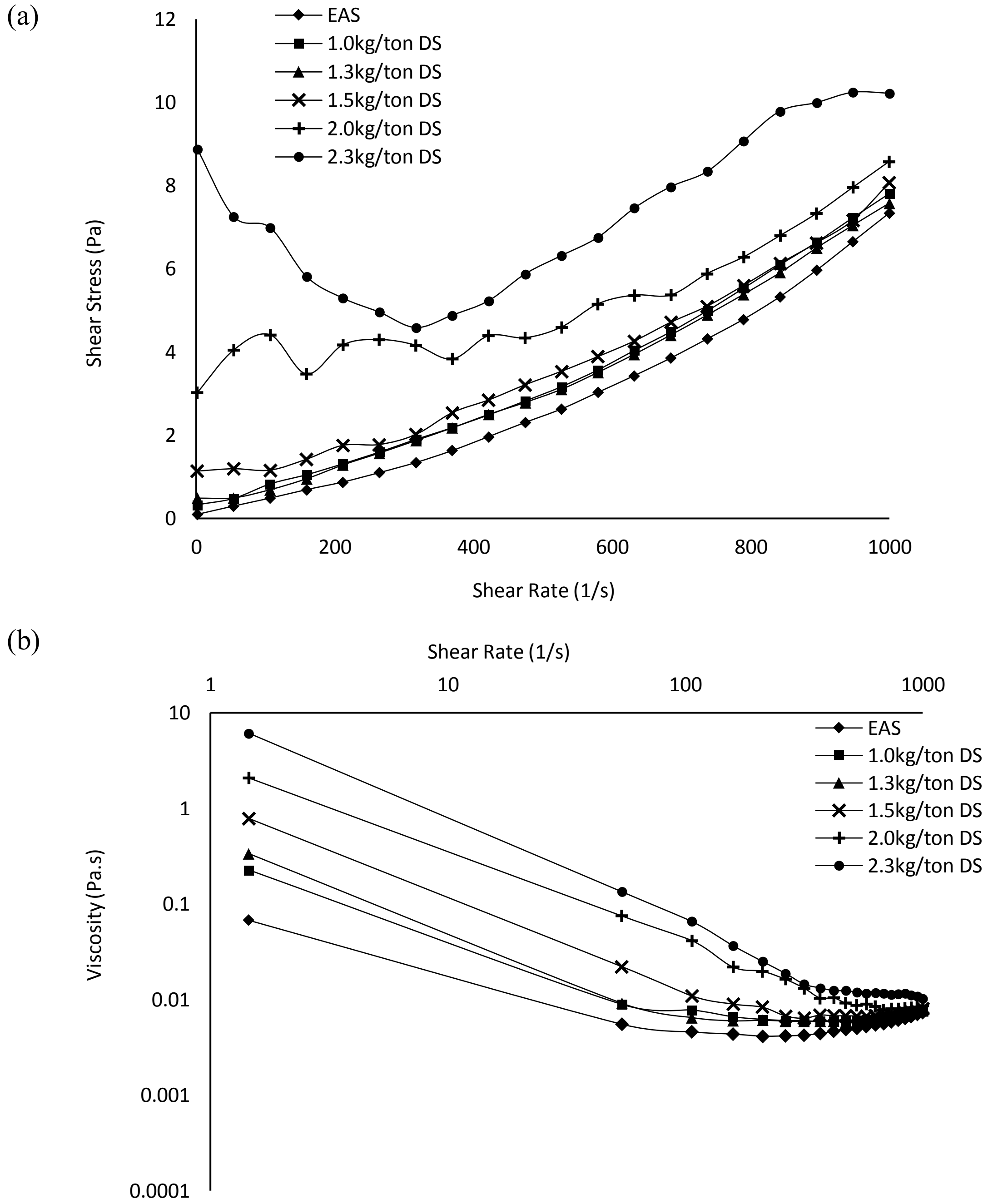

Fig. 4.12 (a) Shear stress-shear rate curves and (b) Viscosity-shear rate curves for different polymer dose of thickening of excess activated sludge at T=25°C, TS=0.8%w/w & pH=7

4.4 Conclusion

This section showed that concentration, temperature and pH are important parameters that significantly influence rheology of thickened excess activated sludge. The decrease in concentration from 3.7% to 3.1% resulted in drastic reduction of yield stress from 27.6Pa to 11.0Pa. It further reduced to 1.3Pa at total solid concentration of 1.3%. The viscosity at the initial stage of shearing decreased from 26.4Pa.s for TS of 3.7% to 4.8Pa.s for TS of 1.3% respectively according to Cross model. Yield stress steadily decreased from 20.1Pa to 8.3Pa when the temperature was raised from 23˚C to 55˚C. Similarly, the initial viscosity of thickened excess activated sludge decreased from 15.24Pa.s to 3.49Pa.s with increase in temperature from 23°C to 55°C. Higher activation energy requirement is associated with increased resistance to flow. The activation energy required at lower shear rate (1.45s^{-1}) was 25.1KJ.mol^{-1}. The yield stress increased from 6.0Pa to 8.3Pa for a pH of 3.6 to pH of 10.0 respectively. The zero-rate viscosity was mostly constant around 3.9Pa.s to 4.9Pa.s for all the pH conditions considered in this study. Yield stress for thickened excess activated sludge was found to be very high 25.1Pa compared to mixed digester feed sludge, raw primary sludge and excess activated sludge according to Herschel-Bulkley model which all showed much lower yield stress of 2.6Pa, 1.9Pa and 0.2Pa respectively. The apparent viscosity also showed a similar decreasing trend with reduction of total solids and organic biomass content with the highest viscosity for thickened excess activated sludge at 26.6Pa.s and the lowest for excess activated sludge at 0.008Pa.s. Consequently, more rheological and flow analysis on thickened excess activated sludge rather than other sludge types helps to improve pumping cost, hydrodynamic mixing and mass transfer in digesters and ultimately the quality of the digested sludge and wastewater treatment plant economics. Besides, optimization of the polymer dose required for thickening of excess activated sludge is of great economic concern and the optimum polymer dose for excess activated sludge thickening was found to be 1.3kg/ton DS.

Reference

[1] Abu-Jdayil, Basim, Fawzi Banat, and Mukheled Al-Sameraiy. 2010. "Steady Rheological Properties of Rotating Biological Contactor (RBC) Sludge." *Journal of Water Resource and Protection* no. 2 (1):1-7. doi: 10.4236/jwarp.2010.21001.

[2] American Public Health Association, American Water Works Association, Water Pollution Control Federation, and Water Environment Federation. 2005. *Standard Methods for the Examination of Water and Wastewater*: American Public Health Association.

[3] Appels, Lise, Jan Degrève, Bart Van der Bruggen, Jan Van Impe, and Raf Dewil. 2010. "Influence of low temperature thermal pre-treatment on sludge solubilisation, heavy metal release and anaerobic digestion." *Bioresource Technology* no. 101 (15):5743-5748. doi: http://dx.doi.org/10.1016/j.biortech.2010.02.068.

[4] Baroutian, Saeid, Nicky Eshtiaghi, and Daniel J. Gapes. 2013. "Rheology of a primary and secondary sewage sludge mixture: Dependency on temperature and solid concentration." *Bioresource Technology* no. 140 (0):227-233. doi: http://dx.doi.org/10.1016/j.biortech.2013.04.114.

[5] Clauss, F., D. Helaine, C. Balavoine, and A. Bidault. 1998. "Improving activated sludge floc structure and aggregation for enhanced settling and thickening performances." *Water Science and Technology* no. 38 (8–9):35-44. doi: http://dx.doi.org/10.1016/S0273-1223(98)00675-1.

[6] Eshtiaghi, Nicky, Flora Markis, Shao Dong Yap, Jean-Christophe Baudez, and Paul Slatter. 2013. "Rheological characterisation of municipal sludge: A review." *Water Research* no. 47 (15):5493-5510. doi: http://dx.doi.org/10.1016/j.watres.2013.07.001.

[7] Farno, Ehsan, Rajarathinam Parthasarathy, Jean Christophe Baudez, and Nicky Eshtiaghi. 2013. Effect of Thermal History on Municipal Digested Sludge Rheology: Experimental and Modeling. In *Chemeca 2013*.

[8] Hasar, Halil, Cumali Kinaci, Ayhan Ünlü, Hasan Toğrul, and Ubeyde Ipek. 2004. "Rheological properties of activated sludge in a sMBR." *Biochemical Engineering Journal* no. 20 (1):1-6. doi: http://dx.doi.org/10.1016/j.bej.2004.02.011.

[9] Li, Huan, Yiying Jin, RasoolBux Mahar, Zhiyu Wang, and Yongfeng Nie. 2008. "Effects and model of alkaline waste activated sludge treatment." *Bioresource Technology* no. 99 (11):5140-5144. doi: http://dx.doi.org/10.1016/j.biortech.2007.09.019.

[10] Liao, BQ, DG Allen, GG Leppard, IG Droppo, and SN Liss. 2002. "Interparticle interactions affecting the stability of sludge flocs." *Journal of colloid and interface science* no. 249 (2):372-380.

[11] Lotito, Vincenzo, and Adriana Maria Lotito. 2014. "Rheological measurements on different types of sewage sludge for pumping design." *Journal of Environmental Management* no. 137 (0):189-196. doi: http://dx.doi.org/10.1016/j.jenvman.2014.02.005.

[12] Manoliadis, Odysseys, and Paul L Bishop. 1984. "Temperature effect on rheology of sludges." *Journal of environmental engineering* no. 110 (1):286-290.

[13] Markis, Flora, Jean-Christophe Baudez, Rajarathinam Parthasarathy, Paul Slatter, and Nicky Eshtiaghi. 2014. "Rheological characterisation of primary

and secondary sludge: Impact of solids concentration." *Chemical Engineering Journal* no. 253 (0):526-537. doi: http://dx.doi.org/10.1016/j.cej.2014.05.085.

[14] Mori, M., I. Seyssiecq, and N. Roche. 2006. "Rheological measurements of sewage sludge for various solids concentrations and geometry." *Process Biochemistry* no. 41 (7):1656-1662. doi: http://dx.doi.org/10.1016/j.procbio.2006.03.021.

[15] Neyens, Elisabeth, Jan Baeyens, Raf Dewil, and Bart De heyder. 2004. "Advanced sludge treatment affects extracellular polymeric substances to improve activated sludge dewatering." *Journal of Hazardous Materials* no. 106 (2–3):83-92. doi: http://dx.doi.org/10.1016/j.jhazmat.2003.11.014.

[16] Örmeci, Banu. 2007. "Optimization of a full-scale dewatering operation based on the rheological characteristics of wastewater sludge." *Water Research* no. 41 (6):1243-1252. doi: http://dx.doi.org/10.1016/j.watres.2006.12.043.

[17] Paul, E., P. Camacho, D. Lefebvre, and P. Ginestet. 2006. "Organic matter release in low temperature thermal treatment of biological sludge for reduction of excess sludge production." *Water Sci Technol* no. 54 (5):59-68.

[18] Piani, Luciano, Claudia Bruna Rizzardini, Adriano Papo, and Daniele Goi. 2014. "Rheology Measurements for Online Monitoring of Solids in Activated Sludge Reactors of Municipal Wastewater Treatment Plant." *The Scientific World Journal* no. 2014:6. doi: 10.1155/2014/590961.

[19] Rao, M Anandha. 2010. *Rheology of fluid and semisolid foods: principles and applications: principles and applications*: Springer Science & Business Media.

[20] Ratkovich, N., W. Horn, F. P. Helmus, S. Rosenberger, W. Naessens, I. Nopens, and T. R. Bentzen. 2013. "Activated sludge rheology: A critical review on data collection and modelling." *Water Research* no. 47 (2):463-482. doi: http://dx.doi.org/10.1016/j.watres.2012.11.021.

[21] Sanin, F. Dilek. 2002. "Effect of solution physical chemistry on the rheological properties of activated sludge." *Water SA* no. 28 (2):207-212.

[22] Seyssiecq, Isabelle, Jean-Henry Ferrasse, and Nicolas Roche. 2003. "State-of-the-art: rheological characterisation of wastewater treatment sludge." *Biochemical Engineering Journal* no. 16 (1):41-56. doi: http://dx.doi.org/10.1016/S1369-703X(03)00021-4.

[23] Spicer, Patrick T., and Sotiris E. Pratsinis. 1996. "Shear-induced flocculation: The evolution of floc structure and the shape of the size distribution at steady state." *Water Research* no. 30 (5):1049-1056. doi: http://dx.doi.org/10.1016/0043-1354(95)00253-7.

[24] Spinosa, L., and V. Lotito. 2003. "A simple method for evaluating sludge yield stress." *Advances in Environmental Research* no. 7 (3):655-659. doi: http://dx.doi.org/10.1016/S1093-0191(02)00041-2.

[25] Tenney, Mark W., and Werner Stumm. 1965. "Chemical Flocculation of Microorganisms in Biological Waste Treatment." *Journal (Water Pollution Control Federation)* no. 37 (10):1370-1388. doi: 10.2307/25035388.

[26] Trávníček, Petr, and Petr Junga. 2014. "Thixotropic behaviour of thickened sewage sludge." *Journal of Environmental Health Science and Engineering* no. 12:72-72. doi: 10.1186/2052-336X-12-72.

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CHAPTER 5

RHEOLOGICAL AND PHYSICO-CHEMICAL CHARACTERISTIC OF MIXED DIGESTER FEED SLUDGE

Abstract

In this chapter, the impacts of solid concentration, temperature, mixing ratio, and ageing of sludge on the rheological behaviour of mixture of raw primary and thickened excess activated sludge (mixed sludge) were investigated. Solid concentration, temperature, primary to thickened excess activated sludge mixing ratio, and sludge age were found to affect the viscosity, yield stress, flow index and flow consistency of mixed sludge. The decrease in total solid concentration of mixed sludge from 30g/L to 20g/L resulted in significant decrease of yield stress from 7.4Pa to 1.1Pa (85% reduction). The decrease in mixing ratio of thickened excess activated sludge to raw primary sludge from 80% to 20% resulted in the decrease of yield stress from 10.2Pa to 1.2Pa confirming the significant contribution of thickened excess activated sludge to the non-Newtonian viscoplastic flow behaviour of the mixture. Similarly, viscosity also showed a decreasing trend with decreasing total solid concentration and percentage of thickened excess activated sludge in the mixture. In contrast, yield stress and viscosity generally showed reduction with increasing temperature. Low temperature storage duration (sludge age) also affected the rheology of mixed sludge. The applicability of various rheological models such as Bingham, Power Law (Ostwald), Herschel-Bulkley, Casson, Sisko, Careau, and Cross models were tested by fitting the models with experimental rheological characteristic of mixed sludge under various physico-chemical process conditions. The rheological data from the best fitted Bingham plastic and Sisko models are discussed here.

Ref: Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2015. "Rheological characteristics of mixture of raw primary and thickened excess activated sludge: impact of mixing ratio, solid concentration, temperature and sludge age." Desalination and Water Treatment:1-12. doi: 10.1080/19443994.2015.1115374.

5.1 Introduction

This chapter outlines the research findings on the impact of physico-chemical characteristics such as total solid concentration, mixing ratio, and ageing of sludge on the rheological properties of mixture of raw primary and thickened excess activated sludge (mixed sludge).

The anaerobic digestion and sludge dewatering processes account for 70% of the overall operation cost of wastewater treatment plants and are vital areas where sludge flow analysis should be conducted (Yeneneh 2014, Yeneneh et al. 2015). The feed to anaerobic digestion process, a mixed sludge, is a mixture of raw primary sludge and thickened excess activated sludge. Raw primary sludge comes from the underflow of primary sedimentation tanks and contains solids separated from sewage feed, while thickened excess activated sludge originates from dissolved air floatation thickeners (DAFT) and is generally thickened form of excess activated sludge from the activated sludge treatment process.

Studies show that the complex nature of sludge necessitates intensive investigation to meet the specific needs of understanding the rheological properties and response to changes in different process parameters. Hence, understanding the characteristic of mixture of raw primary and thickened excess activated sludge under various process conditions will provide better knowledge, and will help to produce correct procedure and estimation method (Markis et al. 2014).

Solids existing within fluid is considered as a key factor that contributes to non-Newtonian flow behaviour. According to Einstein's Law of Viscosity shown in equation (5-1), the presence and the solid content within a fluid is the primary reason for the increase in fluid viscosity (Sanin 2002).

$$\eta/\eta_0 = 1 + 2.5\phi \qquad (5\text{-}1)$$

where η is the viscosity of the dispersion, η_0 is the viscosity of the dispersion medium, and φ is the volume fraction occupied by the particle. The effect of solids content on viscosity of sludge has been examined in a great number of studies (Eshtiaghi et al. 2013). It was found that the viscosity of sludge increases with increase of solid content (Tixier et al. 2003, Pevere et al. 2006, Abu-Jdayil 2011). Increasing solids content will lead to stronger inter-particle interactions which is caused by the size increase of particles in suspension, resulting in higher apparent viscosity within the mixed sludge.

Sludge generally behaves like a non-Newtonian and shear thinning material. Hence, proposing an empirical equation to model the effects of total solid concentration on rheological properties is necessary to understand the sludge behaviour (Sanin 2002, Mori et al. 2006). Lotito et al. (1997) confirmed that solid concentration is one of the major parameters that affects sludge rheology and proved that characteristic of sludge is dynamic in nature and one parameter alone is not sufficient to represent its behaviour. Hence, they recommended analysis of multiple parameters for better understanding of flow behaviour.

Baudez (2008) found that the critical shear stress and shear rate increased with solid concentration depending on the fractal dimensions of the floc which implies that thixotropic effects change with sludge age and solid content. The behaviour of sludge gradually changes with time due to change in the composition of key components like protein, lipid and carbohydrate with the age of the sludge due to degradation and synthesis of volatile fatty acids (Baudez 2008). Most of the studies on rheology are limited to activated sludge system, therefore rheological measurement on other types of sludge particularly on mixed digester feed sludge (mixture of raw primary and thickened excess activated sludge that is fed to the anaerobic digester) as a function of different parameters is essential (Lotito et al. 1997, Abu-Jdayil 2011).

According to Markis et al. (2013) researches on raw primary and thickened excess activated sludge are very few, limited, inconsistent, and most literature focus on the changes of rheological properties of activated sludge and digested sludge. Bhattacharya (1981) and Moeller et al. (1997), have conducted work on sludge rheology prior to the anaerobic digester. Although there are interesting results on sludge characteristics and its implications in a wastewater treatment plants, most of the studies are limited to synthetic sludge system, and rheological behaviour depends on complex nature of sludge (Seyssiecq et al. 2003). Furthermore, to the best of our knowledge there are only few published studies on the effect of primary to thickened excess activated sludge mixing ratio on sludge rheological properties, and there are some inconsistencies on the findings and conclusion of these published literature

(Bhattacharya 1981, Moeller et al. 1997, Baudez et al. 2011, Markis et al. 2013). Operating at optimum mixing ratio can enhances flow hydrodynamics, methane production, effluent sludge quality, dewaterability, pathogen removal, and overall plant economy (Yeneneh 2014, Yeneneh et al. 2015). Hence, thorough investigation on the effect of operational parameters like total solid content and primary to thickened excess activated sludge mixing ratios is essential for all different sludge type.

Khalili Garakani et al. (2011) applied seven different rheological models such as power law, Bingham plastic, Herschel-Bulkley, Casson, Sisko, Carreau, and Cross models to investigate the rheological behaviour of non-Newtonian activated sludge. Lau et al. (2015) also reported the application of various rheological models in sludge conditioning and dewaterability. Nevertheless, there are very limited studies on the applicability of such rheological models to analyse the behaviour of mixed sludge that consists of both primary and thickened excess activated sludge. Besides, the choice of rheological model was found to be very subjective and highly dependent on experimental conditions and type of sludge (Eshtiaghi et al. 2013). Hence, this particular study has the objectives of investigating the rheological behaviour of mixed sludge under the influence of temperature, total solid concentration, primary to thickened excess activated sludge mixing ratio, sludge age and applicability of various rheological models and determination of model parameters.

5.2 Material and method

The detailed material and method on rheometry and rheological modelling has been discussed in Chapter 3. The section below details the materials and methods that are specific and unique to mixed sludge (MS) samples.

5.2.1 Collection of sludge and characterization

Mixed sludge sample was collected from the primary gallery of Beenyup WWTP of Water Corporation, W.A., Australia and carried in sealed containers. Mixed sludge was collected from the sampling point before the anaerobic digesters as shown in Fig. 5.1. Mixed sludge is mostly used in anaerobic digesters instead of primary sludge or activated sludge alone to enhance the rate and extent of biodegradation (Chong et al. 2012). As shown in Fig. 4.1 and Fig. 4.2, unmixed raw primary sludge and thickened excess activated sludge samples were also collected in their corresponding sampling point and were used to investigate the effect of mixing ratio and the characteristics of each of these sludge types on mixed sludge rheological properties and the performance of the anaerobic digestion process. Intensive characterization was conducted on each of the collected sludge samples. The detailed methodology used to determine these physico-chemical and biological parameters can be found in Chapter 3. Furthermore, fresh batch of mixed sludge samples were used in all the experimental investigations to prevent changes in the rheological properties, due to the fermentation and other microbial activities. Samples of mixed sludge were stored in a refrigerator at 4˚C and reheated to 42˚C (temperature of sample at collection point) with the Peltier Concentric Cylinder Temperature System for the investigation on effect of sludge age.

Fig. 5.1 Mixed sludge sampling point at Beenyup WWTP

5.3 Results and discussion

5.3.1 Rheological behaviour of RPS, EAS, TEAS and MS

The rheological behaviours of raw primary sludge (RPS), excess activated sludge (EAS), thickened excess activated sludge (TEAS), and mixture of PRS and TEAS (MS) are presented in Fig. 5.2. As mentioned in section 4.3.2, the shear force requirement of TEAS to achieve normal flow is much higher than RPS and EAS which is associated with significant amount of bio-polymeric material in the sludge which exhibits colloidal properties resulting in greater total solid concentration and change in floc structure (Spicer et al. 1996). Mixture of raw primary sludge and thickened excess activated sludge showed intermediate rheological behaviour but with significantly reduced yield stress of 2.9Pa and viscosity of 0.05Pa.s. The reduction in yield stress and viscosity, as shown in Fig. 5.2(a) and Fig. 5.2(b), in the mixed sludge has significant implications on mixing hydrodynamics, mass transfer and power requirement in the anaerobic digester's performance. In addition, mixed sludge rheological property is largely affected by the concentration of thickened excess activated sludge and both show non-Newtonian pseudoplastic (K<1) behaviour while raw primary and excess activated sludge show slightly dilatant behaviour which can be seen in the results for flow index in Table 5.1.

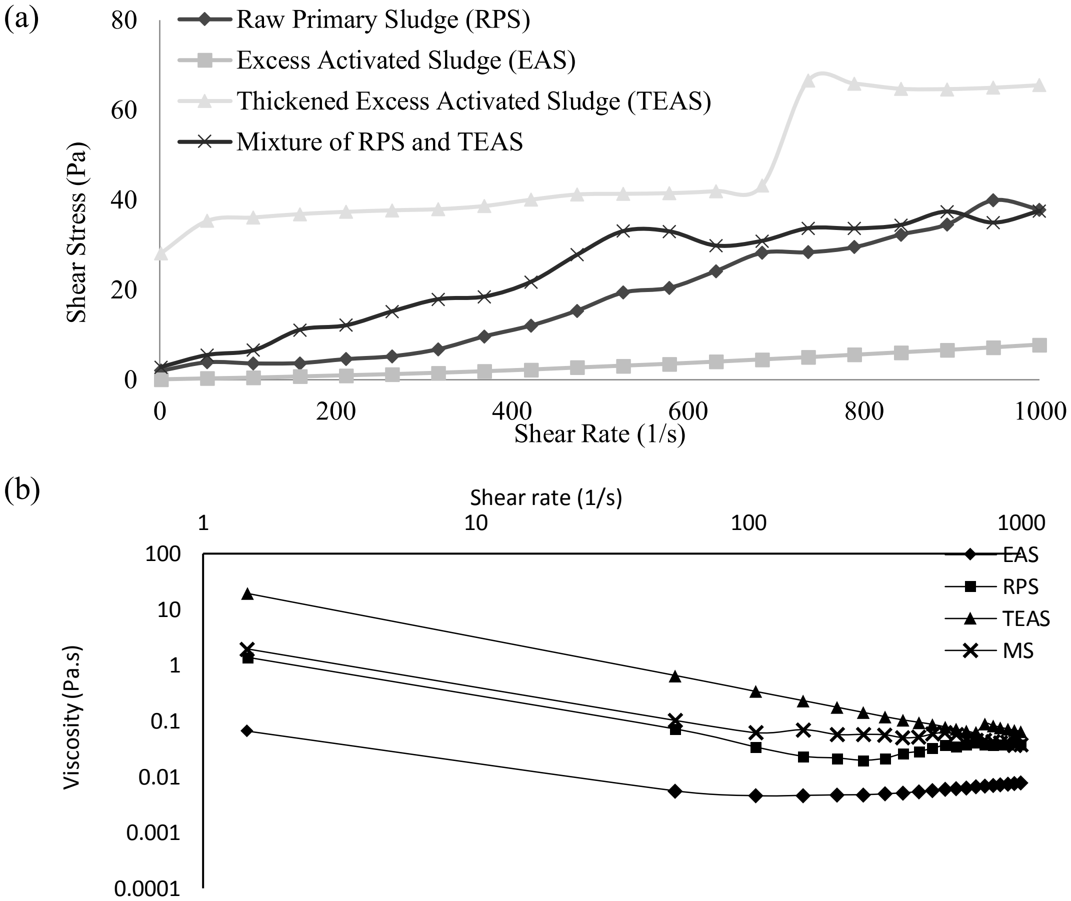

Fig. 5.2 (a) Shear stress-shear rate curves and (b) Viscosity-shear rate curves for different sludge types, EAS: TS=0.8%w/w, T=25°C & pH=7, RPS: TS=2.7%w/w, T=25°C & pH=6, TEAS: TS=3.7%w/w, T=25°C & pH=7, and MS: TS=3.0%w/w, T=25°C & pH=7

Table 5.1 Yield stress, viscosity and flow index based on different rheological models for different sludge types

Sludge Type	Rheological Model	Yield Stress (Pa)	Viscosity (Pa.s)	Flow Index	R^2
Thickened Excess Activated Sludge	Bingham	33	0.02	-	0.82
	Power	-	26.6	0.1	0.94
	Herschel-Bulkley	25.1	3.2	0.3	0.96
Raw Primary Sludge	Bingham	-	0.04	-	0.91
	Power	-	$7.5\text{x}10^{-04}$	1.6	0.97
	Herschel-Bulkley	2.6	$3.5\text{x}10^{-05}$	2.1	0.99
Mixture of RPS and TEAS	Bingham	2.9	0.05	-	0.92
	Power	-	0.18	0.6	0.95
	Herschel-Bulkley	1.9	0.09	0.6	0.95
Excess Activated Sludge	Bingham	0	$6.5\text{x}10^{-03}$	-	0.98
	Power	-	$8.1\text{x}10^{-03}$	1.3	0.99
	Herschel-Bulkley	0.2	$3.4\text{x}10^{-04}$	1.4	0.99

5.3.2 Sludge characterization

The major characteristic properties of each of the mixed sludge samples collected are given in Table 5.2. It can be observed from Table 5.2 that the mixed sludge properties fluctuate from time to time in terms of total solid content, volatile solid content, chemical oxygen demand, pH, and temperature. This justifies the need for the investigation of the effect of these parameters on the overall rheological behaviour of mixed sludge, the anaerobic digestion process and dewatering performance. It appears that total solid content does not change significantly, it remained constant around 28g/L to 30g/L with the average total solid concentration being 28g/L. In addition, the volatile solid content was found to be between 20.3g/L and 26.4g/L with the average being 24.6g/L. While the chemical oxygen demand varied from 28250ppm to 43200ppm.The pH of mixed sludge ranged from 5.6 to 6.4. The temperature of mixed sludge varied from 25˚C to 42˚C due to the ambient weather on sampling day, with the average temperature being at 33˚C.

Table 5.2 Characteristics of mixed sludge samples.

Mixed sludge sample (MS)									Average
Total Solid Content (g/L)	29	30	29	28	27	29	23	30	28
Volatile Solid Content (g/L)	24.7	25.7	26.0	24.7	23.2	25.4	20.3	26.4	24.6
Chemical Oxygen Demand (ppm)	35850	43200	40800	33400	30900	41600	28250	37600	36450
pH	6.4	6.1	5.7	6.0	6.2	6.1	5.6	6.0	6.0
Temperature (˚C)	25	29	28	29	42	42	37	35	33

The characteristics of raw primary sludge, excess activated sludge and thickened excess activated sludge samples are shown in Table 5.3. The total solid content, volatile solid content, chemical oxygen demand, pH and temperature data are also shown for each of these sludge types. The characteristics of various ratios of raw primary to thickened excess activated sludge are shown in Table 5.4.

Table 5.3 Characteristics of raw primary, excess activated and thickened excess activated sludge.

Sludge sample	Raw Primary Sludge (RPS)	Excess Activated Sludge (EAS)	Thickened Excess Activated Sludge (TEAS)
Total Solid Content (g/L)	27	8	37
Volatile Solid Content (g/L)	24.3	6.4	30.4
Chemical Oxygen Demand (ppm)	20 100	1 800	27 500
pH	6	7	7
Temperature (˚C)	24	25	24

Table 5.4 Characteristic of Mixture of Raw Primary and Thickened Excess Activated Sludge for different mixing ratios.

Mixed Ratio (RPS:TEAS)	80:20	70:30	60:40	50:50	40:60	20:80
Total Solid Content (g/L)	29	30	26	28	30	32
Volatile Solid Content (g/L)	25.6	26.4	22.1	24.4	26.0	26.9
pH	6.5	6.5	7	7	7	7
Temperature (˚C)	24	24	24	24	24	24

5.3.3 Effect of total solid concentration on mixed sludge rheology

To study the effects of total solid concentration, samples of mixed sludge were thickened using vacuum filtration technique and diluted by the addition of deionised water to obtain various total solid (TS) concentration (Baroutian et al. 2013, Markis et al. 2013, Lotito et al. 2014, Markis et al. 2014). The effect of total solid concentration was investigated for mixed sludge sample with total solid content of 20g/L, 25g/L and 30g/L. The mixing ratio of raw primary sludge to thickened excess activated sludge in the collected mixed sludge sample was 60%:40% and the temperature during sampling was 25˚C. The rheological behaviour of mixed sludge at different solid concentrations was presented by plotting shear stress-shear rate flow curves shown in Fig. 5.3(a) where shear stress shows an increasing trend with increasing shear rate indicating non-Newtonian pseudo-plastic flow behaviour (Mezger 2006). Such flow behaviour of primary and thickened excess activated sludge was also previously reported by few researchers (Baudez et al. 2001, Baroutian et al. 2013). The experimental data were fitted to various rheological models discussed in Chapter 3. The various fitted model parameters are presented in Table 5.5. The high values of linear correlation coefficient (R^2) indicate the applicability of most rheological models to represent mixed sludge system. However, Bingham model was selected for further analysis due to its practical significance and simplicity (Seyssiecq et al. 2003). The increase in total solid concentration from 20g/L to 30g/L increased the shear stress significantly as shown in Fig. 5.3(a). Markis et al. (2014) also reported similar trends but for a different sludge type. Moreover, viscosity showed some reductions with decreasing solid concentration as shown in Fig. 5.3(b).

The rheology of mixed sludge shows non-Newtonian shear-thinning behaviour with yield stress of 1.1Pa at total solid concentration of 20g/L which increased to 7.4Pa at 30g/L as shown in Table 5.5. An increase of total solid concentration by 33 % resulted in substantial increase of yield stress by 85 % which reflects on the pseudo-plastic flow behaviour and power required during pumping and mixing of sludge. The viscosity on the other hand deceased from 0.021Pa.s for a total solid content of 30g/L to 0.018Pa.s for a total solid content of 20g/L as shown in Table 5.5 while the infinite rate viscosity does not change significantly with increasing total solid concentration as shown in Table 5.6. The increase of total solid concentration has also resulted in increasing non-Newtonian flow behaviour. This is due to larger and denser units of suspension resulting in higher apparent viscosity (Eshtiaghi et al. 2013). Inter-particle interaction also increases with increasing solid concentration (Mori et al. 2006), which is because of stronger network of sludge floc structure with the increase of solid concentration where colloidal and hydrodynamic forces between sludge particles change (Baroutian et al. 2013, Markis et al. 2014).

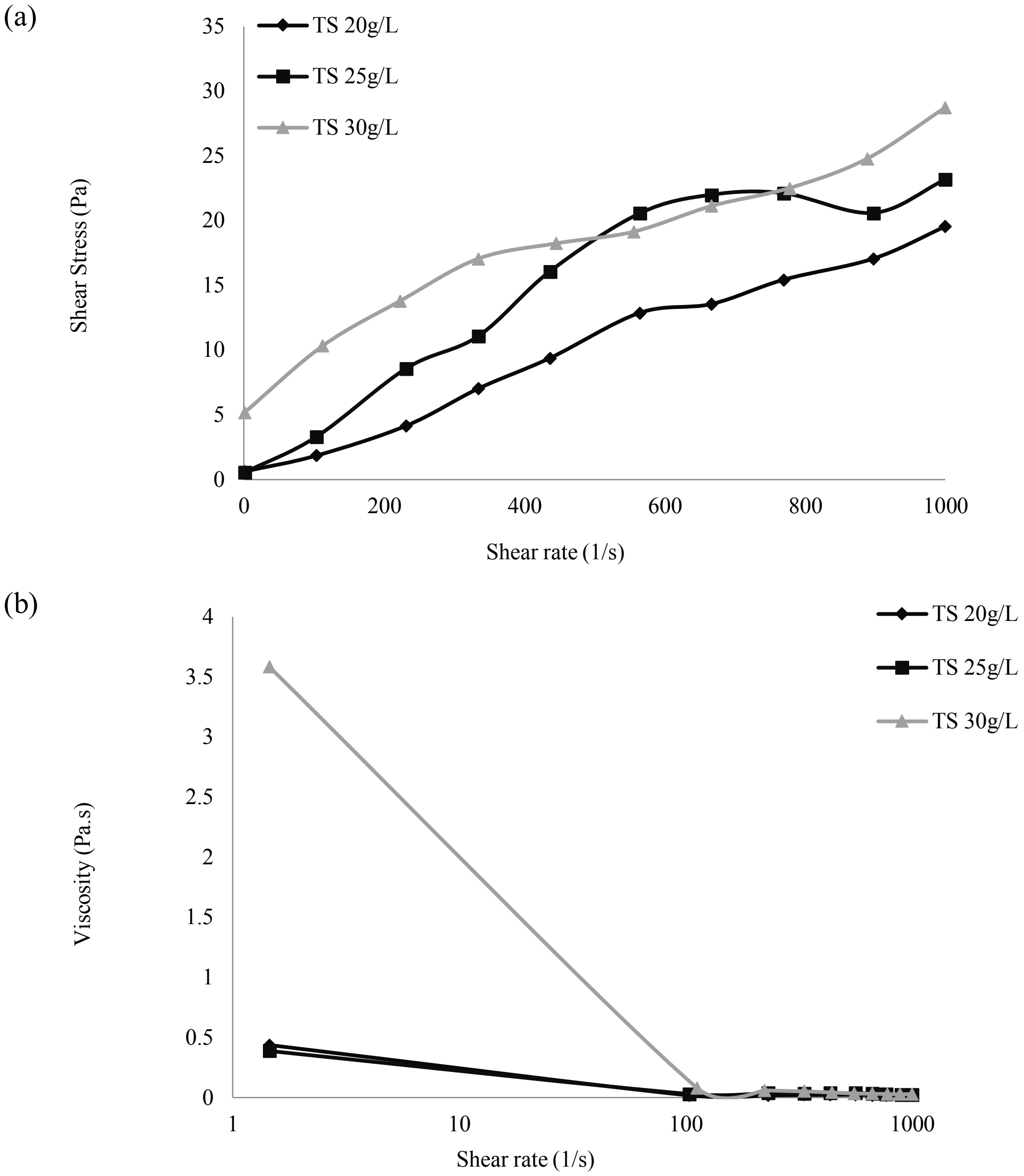

Fig. 5.3 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different solid concentrations of mixed sludge sample

Table 5.5 Yield stress and viscosity of mixed sludge for varying total solid content for various rheological models.

Total solid concentration (g/L)	Rheological model	Yield Stress (Pa)	Viscosity (Pa.s)	Flow Index	R^2
30	Casson	4.6	0.010	-	0.99
	Bingham	7.4	0.021	-	0.98
	Power	-	1.100	0.46	0.94
25	Casson	0.8	0.017	-	0.99
	Bingham	2.1	0.024	-	0.97
	Power	-	0.154	0.73	0.99
20	Casson	0.3	0.015	-	0.98
	Bingham	1.1	0.018	-	0.98
	Power	-	0.061	0.83	0.99

Table 5.6 Infinite-rate viscosity of mixed sludge for varying total solid content based on Sisko model.

Total solid concentration (g/L)	Infinite-rate Viscosity (Pa.s)	Flow Consistency Index (s)	R^2
30	0.02	5.0	0.99
25	-	12.5	0.95
20	0.02	0.9	0.97

5.3.4 Effect of temperature on mixed sludge rheology

The effect of temperature on rheological properties of mixed sludge was studied for temperature conditions of 25°C, 30°C, 35°C, 40°C, and 55°C for a total solid content of 29g/L and a mixing ratio of 60% raw primary sludge to 40% thickened excess activated sludge. The samples were heated by utilizing the Peltier Concentric Cylinder Temperature System which is attached to the Rheometer with a typical temperature heating rate of 10˚C/min (Baroutian et al. 2013). Experimental results show that temperature has a significant effect on the rheological properties of mixed sludge in the temperature range of 35˚C to 55˚C as shown in Fig. 5.4(a) and (b), the rheological properties in the temperature range of 25˚C to 35˚C are not very different from each other. The increase in temperature from 25°C to 35°C showed an increasing trend in yield stress from 6.8Pa to 8.0Pa based on best fitted Bingham model while a decreasing trend from 8.0Pa to 4.5Pa for a temperature range of 40°C to 55°C as shown in Table 5.7. Furthermore, shear stress decreases with increasing temperature as shown in Fig. 5.4(a), the thermal energy resulted in change of the shape and size of flocculated particles, and the degree of dispersion of the soluble organic content of the sludge. These changes directly influenced the rheological properties of the mixed sludge (Sanin 2002). The viscosity, generally showed reduction with increasing temperature and shear rate as shown in Fig. 5.4(b), similar trend was also reported by many authors (Hasar et al. 2004, Eshtiaghi et al. 2013, Farno et al. 2013). The decrease in viscosity with increase in temperature is due to the weakening of inter-molecular cohesive forces which result in the reduction of shear stress and viscosity (Baroutian et al. 2013).

Viscosity reduced from 0.02Pa.s for temperature of 25°C to 0.01Pa.s for a temperature of 55°C for Bingham plastic model when shear force is applied to the system as shown in Table 5.7. As shown in Table 5.8 the viscosity of sludge at different temperatures for higher shear rate range (infinite rate viscosity) is similar to the viscosity determined from the shear stress-rate models. It can be concluded that increase in the temperature of mixed sludge would improve flow behaviour for the temperature range investigated which in turn enhances mixing and mass flow in the anaerobic digesters (Yeneneh 2014, Yeneneh et al. 2015).

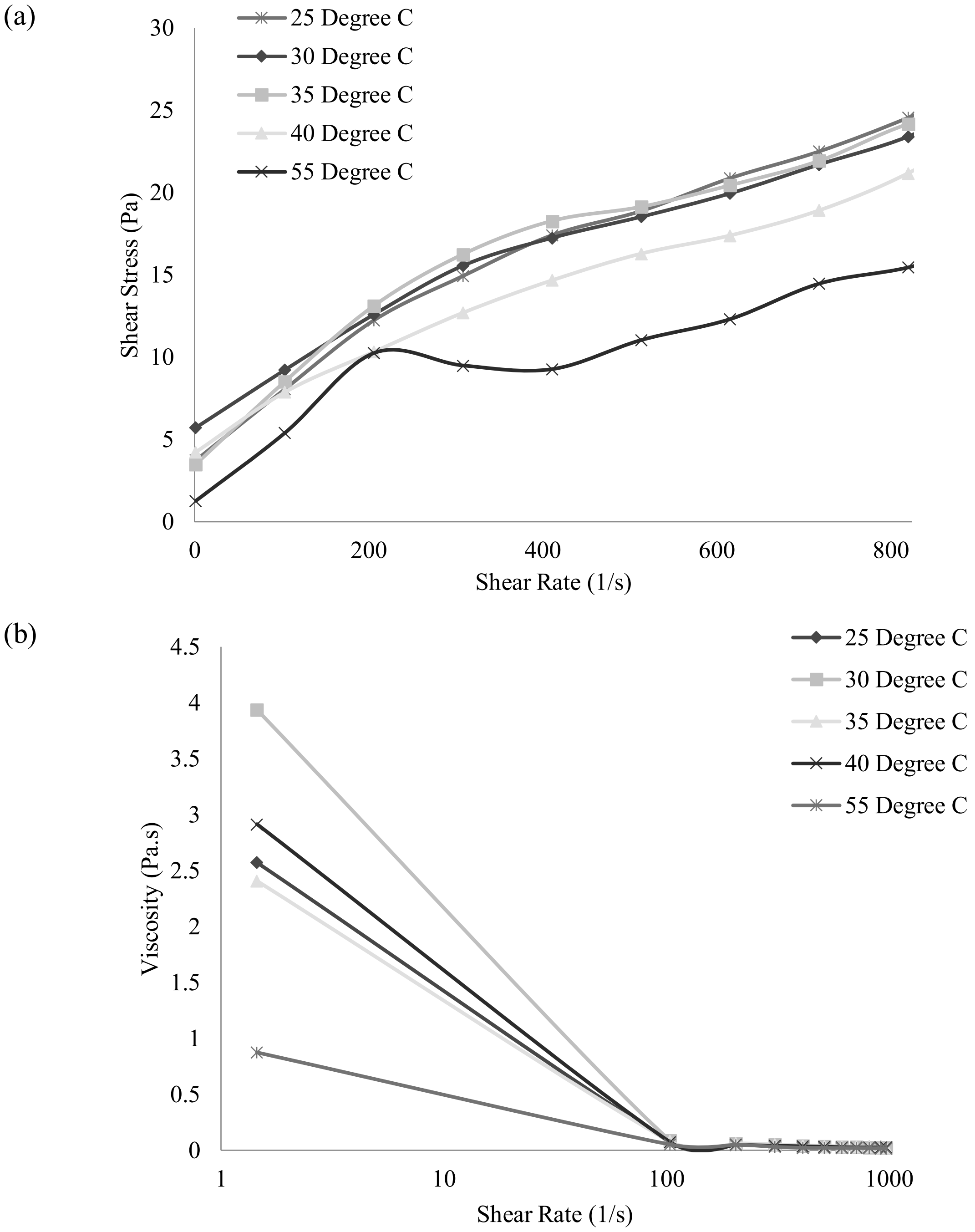

Fig. 5.4 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different temperatures of mixed sludge sample.

Table 5.7 Yield stress and viscosity of mixed sludge for different temperature conditions based on Bingham model.

Temperature (˚C)	Yield Stress (Pa)	Viscosity (Pa.s)	R^2
25	6.8	0.02	0.97
30	7.9	0.02	0.98
35	8	0.02	0.93
40	5.8	0.02	0.98
55	4.5	0.01	0.97

Table 5.8 Zero-rate and infinite-rate viscosity of mixed sludge for varying temperature based on Sisko model.

Temperature (˚C)	Infinite-rate Viscosity (Pa.s)	Flow Consistency Index(s)	Flow Index	R^2
25	0.02	3	0.2	0.99
30	0.02	5	0.1	0.99
35	0.01	3	0.2	0.99
40	0.02	4	0.1	0.99
55	0.01	2	0.2	0.99

5.3.5 Effects of raw primary sludge to thickened excess activated sludge mixing ratio on rheological properties of mixed sludge

The experiments on the effect of sludge mixing ratios were conducted for raw primary sludge: thickened excess activated sludge mixing ratios of 80:20, 70:30, 60:40, 50:50, 40:60, and 20:80 respectively. In the actual industrial operations mixing ratio usually ranges between raw primary sludge: thickened excess activated sludge ratios of 70:30 - 50:50 (Yeneneh 2014, Yeneneh et al. 2015). The mixing ratios investigated for the rheology tests were selected taking the operational conditions into account. The rheological behaviours of different sludge such as raw primary sludge (RPS), excess activated sludge (EAS), thickened excess activated sludge (TEAS), and mixture of PRS and TEAS are presented in Fig. 5.1 (a). As shown in Fig. 5.1 (a) the shear stress-shear rate plot for TEAS shows a shear force requirement that is much higher when compared to the other three types of sludge. This is associated to the presence of significant amount of bio-polymeric material (polysaccharides and proteins) and higher total solid content of thickened excess activated sludge (Baudez et al. 2001, Baudez et al. 2011, Eshtiaghi et al. 2013, Yeneneh et al. 2015). Moreover, the shear stress shows a significant jump from 43.2Pa to 66.6Pa between shear rate ranges of $680s^{-1}$ to $740s^{-1}$. At the experimental temperature condition of 25°C and total solid content of 37g/L, $680s^{-1}$ is the shear rate at which significant change in floc structure of TEAS occurred. The various rheological fitted model parameters are generated from the shear stress-shear rate rheograms are shown in Table 5.1.

Mixture of raw primary sludge and thickened excess activated sludge showed overall rheological behaviour that is partially similar to those of RPS and TEAS, where the yield stress, (2.9Pa) viscosity (0.05Pa.s) and, shear stress-shear rate profiles falls in between those of RPS and TEAS. The reduction in yield stress and viscosity in the mixed digester feed sludge has significant implications on mixing hydrodynamics, mass transfer and power requirement in the anaerobic digester's performance (O'Neil 1985, Wu et al. 2008, Abbassi-Guendouz et al. 2012, Ratkovich et al. 2013).

Raw primary sludge exhibits lower yield stress and un-thickened excess activated sludge directly coming from the activated sludge treatment process has extremely low yield and behaves like a Newtonian fluid as the total solid content is very low. The mixing ratio between raw primary sludge and thickened excess activated sludge is an essential process parameter that affects flow hydrodynamics and the biochemical methane production capacity, digestion kinetics, volatile solid removal, and overall performance of anaerobic digestion process and dewaterability of the digested sludge that comes out of this process (Yeneneh 2014, Yeneneh et al. 2015). Hence, the rheological investigations for different sludge mixing ratios between the two sludge types showed that with increasing percentage of thickened excess activated sludge yield stress and viscosity significantly increased as shown in Fig. 5.5 (a) and (b) respectively. This is also supported by rheological model parameters, which are tabulated in Table 5.9 and Table 5.10 respectively. Yield stress decreased from 10.2Pa to 1.2Pa for Bingham plastic model when the percentage of thickened excess activated sludge was reduced from 80% to 20%. Table 5.10 also shows that the viscosity at higher shear rate consistently decreased from 0.052Pa.s for RPS:TEAS of (20:80 V/V) to 0.027Pa.s for a composition of 80:20 V/V according to Cross models (Björn et al. 2012). Previous studies show that greater percentage of raw primary sludge in the mixed digester feed sludge enhances anaerobic digester performance (Yeneneh 2014, Yeneneh et al. 2015). The findings of this study on the rheological behaviour of different mixing ratios support this finding that greater percentage of raw primary sludge not only favours digester performance but also enhances sludge hydrodynamics and rheology with the significant decrease in yield stress and viscosity.

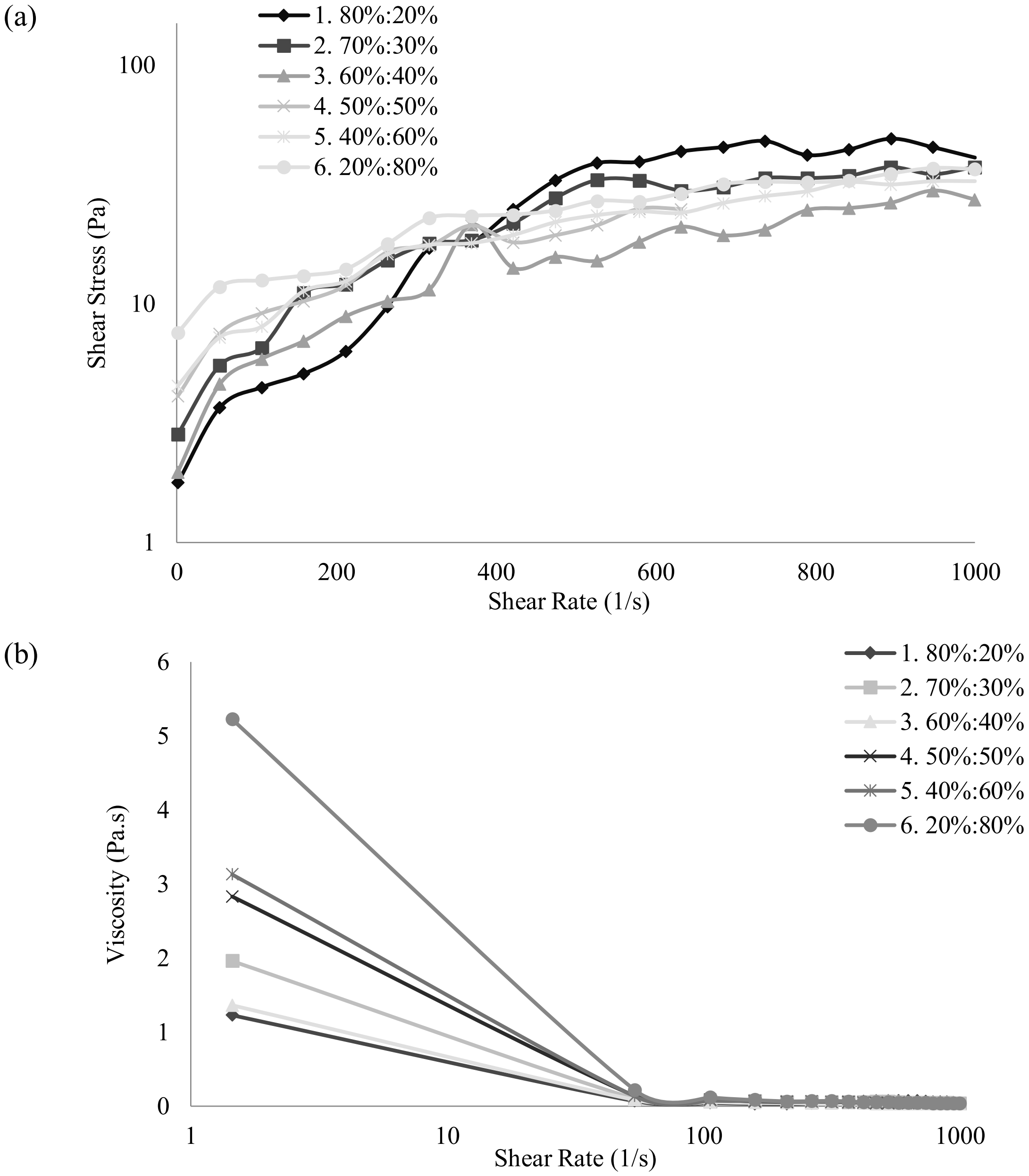

Fig. 5.5 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different mixing ratio of RPS to TEAS.

Table 5.9 Yield stress and viscosity of different raw primary: thickened excess activated sludge mixing ratio based on Bingham model.

#	RPS:TEAS Mixing Ratio	Yield Stress (Pa)	Viscosity (Pa.s)	R^2
1	80%:20%	1.2	0.05	0.88
2	70%:30%	5.9	0.04	0.92
3	60%:40%	3.7	0.03	0.93
4	50%:50%	5.8	0.03	0.94
5	40%:60%	6.8	0.03	0.98
6	20%:80%	10.2	0.03	0.97

Table 5.10 Zero-rate and infinite-rate viscosity of different raw primary: thickened excess activated sludge mixing ratio.

#	RPS:TEAS Mixing Ratio	Infinite-rate Viscosity (Pa.s)	Flow Consistency (s)	Flow Index	R^2
1	80%:20%	0.052	2.33	-	0.88
2	70%:30%	0.040	2.65	0.07	0.98
3	60%:40%	0.024	1.83	0.14	0.98
4	50%:50%	0.029	3.91	0.10	0.99
5	40%:60%	0.028	4.26	0.09	0.99
6	20%:80%	0.027	7.33	0.07	0.99

5.3.6 Effects of sludge age on rheology

The effect of sludge age on the rheological properties of mixed sludge was also investigated. Sludge undergoes chemical and microbiological aging process during storage which resulted in changes of the apparent viscosity and other rheological parameters (Baudez et al. 2001). Hence, investigating the impact of mechanical aging with time on the rheological behaviour is important. The experiments on the effect of low temperature storage time on rheological properties of mixed sludge are shown in Fig. 5.6(a) and (b), where sample MS1, MS2, and MS3 are samples of mixed sludge at different day of storage of day 1, day 15 and day 32 respectively. Table 5.11 shows that total solid and volatile solids content decreased over time. Samples of mixed sludge at an initial total solid content of 29g/L and volatile solid content of 25.4g/L degraded to 25g/L and 21.65g/L respectively after a period of 30 days. It can be seen that the changes within the first 15 days were insignificant, with the total solid reduction of 3.5% while the total volatile solid reduce by 2.0% in the following 15 days due to hydrolysis and organic degradation as shown in Table 5.11. The results showed that within a period of a month, the yield stress has decreased from 5.8Pa to 4.9Pa, as shown in Table 5.12 for Bingham plastic model, which is caused by slow hydrolysis of extra cellular polymeric substances, deflocculation and degradation of organic matrix (Baudez et al. 2001). Similar trend was observed in viscosity tests, as days of storage progress, the viscosity of the mixed sludge decreased from a value of approximately 0.02Pa.s to 0.016Pa.s for Bingham plastic model as shown in Table 5.12. The flow index shown in Table 5.13 supports the non-Newtonian flow behaviour which generally decreases with increasing storage time.

It can be concluded that mixed sludge samples degrade during storage and the rheological properties change significantly with time. All the sludge samples according to shear stress-rate curves in Fig. 5.6(a) show Bingham pseudo-plastic shear thinning behaviour up until shear rate of 600s-1 and this trend is reverted with further increase in shear rate until 1 000s-1. Fig. 5.6(a) and Table 5.12 show that the yield stress and viscosity showed an increasing trend during storage in the first 15 days and later decreased after 30 days of storage. Fig. 5.6(b) and Table 5.13 show that the viscosity at higher shear rate shows a decreasing behaviour with the increase in storage time. Generally, the biodegradation of organics enhances the shear thinning behaviour; yield stress and viscosity reduce gradually over time which is because of the change in composition of key components like protein, lipid and carbohydrate with the age of the sludge and due to synthesis of volatile fatty acids (Baudez 2008). This implies that in the course of the anaerobic digestion process the viscosity of mixed sludge significantly decreases with time favouring better mass transfer and mixing.

Table 5.11 Effects of mixed sludge age on total solid and volatile solid content.

Mixed sludge (MS)	MS1	MS2	MS3
Day	1	15	32
Total Solid Content (g/L)	29	28	25
Volatile Solid Content (g/L)	25.4	24.9	21.65

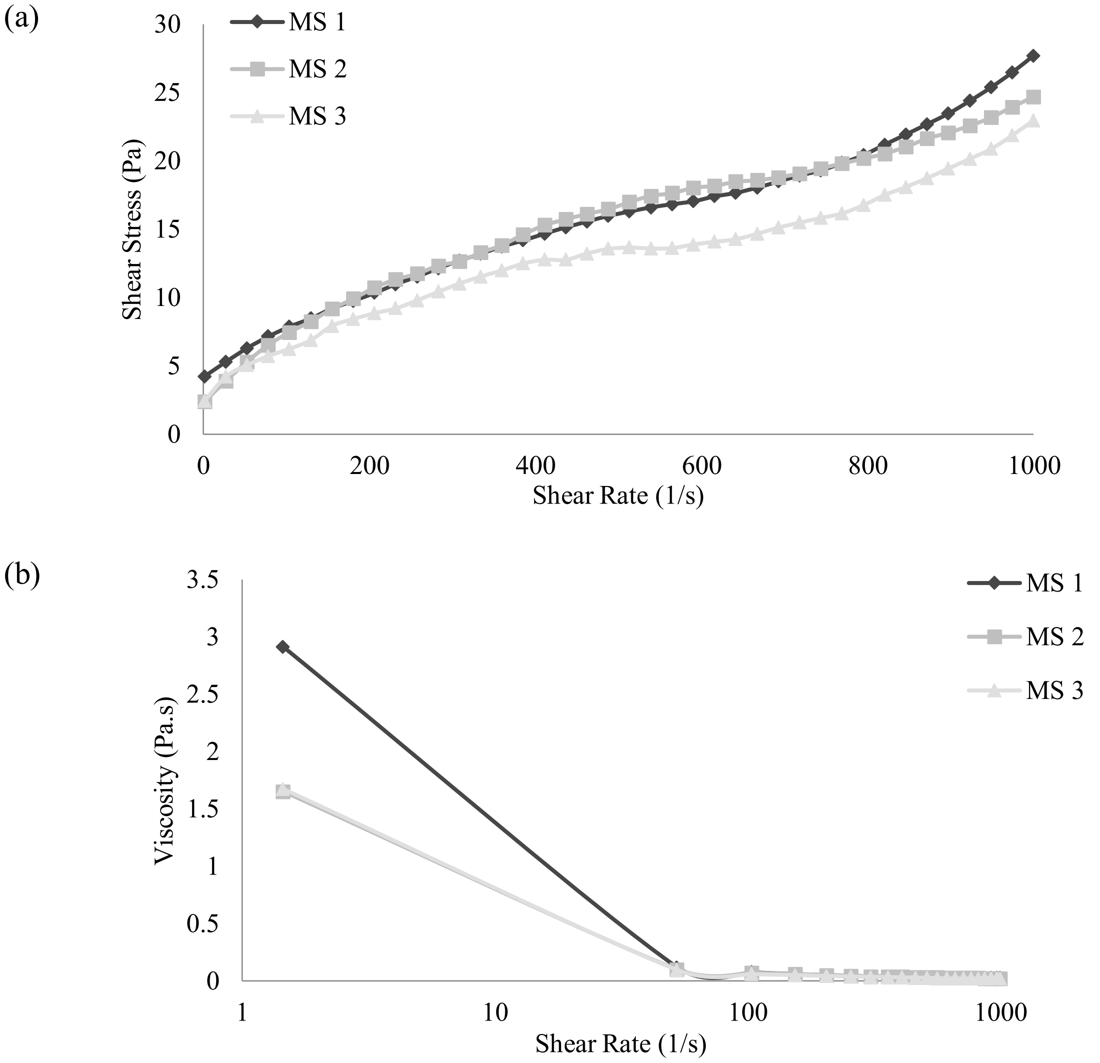

Fig. 5.6 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for mixed sludge at various aging stage.

Table 5.12 Yield stress and viscosity of mixed sludge for different sludge age based on Bingham model.

RPS:TEAS Mixing Ratio	Yield Stress (Pa)	Viscosity (Pa.s)	R^2
MS1	5.8	0.020	0.98
MS2	6.1	0.019	0.96
MS3	4.9	0.016	0.96

Table 5.13 Zero-rate and infinite-rate viscosity of mixed sludge age based on Sisko model.

RPS:TEAS Mixing Ratio	Infinite-rate Viscosity (Pa.s)	Flow Consistency (s)	Flow Index	R^2
MS1	0.02	3.9	0.1	0.99
MS2	0.01	1.9	0.3	0.99
MS3	0.01	2.2	0.2	0.99

5.4 Conclusion

The rheological behaviour of mixed sludge was observed to be affected by several physico-chemical factors including total solid concentration, temperature, raw primary sludge to thickened excess activated sludge mixing ratio and sludge age. The decrease in total solid concentration for mixed sludge from 30g/L to 20g/L resulted in the reduction of yield stress by 85.4% proving the impact of suspended solids interacting together on the power required to disrupt the network and overcome the yield stress. In this study, it was also found that yield stress decreased from 6.8Pa to 4.5Pa and viscosity decreased from 0.022Pa.s to 0.013Pa.s when temperature was increased from 25˚C to 55˚C.

Similar to the findings of other researchers the effect of temperature on shear stress and viscosity of mixed sludge in the temperature range of 25˚C to 35˚C was limited compared to the effect at higher temperatures of 40˚C and 55˚C where significant reduction in yield stress and viscosity was observed. The rheological investigations for different mixing ratios between raw primary sludge and thickened excess activated sludge show that with decreasing percentage of thickened excess activated sludge, from 80% to 20%, yield stress decreased from 10.2Pa to 1.2Pa. Hence, greater percentage of raw primary sludge in mixed digester feed sludge not only favours digester performance but also enhances sludge hydrodynamics and rheology with the significant decrease in yield stress and viscosity.

Furthermore, based on the investigation of anaerobic aging over a period of a month, it can be concluded that, although samples are stored under refrigerated condition under 5˚C the rheological behaviour changed gradually due to limited hydrolysis and release of extracellular polymeric substances and organic degradation as the storage time progresses and further investigation is required to better understand ageing of mixed sludge.

Reference

[1] Abbassi-Guendouz, Amel, Doris Brockmann, Eric Trably, Claire Dumas, Jean-Philippe Delgenès, Jean-Philippe Steyer, and Renaud Escudié. 2012. "Total solids content drives high solid anaerobic digestion via mass transfer limitation." *Bioresource Technology* no. 111:55-61. doi: http://dx.doi.org/10.1016/j.biortech.2012.01.174.

[2] Abu-Jdayil, Basim. 2011. "Rheology of sodium and calcium bentonite–water dispersions: Effect of electrolytes and aging time." *International Journal of Mineral Processing* no. 98 (3–4):208-213. doi: http://dx.doi.org/10.1016/j.minpro.2011.01.001.

[3] Baroutian, Saeid, Nicky Eshtiaghi, and Daniel J. Gapes. 2013. "Rheology of a primary and secondary sewage sludge mixture: Dependency on temperature and solid concentration." *Bioresource Technology* no. 140 (0):227-233. doi: http://dx.doi.org/10.1016/j.biortech.2013.04.114.

[4] Baudez, J. C., F. Markis, N. Eshtiaghi, and P. Slatter. 2011. "The rheological behaviour of anaerobic digested sludge." *Water Research* no. 45 (17):5675-5680. doi: http://dx.doi.org/10.1016/j.watres.2011.08.035.

[5] Baudez, Jean-Christophe. 2008. "Physical aging and thixotropy in sludge rheology." *Applied Rheology* no. 18:1123-1139.

[6] Baudez, Jean-Christophe, and Philippe Coussot. 2001. "Rheology of aging, concentrated, polymeric suspensions: Application to pasty sewage sludges." *Journal of Rheology* no. 45 (5):1123-1140. doi: 10.1122/1.1392298.

[7] Bhattacharya, SN. 1981. "Flow characteristics of primary and digested sewage sludge." *Rheologica Acta* no. 20 (3):288-298.

[8] Björn, Annika, Anna Karlsson, Bo H Svensson, Jörgen Ejlertsson, and Paula Segura de La Monja. 2012. *Rheological characterization*. Edited by Sunil Kumar, *Biogas*. Rijeka, Croatia: InTech.

[9] Chong, Siewhui, Tushar Kanti Sen, Ahmet Kayaalp, and Ha Ming Ang. 2012. "The performance enhancements of upflow anaerobic sludge blanket (UASB) reactors for domestic sludge treatment–A State-of-the-art review." *Water research* no. 46 (11):3434-3470.

[10] Eshtiaghi, Nicky, Flora Markis, Shao Dong Yap, Jean-Christophe Baudez, and Paul Slatter. 2013. "Rheological characterisation of municipal sludge: A review." *Water Research* no. 47 (15):5493-5510. doi: http://dx.doi.org/10.1016/j.watres.2013.07.001.

[11] Farno, Ehsan, Rajarathinam Parthasarathy, Jean Christophe Baudez, and Nicky Eshtiaghi. 2013. Effect of Thermal History on Municipal Digested Sludge Rheology: Experimental and Modeling. In *Chemeca 2013*.

[12] Hasar, Halil, Cumali Kinaci, Ayhan Ünlü, Hasan Toğrul, and Ubeyde Ipek. 2004. "Rheological properties of activated sludge in a sMBR." *Biochemical Engineering Journal* no. 20 (1):1-6. doi: http://dx.doi.org/10.1016/j.bej.2004.02.011.

[13] Khalili Garakani, A. H., N. Mostoufi, F. Sadeghi, M. Hosseinzadeh, H. Fatourechi, M. H. Sarrafzadeh, and M. R. Mehrnia. 2011. "Comparison Between Different Models for Rheological Characterization of Activated Sludge." *Iranian Journal of Environmental Health Science & Engineering* no. 8 (3):255-264.

[14] Lau, Shiew Wei, Tushar Sen, Han Bing Chua, and Ming Ang Ha. 2015. "Conditioning Aids and Their Applications for Sludge Dewatering." In *Physical, Chemical and Biological Treatment Processes for Water and Wastewater*, edited by Tushar Sen. USA: Nova Publishers.

[15] Lotito, V., L. Spinosa, G. Mininni, and R. Antonacci. 1997. "The rheology of sewage sludge at different steps of treatment." *Water Science and Technology* no. 36 (11):79-85. doi: http://dx.doi.org/10.1016/S0273-1223(97)00672-0.

[16] Lotito, Vincenzo, and Adriana Maria Lotito. 2014. "Rheological measurements on different types of sewage sludge for pumping design." *Journal of Environmental Management* no. 137 (0):189-196. doi: http://dx.doi.org/10.1016/j.jenvman.2014.02.005.

[17] Markis, Flora, Jean-Christophe Baudez, Rajarathinam Parthasarathy, Paul Slatter, and Nicky Eshtiaghi. 2014. "Rheological characterisation of primary and secondary sludge: Impact of solids concentration." *Chemical Engineering Journal* no. 253 (0):526-537. doi: http://dx.doi.org/10.1016/j.cej.2014.05.085.

[18] Markis, Flora, Kevin Hii, Rajarathinam Parthasarathy, Jean-Christophe Baudez, Paul Slatter, and Nicky Eshtiaghi. 2013. Rheological Characterisation of blends of Primary and Secondary Sludge. In *Chemeca 2013*.

[19] Mezger, T.G. 2006. *The Rheology Handbook: For Users of Rotational and Oscillatory Rheometers*. Edited by 2nd. Hannover, Germany Vincentz Network GmbH & Co KG.

[20] Moeller, Gabriela, and Luis Gilberto Torres. 1997. "Rheological characterization of primary and secondary sludges treated by both aerobic and anaerobic digestion." *Bioresource Technology* no. 61 (3):207-211. doi: http://dx.doi.org/10.1016/S0960-8524(97)00061-8.

[21] Mori, M., I. Seyssiecq, and N. Roche. 2006. "Rheological measurements of sewage sludge for various solids concentrations and geometry." *Process Biochemistry* no. 41 (7):1656-1662. doi: http://dx.doi.org/10.1016/j.procbio.2006.03.021.

[22] O'Neil, Daniel J. 1985. "Rheology and mass/heat transfer aspects of anaerobic reactor design." *Biomass* no. 8 (3):205-216. doi: http://dx.doi.org/10.1016/0144-4565(85)90048-4.

[23] Pevere, A., G. Guibaud, E. van Hullebusch, P. Lens, and M. Baudu. 2006. "Viscosity evolution of anaerobic granular sludge." *Biochemical Engineering Journal* no. 27 (3):315-322. doi: http://dx.doi.org/10.1016/j.bej.2005.08.008.

[24] Ratkovich, N., W. Horn, F. P. Helmus, S. Rosenberger, W. Naessens, I. Nopens, and T. R. Bentzen. 2013. "Activated sludge rheology: A critical review on data collection and modelling." *Water Research* no. 47 (2):463-482. doi: http://dx.doi.org/10.1016/j.watres.2012.11.021.

[25] Sanin, F. Dilek. 2002. "Effect of solution physical chemistry on the rheological properties of activated sludge." *Water SA* no. 28 (2):207-212.

[26] Seyssiecq, Isabelle, Jean-Henry Ferrasse, and Nicolas Roche. 2003. "State-of-the-art: rheological characterisation of wastewater treatment sludge."

Biochemical Engineering Journal no. 16 (1):41-56. doi: http://dx.doi.org/10.1016/S1369-703X(03)00021-4.

[27] Tixier, N., G. Guibaud, and M. Baudu. 2003. "Determination of some rheological parameters for the characterization of activated sludge." *Bioresource Technology* no. 90 (2):215-220. doi: http://dx.doi.org/10.1016/S0960-8524(03)00109-3.

[28] Wu, Binxin, and Shulin Chen. 2008. "CFD simulation of non-Newtonian fluid flow in anaerobic digesters." *Biotechnology and Bioengineering* no. 99 (3):700-711. doi: 10.1002/bit.21613.

[29] Yeneneh, Anteneh Mesfin. 2014. *Study on performance enhancement of anaerobic digestion of municipal sewage sludge*. PhD Thesis, Chemical Engineering Department, Curtin University, Perth, Australia.

[30] Yeneneh, Anteneh Mesfin, Ahmet Kayaalp, Tushar Kanti Sen, and Ha Ming Ang. 2015. "Effect of Combined Microwave-Ultrasonic Pretreatment of Real Mixed Sludge on the Enhancement of Anaerobic Digester Performance." *Water, Air, & Soil Pollution* no. 226 (9):1-14. doi: 10.1007/s11270-015-2586-0.

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CHAPTER 6

RHEOLOGICAL AND PHYSICO-CHEMICAL CHARACTERISTIC OF DIGESTED SLUDGE, BIOSOLID AND CENTRATE

Abstract

This chapter aims at investigating the impacts of total solid concentration, temperature and polymer dose on the rheological characteristics and the dewaterability of digested sludge. The relationship between the rheological and other physico-chemical characteristics of digested sludge, centrate, and biosolid were also investigated. The shear stress-shear rate and viscosity-shear rate curves were then developed before and after polymer conditioning at various temperatures and solid concentrations. Different rheological models were fitted to the shear stress-shear rate and viscosity-shear rate rheograms. The model with the best fitting and more practical significance was selected to determine key rheological parameters. The relationship between dewaterability and digested sludge rheology was also developed. The rheological characteristics of digested sludge during polymer conditioning and flocculation process was significantly affected by temperature and solid concentration; hence, polymer dose can be reduced by operating the dewatering process at optimum temperature condition and varying the poly dose as a function of the total solid concentration and viscosity of the digested sludge. The dewaterability as measured in CST improved with increasing polymer dose up to 12kg/t DS but further increase in polymer dose resulted in the deterioration of the dewaterability due to overdosing. Moreover, it was also observed that volatile solid content and chemical oxygen demand (COD) of digested sludge and centrate showed an inverse relationship with biosolid capture rate. Rheological parameters of digested sludge and centrate, such as yield stress and viscosity, were observed to change proportionally with total solid concentration, volatile solid content, and COD. Furthermore, dilution of digested sludge or polymer by reclaimed effluent from the wastewater treatment plant was observed to reduce polymer consumption. In brief, polymer dose monitoring and optimizing dose can be conducted by using rheological model parameters, total solid concentration and volatile solid concentration.

Ref: Yeneneh, Anteneh Mesfin, Eugene Hong, Tushar Kanti Sen, Ahmet Kayaalp, and Ha Ming Ang. 2016. "Effects of Temperature, Polymer Dose, and Solid Concentration on the Rheological Characteristics and Dewaterability of Digested Sludge of Wastewater Treatment Plant (WWTP)." Water, Air, & Soil Pollution no.227 (4):1-14

6.1 Introduction

This chapter outlines the research findings on the impact of physico-chemical characteristics such as total solid concentration, temperature and polymer dose of on the rheological characteristics and the dewaterability of digested sludge (DS) centrate, and biosolid and their relationship between each other. The rheological characteristics of digested sludge depend on many factors such as source, solid concentration, temperature, and sludge treatment method (Abu-Jdayil et al. 2010, Ratkovich et al. 2013, Hong et al. 2016a, b). Total solid concentration is one of the major factors that affect the rheology and flow behaviour of digested sludge. Baroutian et al. (2013) and Farno et al. (2013) investigated the effect of total solid concentration on sludge rheology and observed that yield stress of digested sludge is directly related to the total solid content of the system. The increase in shear stress with solid concentration was observed to be more noticeable at higher shear rates. The existence of solids within the fluid is responsible for the shear-thinning flow behaviour. The existence of solids within a fluid is the major reason for the increase in the fluid viscosity (Sanin 2002). Sludge characteristic curve for low solid concentrations differs from that for high solid concentration where there is a strong interaction between solid particles. The apparent viscosity of sludge reflects the internal and external interactions and forces occurring within sludge flocs and fluid (Yang et al. 2009). Forster (1981) showed an exponential relationship between total solid concentration and yield stress. Besides, rheological properties of digested sludge are known to mainly depend on the organic fraction and duration of the anaerobic biochemical degradation. By extracting the main solids components (minerals, proteins, lipids, carbohydrates) it was shown that the rheological behaviour is governed by the synthesis of volatile fatty acids (Baudez et al. 2001).

Temperature is another factor that influences the rheological properties of digested sludge. Thermal energy results in a change of the shape and size of flocculated particles, and the degree of dispersion of the soluble organic content of sludge. These changes directly influence the rheological properties of digested sludge during dewatering (Sanin 2002). Viscosity generally lowers with higher temperature and shear rate, a similar trend was reported by many researchers (Hasar et al. 2004, Eshtiaghi et al. 2013, Farno et al. 2013, Yeneneh 2014, Hong et al. 2016a, b).

Polymer dose is another very important parameter that significantly affects the rheology, the dewaterability of digested sludge and the operational cost of the dewatering unit. Campbell et al. (1983) observed the relationship between digested sludge conditioning for varying polymer dose with yield stress and overall rheological property of the sludge. Campbell et al. (1983) showed that the initial yield stress of sludge increased with increasing polymer dose. They also identified the critical point in the rheograms where the curve profile changes indicating point of optimum dose. The initial yield stress peak is associated to the elastic floc network that the polymer creates due to its bridging effect; it is at this yield point where this network also ruptures. The increase in viscosity with increasing polymer dose is also associated to the bridging effect of the conditioning polymer (Abu-Orf et al. 1999). Besides, rheological investigations for varying polymer dose provides more reliable results compared to characterization and dewaterability test on the digested sludge (Örmeci 2007). Yet, there are limited number of studies on the effects of polymer dose, other process parameters including temperature and solid concentration on digested sludge rheology, and on the role of rheological investigations to optimize polymer dose, dewaterability of digested sludge, and lower operating cost by avoiding excessive use of polymer.

Hence, this study focuses on investigating the influence of variation in polymer dose, temperature and total solid concentration on the rheological properties of digested sludge and its dewaterability. Besides, optimum polymer dose for better dewaterability was determined and the relationship between total solid content, temperature and polymer dose versus the rheological and physico-chemical characteristics of digested sludge were developed. The rheological models that best represents the rheological behaviour of digested sludge for varying temperature, total solid concentration and polymer dose conditions were selected.

6.2 Material and Method

The detailed material and method on rheometry and rheological modelling has been discussed in Chapter 3. The section below details the materials and methods that are specific and unique to digested sludge (DS) samples.

6.2.1 Collection of sludge and characterization

In this study, digested sludge, centrate and biosolid samples were collected from the dewatering centrifuges and the polymer samples were collected from the polymer mixing tank at Beenyup Wastewater Treatment Plant (BWWTP), Perth, Western Australia. The collected samples were used for rheological investigation on the same day to prevent the change in the rheological properties of the sludge samples except for the study on sludge age. All samples were refrigerated at 4˚C after use.

Intensive characterization was conducted on the collected digested sludge samples. The detailed methodology used to determine these physico-chemical and biological parameters can be found in Chapter 3.

6.2.2 Rheological investigations on digested sludge, centrate and biosolid

In this work, the rheological behaviour of digested sludge and the corresponding centrate and biosolid produced during the dewatering process were investigated. Rheogram (shear stress-rate and viscosity-shear rate) were generated with the use of a rheometer described in Chapter 3. The temperature of samples were homogenised in the rheometer before each set of experiment. Five equilibrium points were used to plot a single data point within the shear stress-rate and viscosity-shear rate curves, producing replicable and consistent. The plots were assessed by fitting the rheological curves to different rheological models. For this study, Herschel-Bulkley, Sisko, Bingham, Cross, Ostwald, and Careau model were used to find most suitable model for digested sludge and the corresponding centrate and biosolid (Mori et al. 2006, Khalili Garakani et al. 2011, Ratkovich et al. 2013). The models that best describe the overall rheological properties such as yield stress, viscosity and flow and more practical significance were then selected for further rheological analysis (Hong et al. 2016a, b, Yeneneh et al. 2016).

6.3 Results and Discussion

6.3.1 Sludge characterization

The total solid concentration, volatile solid concentration, pH, temperature and total chemical oxygen demand were determined for all collected samples as shown in Table 6.1. The total solid and volatile solid concentrations of the digested sludge samples varied from 1.6 – 2.0% and 74 - 82% respectively, depending on the composition of the feed and performance of the anaerobic digesters. The temperature of the digested sludge samples was about 31˚C on average but it fluctuated between 28 - 37˚C based on the temperature of the ambient environment and the operational temperature of the anaerobic digesters. The pH of digested sludge was mostly constant with average value of 7 over the period the investigation was conducted. Generally, the pH varied in the range of 6.9 - 7.3. The chemical oxygen demand for the digested sludge samples fluctuated in the range of 17400 - 25500 mg/L based on the performance of the anaerobic digesters. The polymer dose and its characteristics were maintained constant in the operation of Beenyup WWTP, despite the changes in the composition and characteristics of the digested sludge.

Table 6.1 Characterization of digested sludge samples collected at different days

Digested sludge Sample	Temperature (˚C)	pH	Total Solid Content (%)	Total Volatile Solids Content (%)	Chemical Oxygen Demand (mg/L)
S1	30	6.9	1.7	74.0	8800
S2	28	7.1	2.0	81.3	25500
S3	30	6.9	1.7	79.3	21300
S4	33	7	1.9	79.4	17400
S5	37	7.1	1.6	82.3	26555
S6	37	6.9	1.6	74.6	9740
S7	20	7.3	1.3	82.8	27640
Average	**30.7**	**7.0**	**1.7**	**79.1**	**18250**

In addition, the corresponding characteristics of centrate and biosolid were also collected. The total solid concentration, volatile solid concentration, total dissolved solid concentration, pH, temperature, conductivity and TCOD for all collected samples are presented in Table 6.2. The total solid concentrations of centrate and biosolid samples varied from 0.2–0.6% w/w and 17.3–23.2% w/w respectively. The temperature of centrate and biosolid samples fluctuated between 29–37˚C and 30–39˚C respectively. The pH of all sample types were often constant (average of 7.0) over the period of the investigation. The COD for centrate samples fluctuated in the range of 140–4500mg/L. The performance of the anaerobic digesters and the varying organic content of the feed are the reasons behind the variation in COD value (Yeneneh 2014, Yeneneh et al. 2015). Based on the intensive investigation conducted over a period of 45 days on the physiochemical and rheological characteristics of digested sludge, centrate, biosolid and polymer samples, different correlations of practical importance were developed.

Table 6.2 Characteristics of digested sludge, centrate and biosolid of Beenyup wastewater treatment plant, WA

Characteristic parameters	**Digested Sludge**	**Centrate**	**Biosolid**
Temperature (˚C)	28–37	29–37	30–39
pH	6.9–7.1	7.1–7.2	7.1–7.2
Conductivity (mS cm^{-1})	5.8–6.55	5.53–6.51	-
Total Dissolved Solids (ppm)	0.4–0.5	0.4–0.5	-
Total Solid (% w/w)	1.6–2.0	0.2–0.6	17.3–23.2
Volatile Solids (% w/w)	1.2–1.6	0.1–0.5	14.3–20.0
Total Chemical Oxygen Demand (mg/L)	8800–25500	140–4500	-

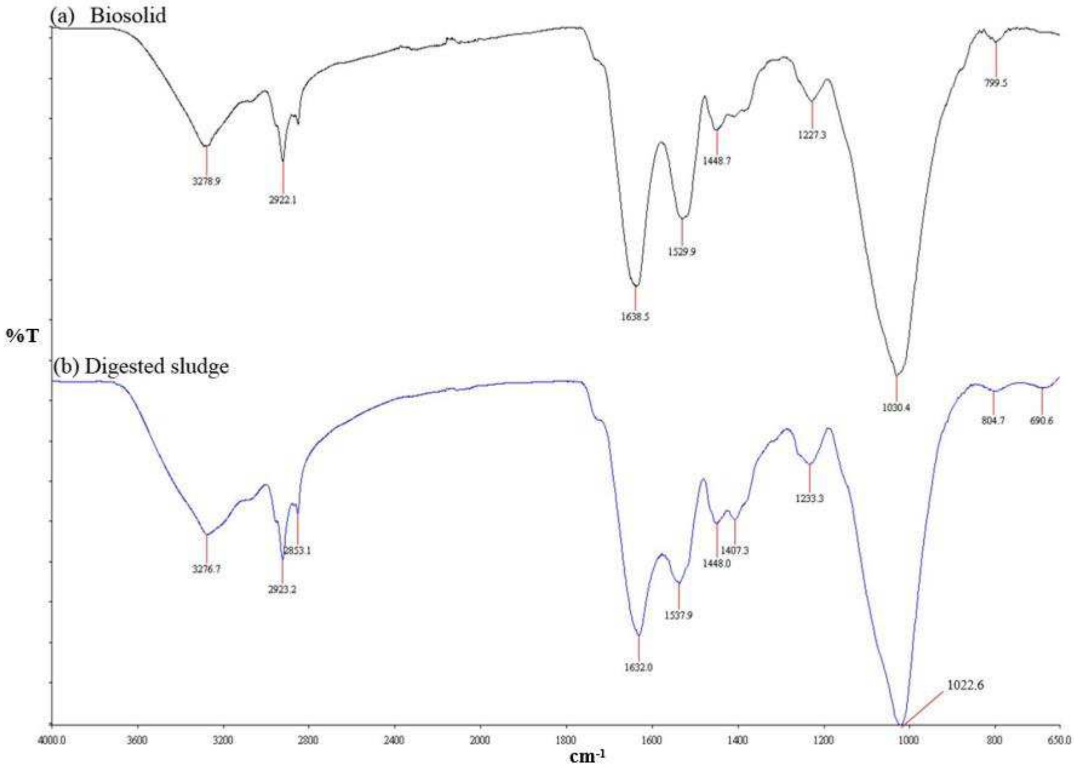


Fig. 6.1 FTIR spectra of typical biosolid and digested sludge sample from BWWTP

Fourier-transform infrared spectroscopy (FTIR) plots were also generated to understand the chemistry and flocculation behaviour of the digested sludge and its interaction with the conditioning polymer. Fig. 6.1 shows the FTIR spectra for digested sludge and biosolid sample. FTIR bands around 1100–1000cm^{-1} show the presence of polysaccharides. Bands around 2925–2950cm^{-1} represent the decomposed fatty acids and lipid groups, bands of amide I, II, III around 1630–1650cm^{-1} are due to proteins and amino acids. Bands of carbonyl groups and hydroxyl groups around 2920–2950cm^{-1} and 3600–3200cm^{-1} respectively represent proteins, carboxylic acids, phenols and water (Lay et al. 1999, Show et al. 2007, Yeneneh 2014). The polysaccharides, amino acids and proteins represented by the peaks significantly affect the dewaterability of digested sludge (Neyens et al. 2004, Yin et al. 2004, Raszka et al. 2006, Yeneneh et al. 2016). The contribution of the organic components of the digested sludge on biosolid capture rate was also investigated in this work.

6.3.2 Beenyup polymer characterization

The conditioning polymer sample collected from the primary polymer concentrate dilution tank was also characterized. The characteristics shown in Table 6.3 indicate that the total solid content was 0.4%w/w. The pH was neutral in all the collected samples with an average value of 7.2. The FTIR spectra, as shown in Fig. 6.2, generated for moisture free dried polymer sample shows that the polymer constitutes an array of organic functional groups including OH^- (3600 cm^{-1}), stretching N-H and C-H group (2800 - 2900 cm^{-1}), $COOH^-$, C=O, P=O. The functional groups play important role in forming the network between the digested sludge particles enhancing flocculation and further separation of the biosolid from centrate (Yin et al. 2004).

Table 6.3 Characteristics of the conditioning polymer used in the study

Polymer Sample	**pH**	**Total Solid Content (%w/w)**
EMA	**7.2**	**0.4**

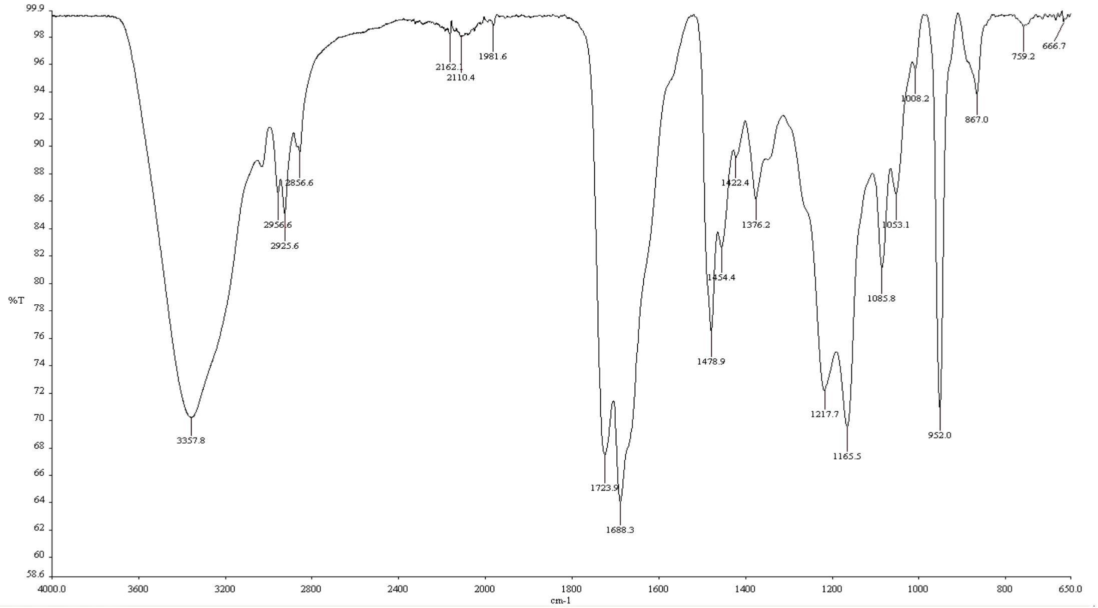


Fig. 6.2 FTIR spectra of the conditioning polymer

6.3.3 Rheological dynamics of Beenyup WWTP digested sludge

Digested sludge samples collected from the centrifuge of Beenyup WWTP were homogenised and used for rheological investigation on the same day of collection. The temperature during the rheological tests was adjusted to the temperature of the samples upon collection. The shear stress-shear rate and viscosity-shear rate curves of all the digested sludge samples were later generated as shown in Fig. 6.3(a) and Fig. 6.3(b). It can be observed that the effect of total solid concentration on the rheological behaviour of digested sludge is more significant than the effect of temperature or volatile solid concentration. This is because of stronger inter-particle interactions which is caused by the increase in total solid content and size of particles in suspension, resulting in higher apparent viscosity and yield stress (Eshtiaghi et al. 2013). The shear stress versus shear rate curves were fitted to different rheological models and Herschel-Bulkley model was selected as it fits best to the rheograms and better represents the complex shear thinning behaviour of digested sludge. The apparent yield stress ranges from 0.53Pa to 1.04Pa and the apparent viscosity ranges from 0.00012 – 0.002Pa.s as shown in Fig. 6.4(a). The viscosity versus shear rate curves were found to best fit to Cross model. Initial or zero-rate viscosity and infinite-rate viscosity values determined from this model are reported in Fig. 6.4(b). The presence of initial yield stress in shear thinning fluids like digested sludge is due to the resistance of the sludge flocs for shearing unless sufficient amount of stress is developed that overcomes the resistance which varies with floc size and structure (Lotito et al. 1997). Furthermore, hysteresis tests were carried out for digested sludge sample to have a better understanding of the rheological behaviour within the hysteresis loop. The upward and downward curves of the shear stress-shear rate and viscosity-shear rate plots of digested sludge show shear thinning thixotropic behaviour as shown in Fig. 6.5 (Piani et al. 2014).

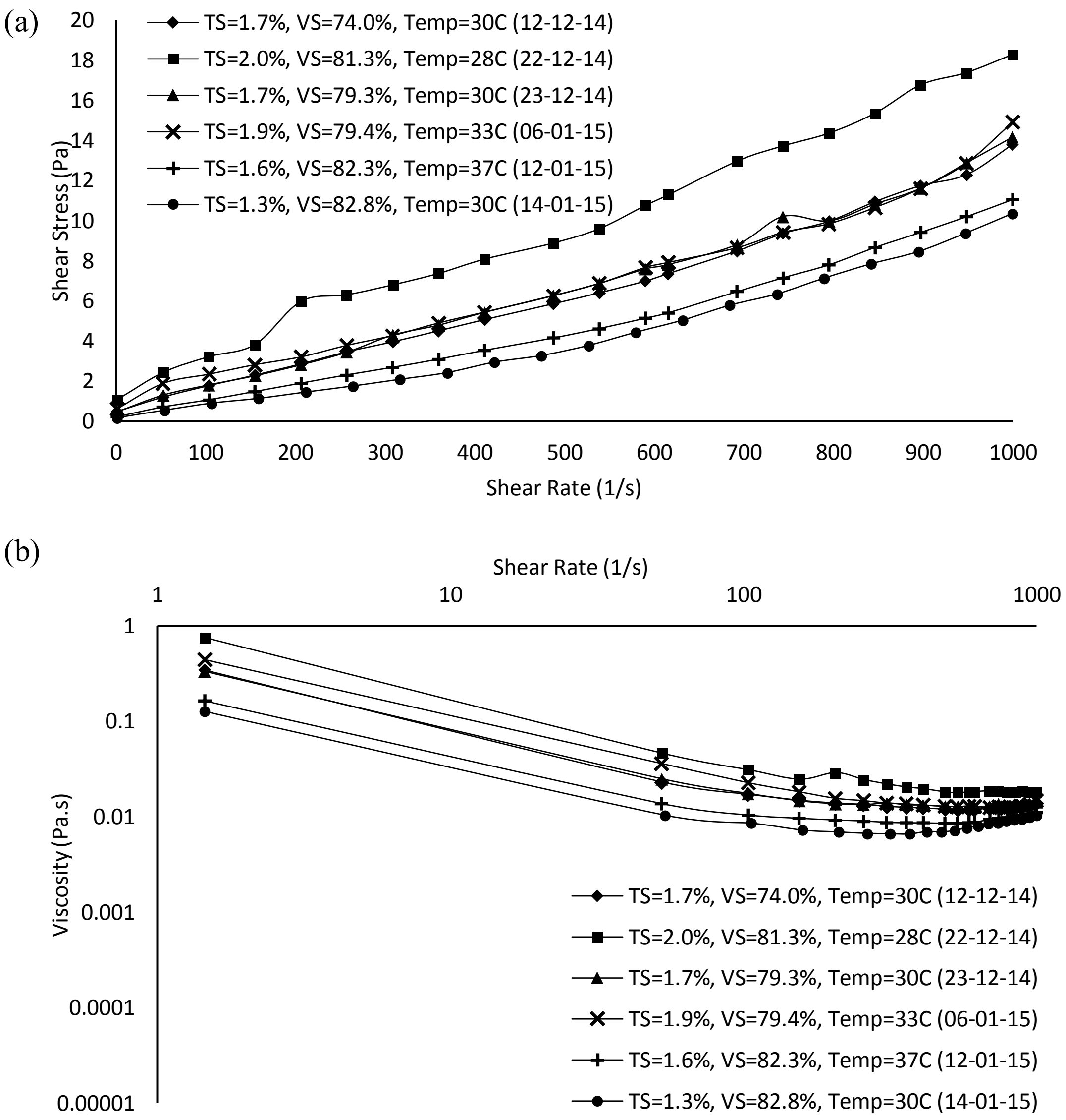


Fig. 6.3 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for digested sludge from different collection days (total solid and volatile solid content in % w/w, and temperature in ˚C)

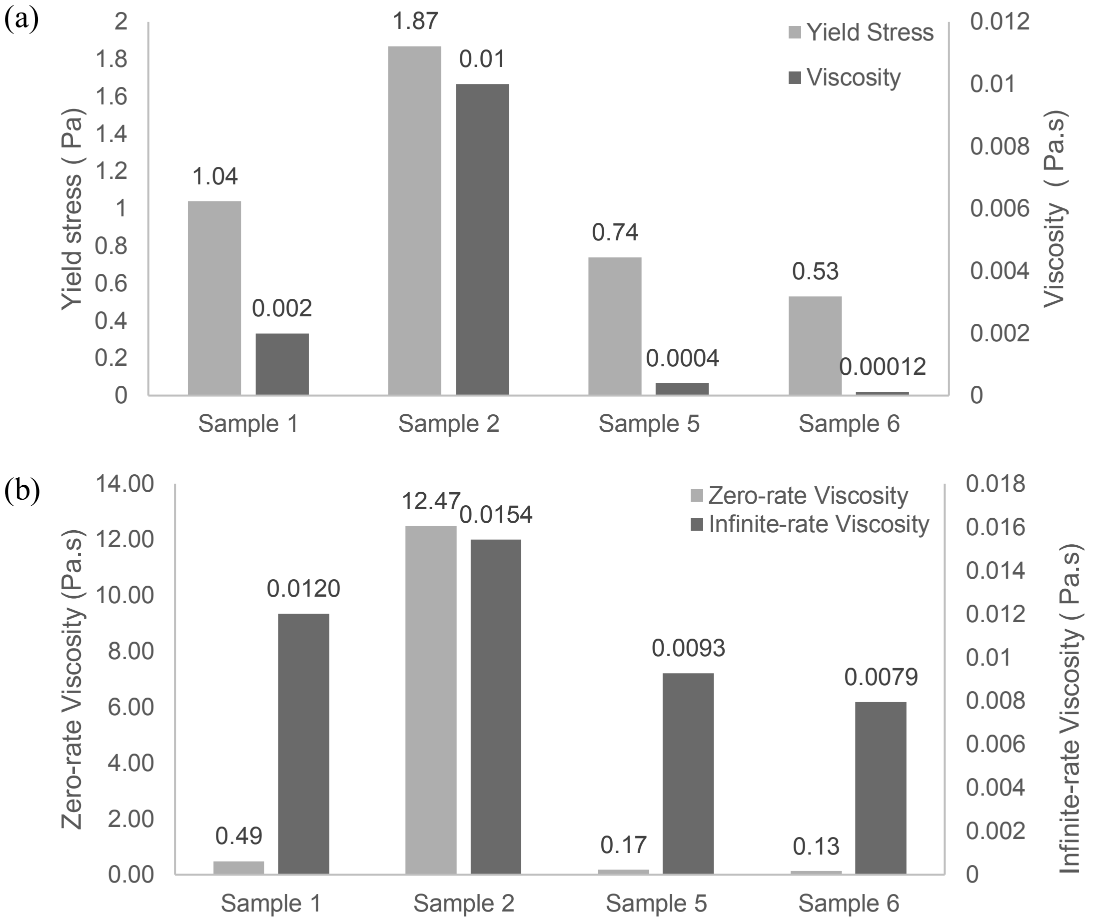


Fig. 6.4 Rheological model based parameters for digested sludge from different collection days (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

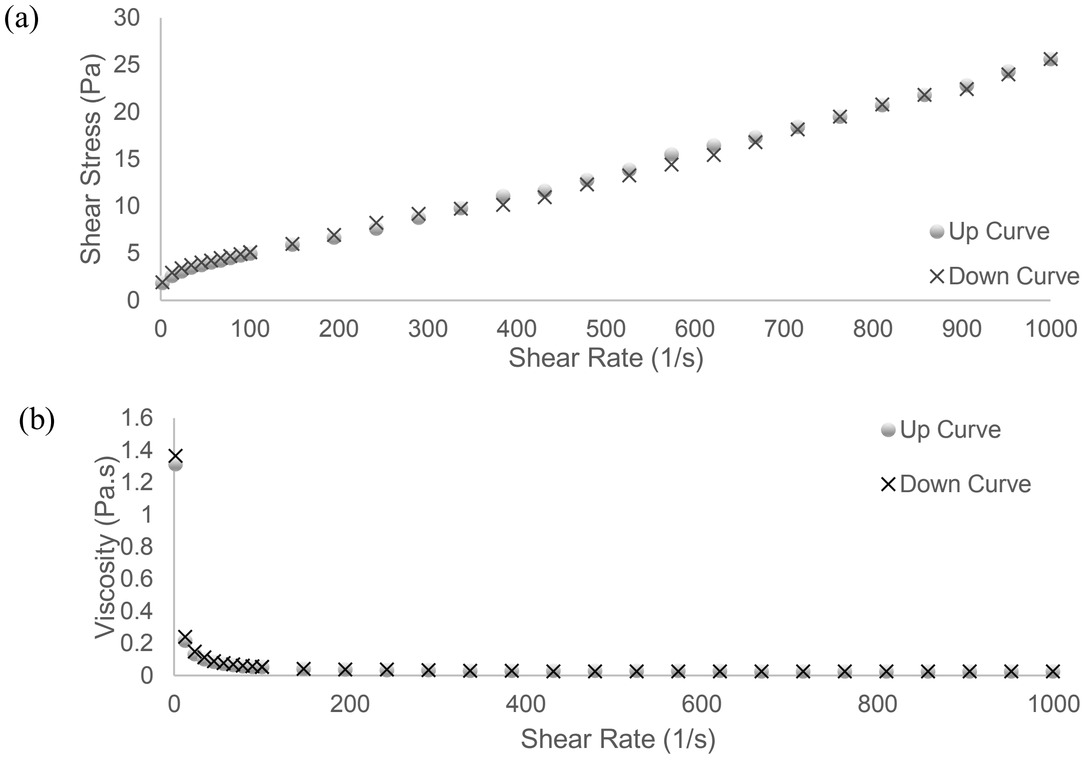


Fig. 6.5 Hysteresis test: (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for digested sludge sample with TS=2.3% w/w, pH=6.6 and Temperature=25˚C

6.3.4 Rheological characteristics of digested sludge compared to centrate and biosolid.

In this section, the rheological characteristics of all collected digested sludge, centrate and biosolid sample were determined and compared. The rheological characteristics of representative digested sludge, centrate and biosolid samples are shown in Fig. 6.6 (a) and Fig. 6.6 (b). Shear stress-shear rate and viscosity shear rate profiles of digested sludge, centrate and biosolid samples were fitted to different rheological models and the models that best represent the rheological properties were used for further analysis and interpretation. The shear stress-rate and viscosity-shear rate profile of digested sludge and centrate are not significantly different from each other and they exhibited less non-Newtonian flow behaviour compared to that of biosolid as shown in Fig. 6.6 (a) and Fig. 6.6 (b). Whereas, the shear stress-rate and viscosity shear rate profiles shown in Fig. 6.6 (a) and Fig. 6.6 (b) indicate that the shear force requirement of biosolid is significantly higher than that of digested sludge and centrate. The biosolid sample was diluted before the rheological test on the rheometer. The shear stress-rate rheograms of digested sludge, centrate and biosolid were found to fit best to Herschel-

Bulkley rheological model, which is mostly used to represent similar non-Newtonian viscoelastic shear thinning flow behaviour. Important rheological model parameters including yield stress, apparent viscosity and flow index were determined based on this model. The yield stress for the diluted biosolid was 83.5Pa while the yield stress values for digested sludge and centrate were 1.2Pa and 0.2Pa respectively as shown in Table 6.4. The viscosity shear-rate rheograms of digested sludge, centrate and biosolid were found to fit best to Careau-Yashua rheological model. The zero-rate and infinite rate viscosities determined using this model also showed the same trend that biosolid was observed to have the highest initial rate viscosity of 2.4Pa.s, followed by digested sludge and centrate viscosities of 0.45Pa.s and 0.075Pa.s respectively as shown in Table 6.5. Fig. 6.6 (a) showed non-Newtonian shear thinning behaviour where viscosity deceased with increasing shear rate. The significant deviation in the yield stress, zero-rate and infinite-rate viscosities of biosolid compared to that of digested sludge and centrate is mainly due the increase in total solid concentration and flocculation colloidal effect of the polymer due to bridging effect and increase of the network strength between sludge flocs particles (Sun et al. 2014, Yeneneh et al. 2016). Baudez et al. (2011) and Farno et al. (2016) reported similar rheological behaviour of digested sludge but not on biosolid. The shear force requirement and torque of biosolid is also more than 100 times higher than that of digested sludge and centrate and the shear modulus showed a similar trend as shown in Fig. 6.7 (a) and Fig. 6.7 (b). The shear modulus of biosolid, digested sludge and centrate were measured to be 2.1 Pa, 0.23 Pa and 0.003 Pa respectively at an initial shear rate of 1.45 1/s as shown in Fig. 6.7 (a). Similarly, the initial torque measured for biosolid, digested sludge and centrate were 3.4N.m, 0.036N.m and 0.006N.m respectively. The significant deviation in torque requirement and shear modulus of biosolid shows the network strength and strong non-Newtonian viscoelastic behaviour of the biosolid floc particles, which is responsible for higher pumping cost and centrifuge power requirement (Seyssiecq et al. 2003). Optimization measures to improve rheological flow behaviour of biosolid and digested sludge will have significant implications in the economy of WWTP operation.

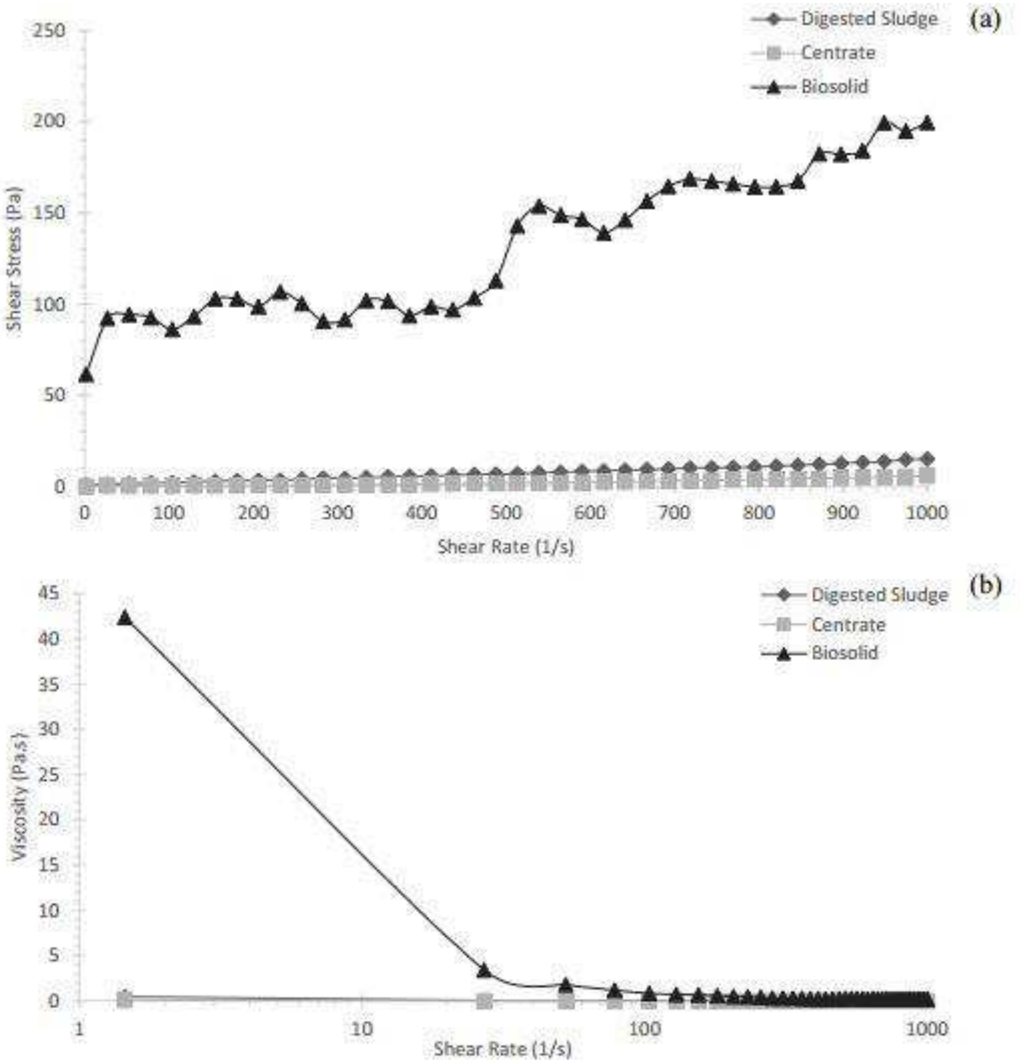


Fig. 6.6 Shear stress-rate (a) and viscosity-shear rate (b) profile for digested sludge, centrate and diluted biosolid samples

Table 6.4 Yield stress and viscosity of digested sludge centrate and biosolid based on Herschel-Bulkley model

Sample Type	Model	Yield Stress (Pa)	Viscosity (Pa.s)	R^2
Digested Sludge	Herschel-Bulkley	1.2	0.003	0.99
Centrate	Herschel-Bulkley	-	0.00002	0.99
Biosolid	Herschel-Bulkley	83.5	0.004	0.92

Table 6.5 Zero-rate and infinite-rate viscosity of digested sludge, centrate and biosolid based on Carreau-Yasuda model

Sample Type	Model	Zero-rate Viscosity (Pa.s)	Infinite-rate Viscosity (Pa.s)	R^2
Digested Sludge	Carreau-Yasuda	0.458	0.013	0.99
Centrate	Carreau-Yasuda	0.075	0.004	0.76
Biosolid	Carreau-Yasuda	42.395	0.154	0.99

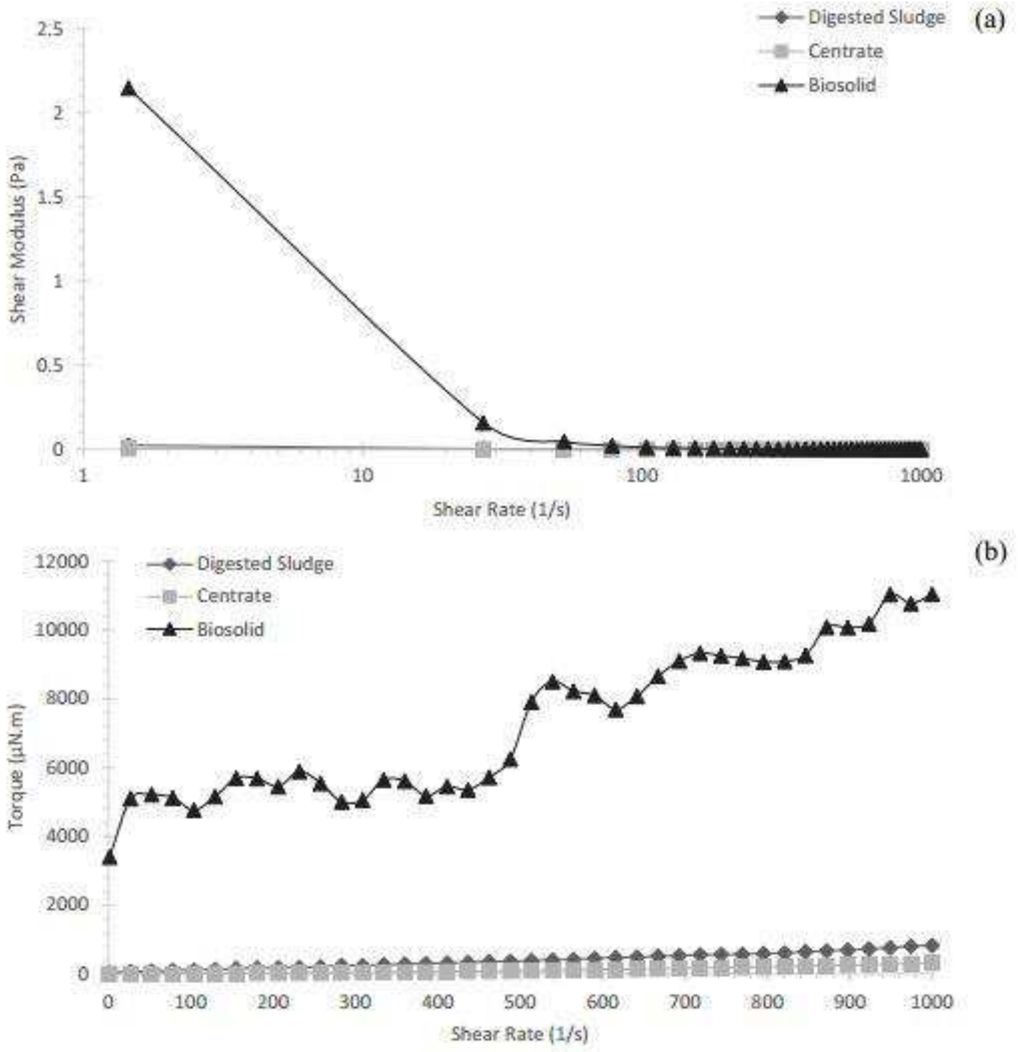


Fig. 6.7 Shear modulus-rate (a) and torque-shear rate (b) profile for digested sludge, centrate and diluted biosolid samples

6.3.5 Effect of total solid concentration on digested sludge rheology

The effect of change in total solid concentration on digested sludge rheological properties and dewaterability was investigated for total solid concentrations of 1.0%, 1.3%, 1.6%, 1.8%, and 2.0%. The desired solid concentrations were achieved by using vacuum filtration technique and by dilution method using deionised water (Baroutian et al. 2013, Lotito et al. 2014, Markis et al. 2014). The rheological behavior of digested sludge at these solid concentrations was investigated by plotting shear stress-shear rate and viscosity-shear rate curves as shown in Fig. 6.8(a) and Fig. 6.8(b). The shear stress-shear rate and viscosity-shear rate rheograms were found to best fit to Herschel-

Bulkley model. The yield stress and viscosity determined from the model fitting showed that digested sludge with higher total solid concentration have higher yield stress compared to digested sludge with lower total solid concentration. Fig. 6.9(a) shows that total solid content of 2.0% resulted in yield stress of 1.2Pa where as 1.0% total solid content showed significantly smaller yield stress of 0.2Pa. Similarly, the viscosity at the initial stage of shearing increased from 0.008Pa.s to 0.331Pa.s when total solid concentration of digested sludge was increased from 1% w/w to 2% as shown in Fig. 6.9(b). This is due to stronger network of sludge floc structure with the increase of solid concentration where colloidal and hydrodynamic forces between sludge particles change (Baroutian et al. 2013, Markis et al. 2014). The study on the relationship between sludge dewaterability and total solid concentration showed that smaller total solid concentration of digested sludge favours the dewatering process as shown in Fig. 6.10 (Sanin 2002, Baudez et al. 2011). This confirms that a significant improvement in sludge dewatering can be achieved by improving the performance of anaerobic digesters to enhance the total solid and volatile solid reduction.

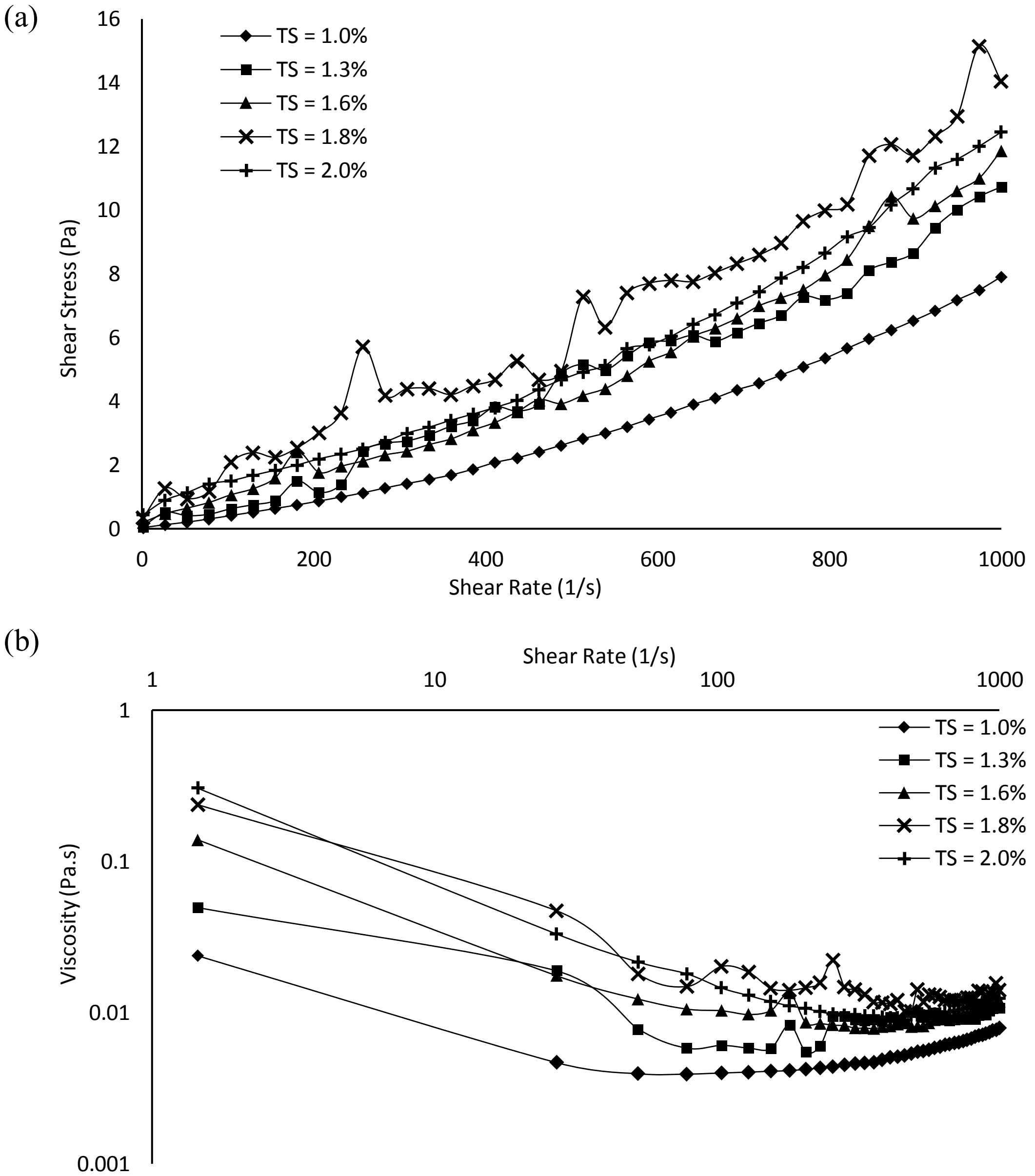


Fig. 6.8 (a) Shear stress-shear rate curves and (b) viscosity-shear rate curves for different total solid concentration (% w/w) of unconditioned digested sludge

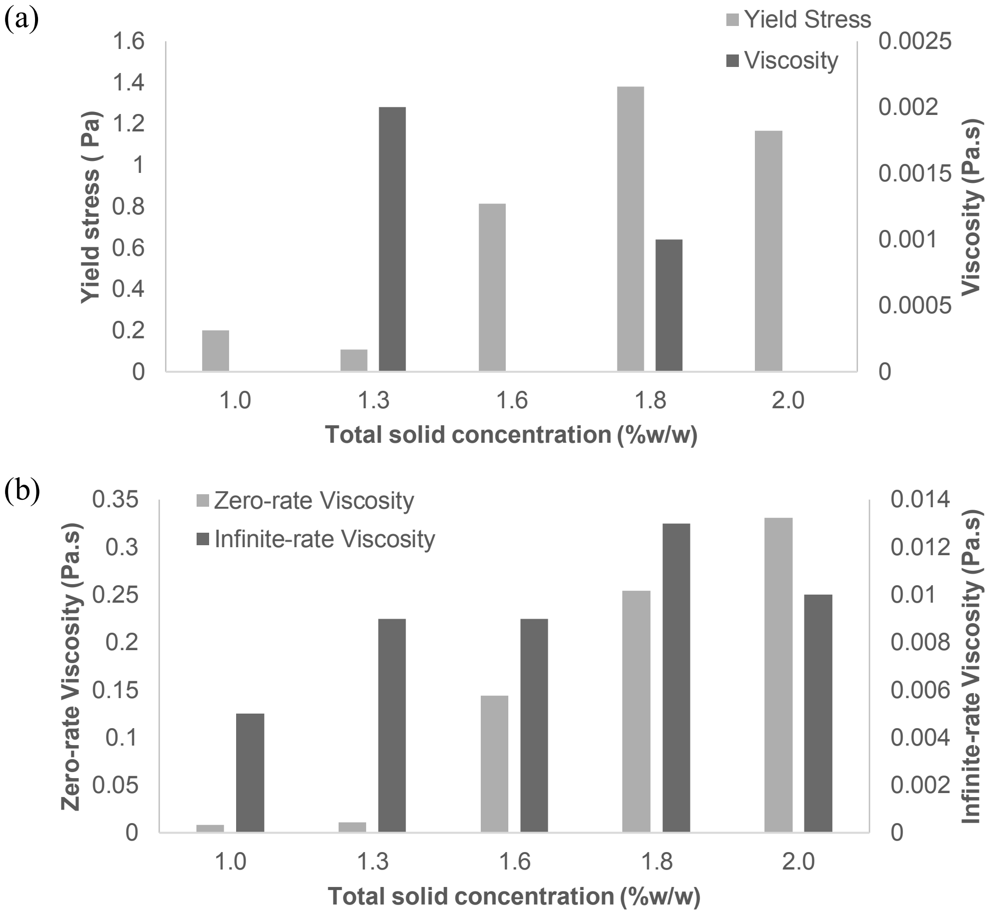


Fig. 6.9 Rheological model based parameters for different total solid concentration of unconditioned digested sludge (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

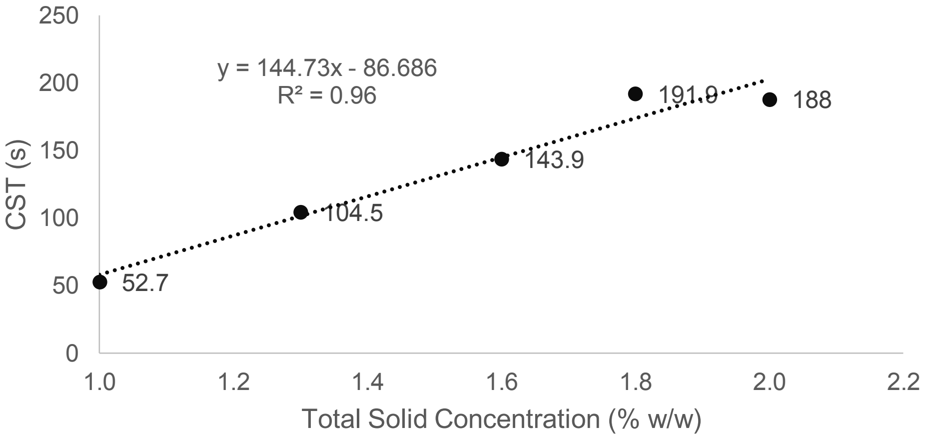


Fig. 6.10 Effect of total solid concentration on the dewaterability of digested sludge

6.3.6 Effect of temperature on digested sludge rheology

The rheological characteristics of polymer conditioned and unconditioned digested sludge were also investigated for varying temperatures of 20˚C, 35˚C, 40˚C and 50˚C. Fig. 6.11(a) and Fig. 6.11(b) show shear stress-shear rate and viscosity-shear rate rheogram for digested sludge after polymer conditioning respectively. The shear stress-shear rate and viscosity-shear rate flow curves were plotted and the results show that the shear stress-shear rate flow curve of polymer conditioned digested sludge at 20˚C is relatively higher than the shear stress-shear rate curves for the range of 35˚C to 50˚C as shown in Fig. 6.11(a) which is due to the stronger bridging and networking effect and greater viscosity of the polymer at lower temperature of 20˚C. The apparent viscosity at the start of shearing, generally showed reduction with increasing temperature as shown in Fig. 6.11(b). The increase in temperature from 20˚C to 50˚C resulted in steady decrease of apparent viscosity from 0.0053Pa to 0.0011Pa based on Herschel-Bulkley model as shown in Fig. 6.12(a). Yield stress of polymer conditioned digested sludge also showed a decreasing trend with increasing temperature in the temperature range of 20-40 ˚C and it increased again at 50˚C as shown in Fig. 6.12(a). Infinite rate viscosity showed a decreasing trend with increasing temperature from 20-50˚C as shown in Fig. 6.12(b) as the thermal energy results in change of the shape and size of flocculated particles, and the degree of dispersion of the soluble organic content of the sludge (Abu-Orf et al. 2005). Fig. 6.13(a) and Fig. 6.13(b) show shear stress-shear rate and viscosity-shear rate rheograms respectively for unconditioned digested sludge. The temperature range considered for this study is similar to the polymer conditioned digested sludge (20˚C - 50˚C) and the trends both for shear stress-shear rate and viscosity-shear rate rheograms are similar to the result obtained in the case of polymer conditioned digested sludge, yet, Fig. 6.14(a) and Fig. 6.14(b) show that apparent yield stress and apparent viscosity of unconditioned digested sludge are more consistent than the polymer conditioned one. Apparent yield stress showed an increasing trend in the range of 20-35˚C and it started to decrease again in the range of 35-50˚C, the viscosity on the other hand was observed to decrease from 20-50 ˚C as shown in Fig. 6.14(a). The addition of polymer resulted in the increase of the floc network strength contributing to the increase in yield stress and viscosities (Örmeci 2007, Wang et al. 2010).

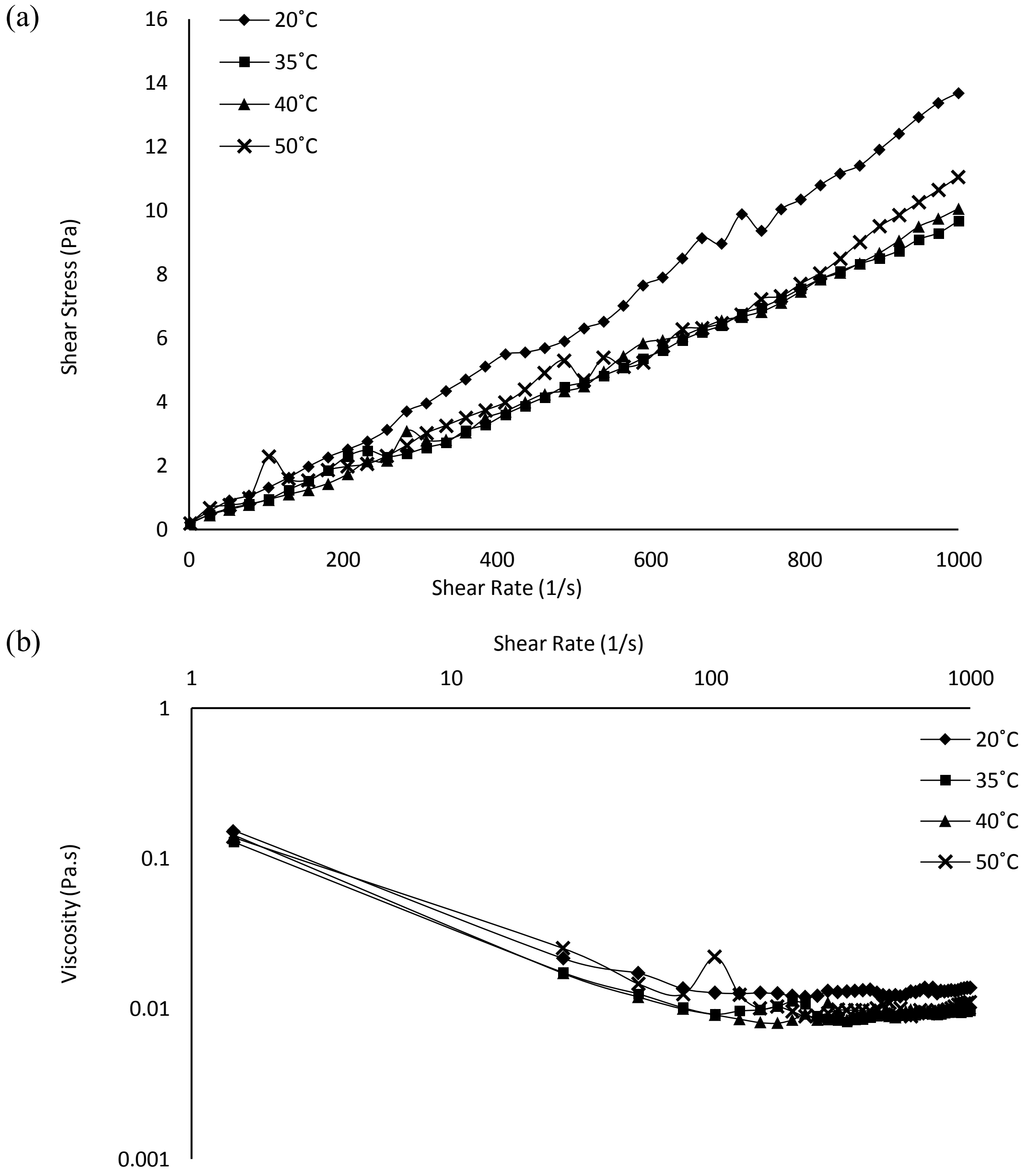


Fig. 6.11 (a) Shear stress-shear rate curves and (b) viscosity-shear rate curves for different temperatures of polymer conditioned digested sludge

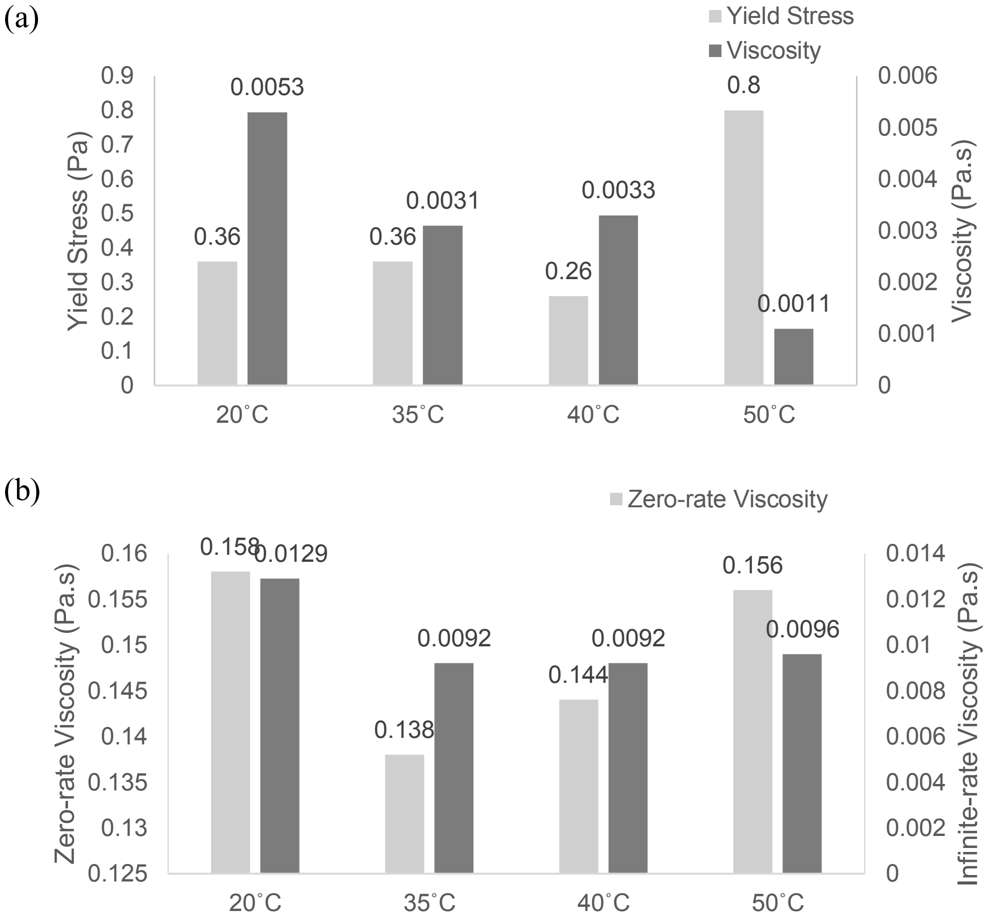


Fig. 6.12 Rheological model based parameters for varying temperature of polymer conditioned digested sludge (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

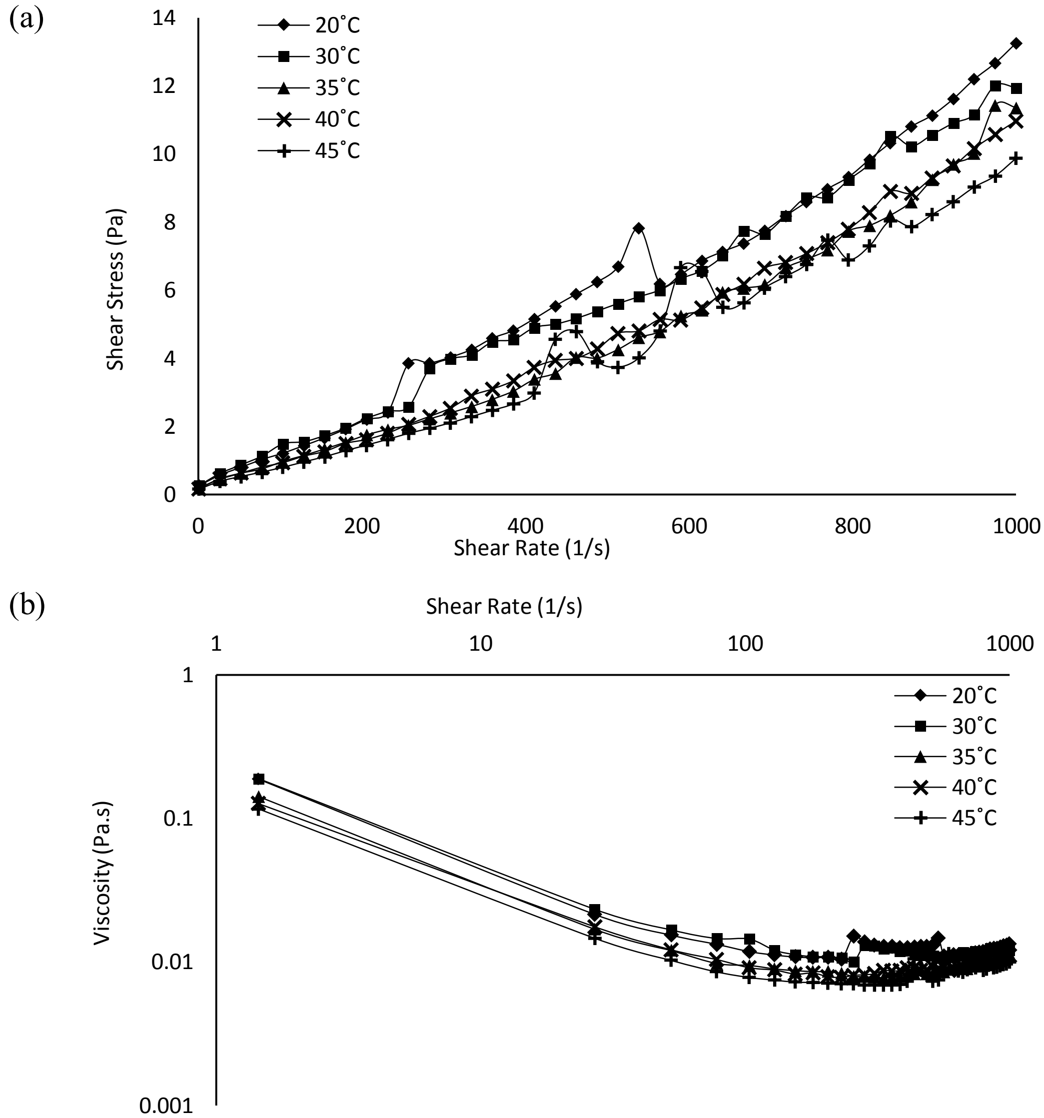


Fig. 6.13 (a) Shear stress-shear rate curves and (b) viscosity-shear rate curves for different temperatures unconditioned digested sludge

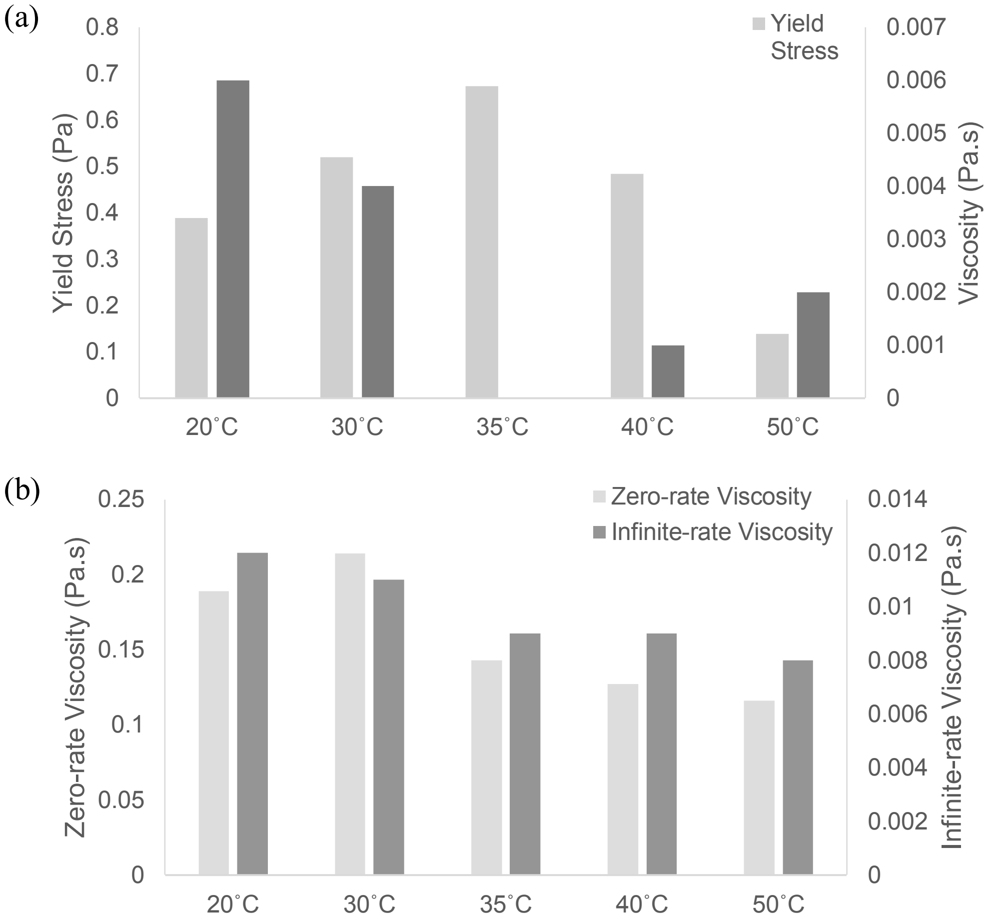


Fig. 6.14 Rheological model based parameters for varying temperature of unconditioned digested sludge (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross)

6.3.7 Effect of temperature and pre-shearing on digested sludge rheology

The effect of temperature on dewaterability of pre-sheared digested sludge was studied at different temperatures of 20˚C, 30˚C, 35˚C, 40˚C, and 50˚C respectively. The desired temperature and pre-shearing effect were achieved by using a rheometer equipped with concentric cylinder and vane geometry. Fig. 6.15 shows the effect of pre-shearing on digested sludge dewaterability under different temperature and polymer dose conditions. Pre-shearing resulted in significant improvement in the dewaterability of digested sludge as shown in Fig. 6.15(a). The dewaterability improved from 172s to 49s when the shear rate was increased from $0s^{-1}$ to $1000s^{-1}$. This is due to the destruction of floc network and release of bound water and decrease in floc network strength and viscosity that improves flow behaviour of the digested sludge (Yen et al. 2002). Higher temperature was observed to enhance dewatering performance for unconditioned pre-sheared digested sludge as shown in Fig. 6.15(b). In case of polymer conditioned digested sludge the optimum dewaterability was achieved for a temperature of 35˚C as shown in Fig. 6.15(c). The dewaterability of digested sludge showed a decreasing trend with increasing temperature in the range of 35-50˚C. This is an interesting finding that maintaining the temperature of the digested sludge at the digester operating condition of 35-36˚C is beneficial to the dewatering process.

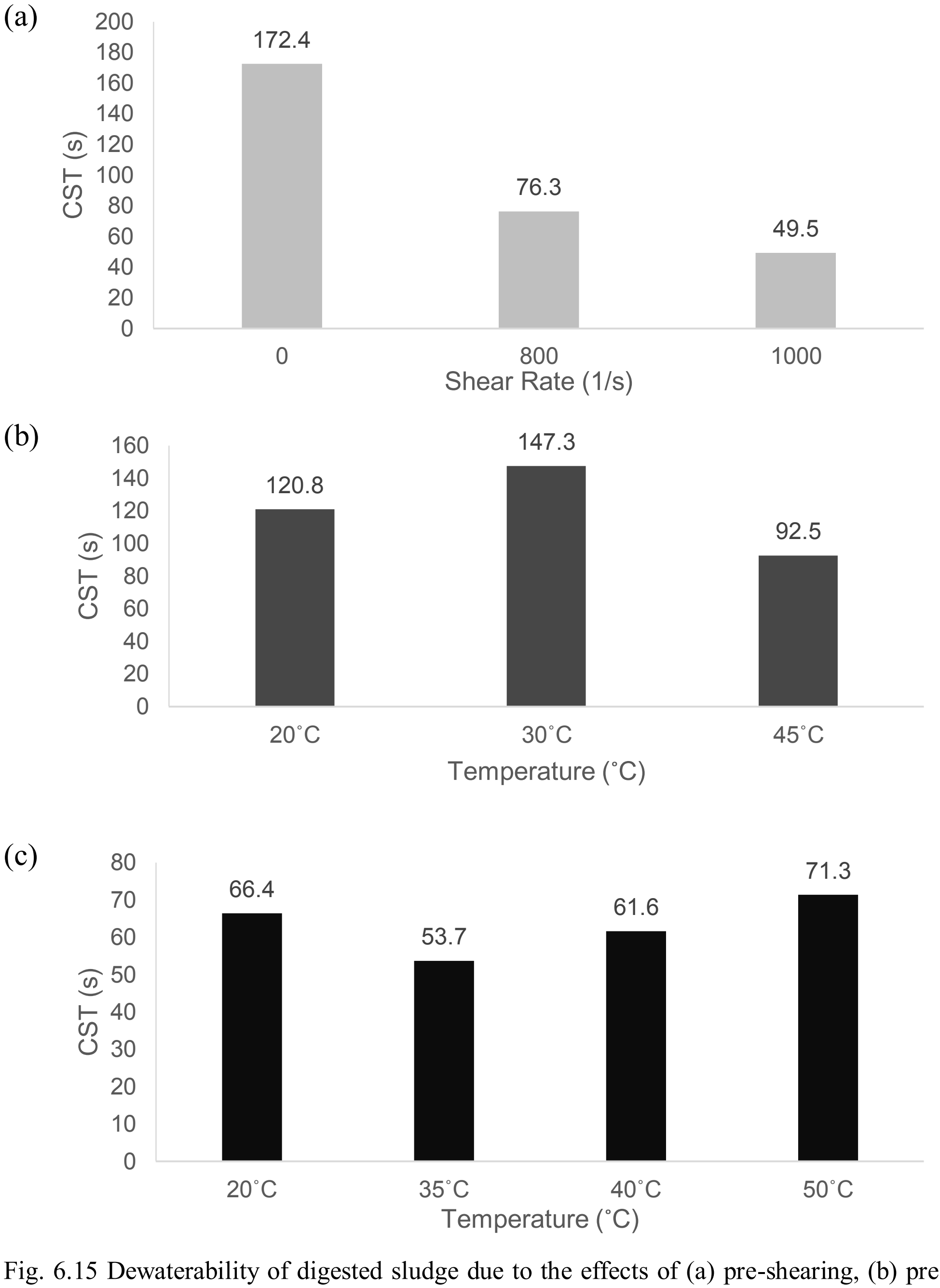


Fig. 6.15 Dewaterability of digested sludge due to the effects of (a) pre-shearing, (b) pre-shearing at $1000s^{-1}$ & temperature (c) pre-shearing at $1000s^{-1}$ and polymer conditioning at different temperatures

6.3.8 Effects of polymer dose on digested sludge dewaterability and rheology

It is known that conditioning polymer added to digested sludge to enhance dewaterability is an important cost factor in the operation of the dewatering process. Different polymer dose of 18kg/day, 12kg/day, 9kg/day, 7kg/day and 5kg/day were selected for experimental polymer dose optimization test. These polymer doses were selected based on polymer consumption trend in BWWTP. Fig. 6.16 shows the effect of different polymer doses on the dewaterability of digested sludge. The dewaterability was measured in capillary suction timer (CST). It was observed that increase in polymer dose from 7kg/t DS to 18kg/t DS improved the dewaterability from 124.4s to 7s. The dewaterability of unconditioned digested sludge was 158s. In a separate jar test conducted on 500ml of digested sludge sample the dewaterability for polymer doses of 7kg/t DS, 9 kg/t DS, 12kg/t DS, 13kg/t DS, 14kg/t DS, 15kg/t DS, and 18kg/t DS was found to be 139.7s, 123.5s, 22.5s, 21.5s, 20.5s, 13.7s and 9.1s as shown in Fig. 6.17. The floc structure for polymer dose of 18kg/t DS showed that this is an over dose condition. The dewaterability measured for this condition was of pure water (very low) and does not realistically represent the flocculation that took place under this condition. Hence, polymer dose of 12kg/t DS provides reasonably acceptable separation of water (53.9s) and better dewatering performance.

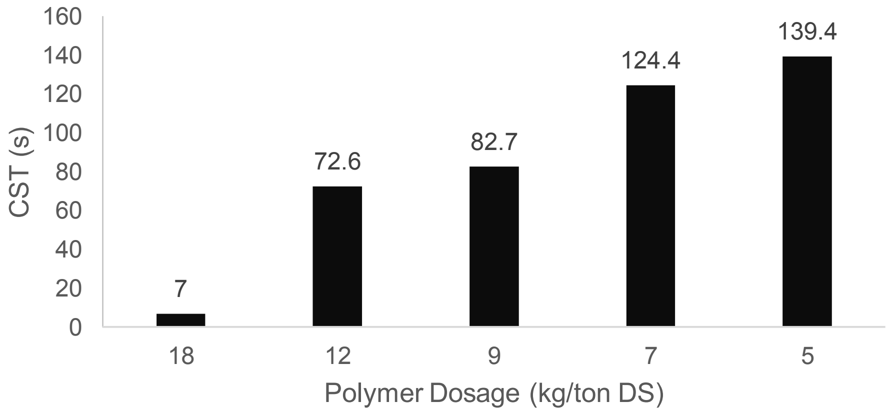


Fig. 6.16 Effect of polymer dose on digested sludge dewaterability

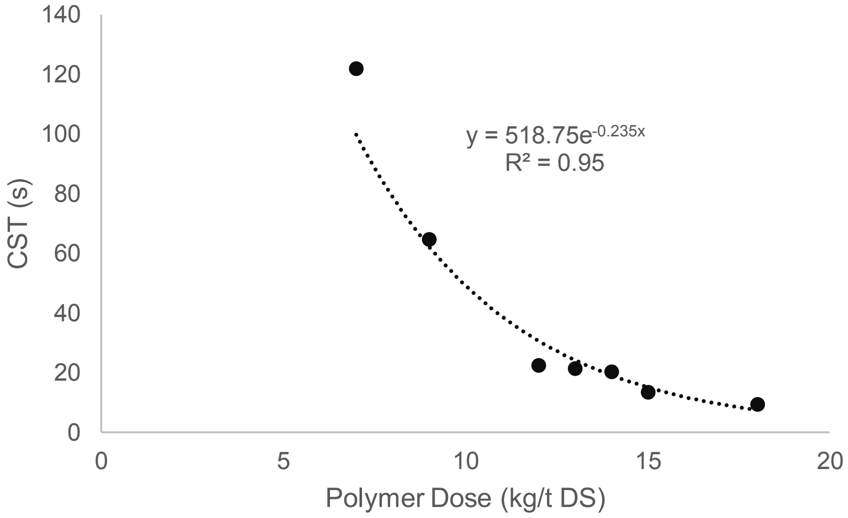
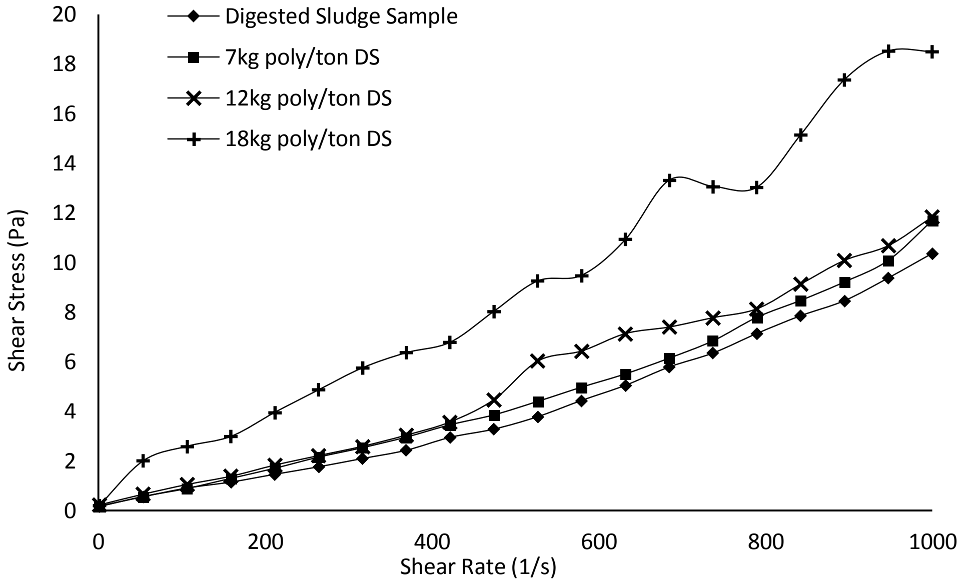


Fig. 6.17 Effect of polymer dose on digested sludge dewaterability

The effect of polymer dose on the rheological behaviour of digested sludge was also investigated for polymer dose in the range of 7kg/t DS to 18kg/t DS. Fig. 6.18(a) and Fig. 6.18(b) show the effect of different polymer doses on shear stress-rate and viscosity shear-rate profile of polymer conditioned digested sludge. The model fitting analysis showed that the shear stress-rate curves fit better to Herschel-Bulkley non-Newtonian rheological model whereas the Sisko model was selected to represent viscosity shear-rate rheograms. Fig. 6.19(a) and Fig. 6.19(b) show the rheological model parameters derived from Herschel-Bulkley and Sisko models respectively. It was observed that unconditioned digested sludge had an initial yield stress of 0.5Pa and as polymer dose was increased from 7kg/t DS to 18kg/t DS, the yield stress of digested sludge increased from 0.6Pa to 1.1Pa due to formation of bigger floc with increasing polymer dose as shown in Fig. 6.19(a) (Wang et al. 2010). However, polymer dose of 18kg/t DS can be considered as an overdose condition due to the very loose and big floc structure which negatively influenced dewaterability. It was found that, polymer dose of 12kg/t DS had the lowest yield stress value making this dose optimum both from dewaterability and rheological point of view. Similarly, the viscosity of unconditioned digested at higher shear rate was observed to increase from 0.008Pa.s to 0.02Pa.s when polymer dose was increased from 0kg/t DS to 18kg/t DS as shown in Fig. 6.19(b). The polymer dose tests were conducted for a fixed total solid concentration. However, the test on dewaterability of digested sludge as a function of varying total solid concentration confirms that the polymer consumption can be optimized based on the totals solid content of the digested sludge being conditioned. The model equation shown on Fig. 6.10 can be related to polymer dose test shown in this section for optimization purposes.

(a)



(b)

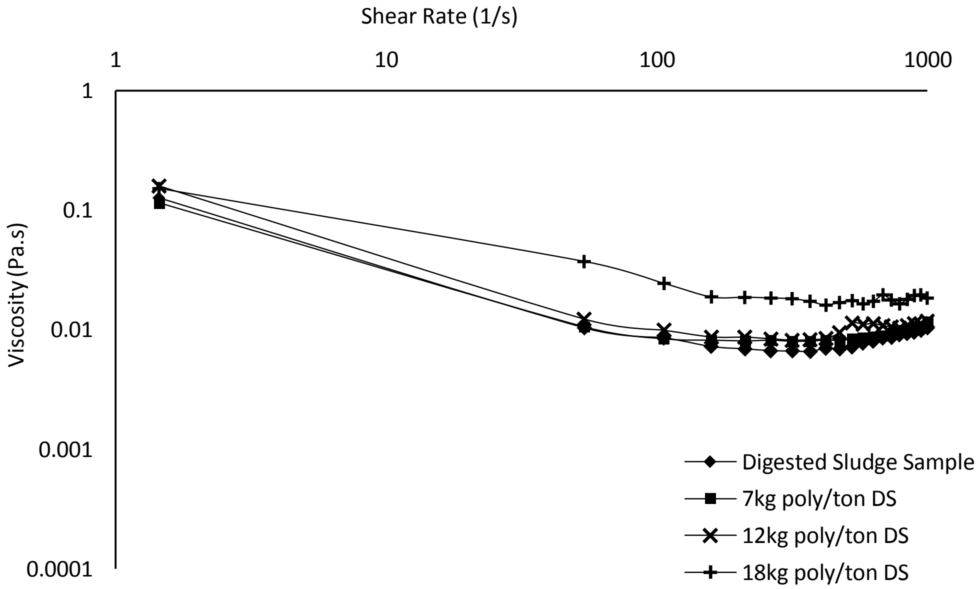


Fig. 6.18 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different polymer dose of digested sludge

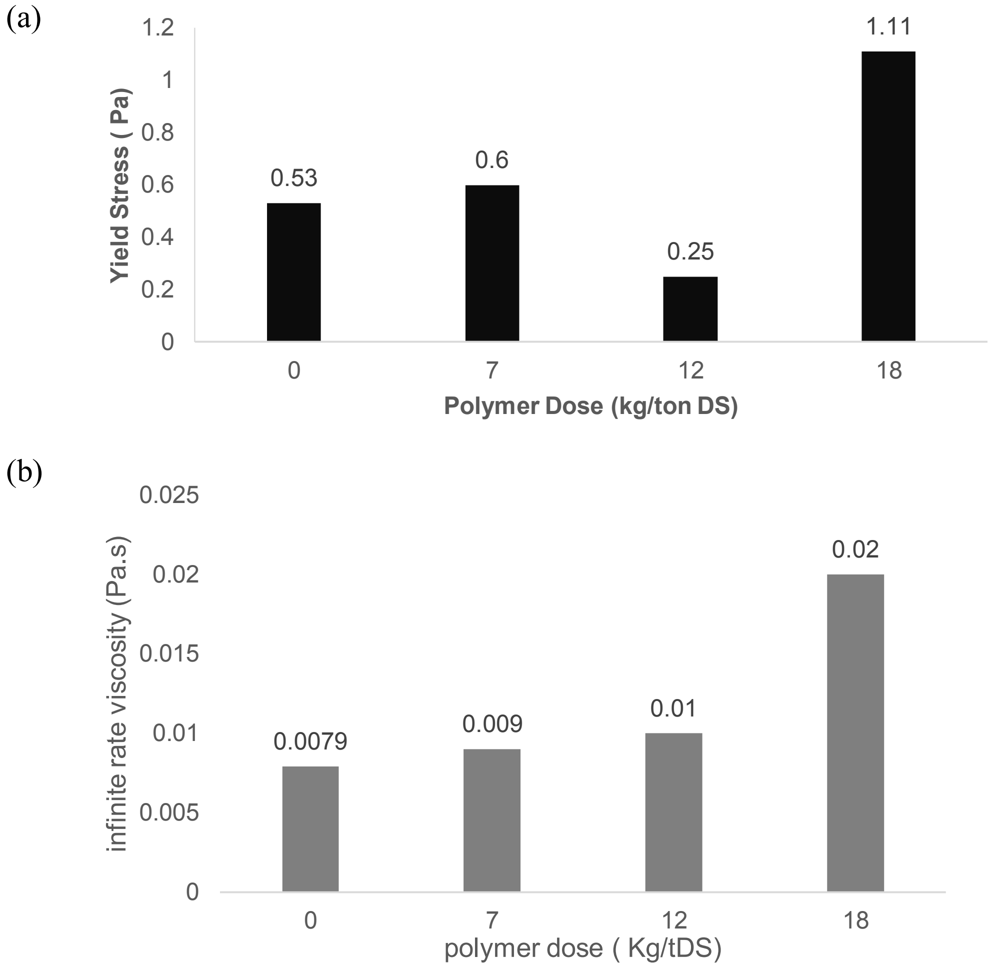


Fig. 6.19 Rheological model based parameters for different polymer dosage of digested sludge (a) yield stress & viscosity (Herschel-Bulkley), (b) infinite-rate viscosity (Sisko)

6.3.9 Effects of sludge age on rheology

The effect of storage time (age of sludge) on the rheological property of digested sludge was investigated over a period of 23 days. Rheological tests were conducted on digested sludge samples at the time of collection and after 8, and 22 days of storage in refrigerated environment at 4°C. It can be observed that the degradation and change in rheological property of the digested sludge sample during the 22 days of storage was significant. The shear stress-rate profile showed a significant decrease in the first 8 days as shown in Fig. 6.20(a). Similar trend was observed in viscosity tests, as days of storage progresses, the viscosity of the digested sludge decreased as shown in Fig. 6.20(b). It can be concluded that digested sludge samples degrade during storage and the rheological properties change significantly with time. The shear thinning behaviour is generally enhanced by the biodegradation of organics within the sludge (Markis et al. 2014). Yield stress and viscosity also decreased over time as shown in Fig. 6.21(a) and Fig. 6.21(b) respectively due to biodegradation of important organic components such as protein, lipid and carbohydrate, and synthesis of volatile fatty acids which affect the rheology (Baudez 2008). This implies that in the course of the anaerobic digestion process the viscosity of sludge significantly decreases as observed in this study, favouring better flowability mass transfer, mixing, and anaerobic degradation.

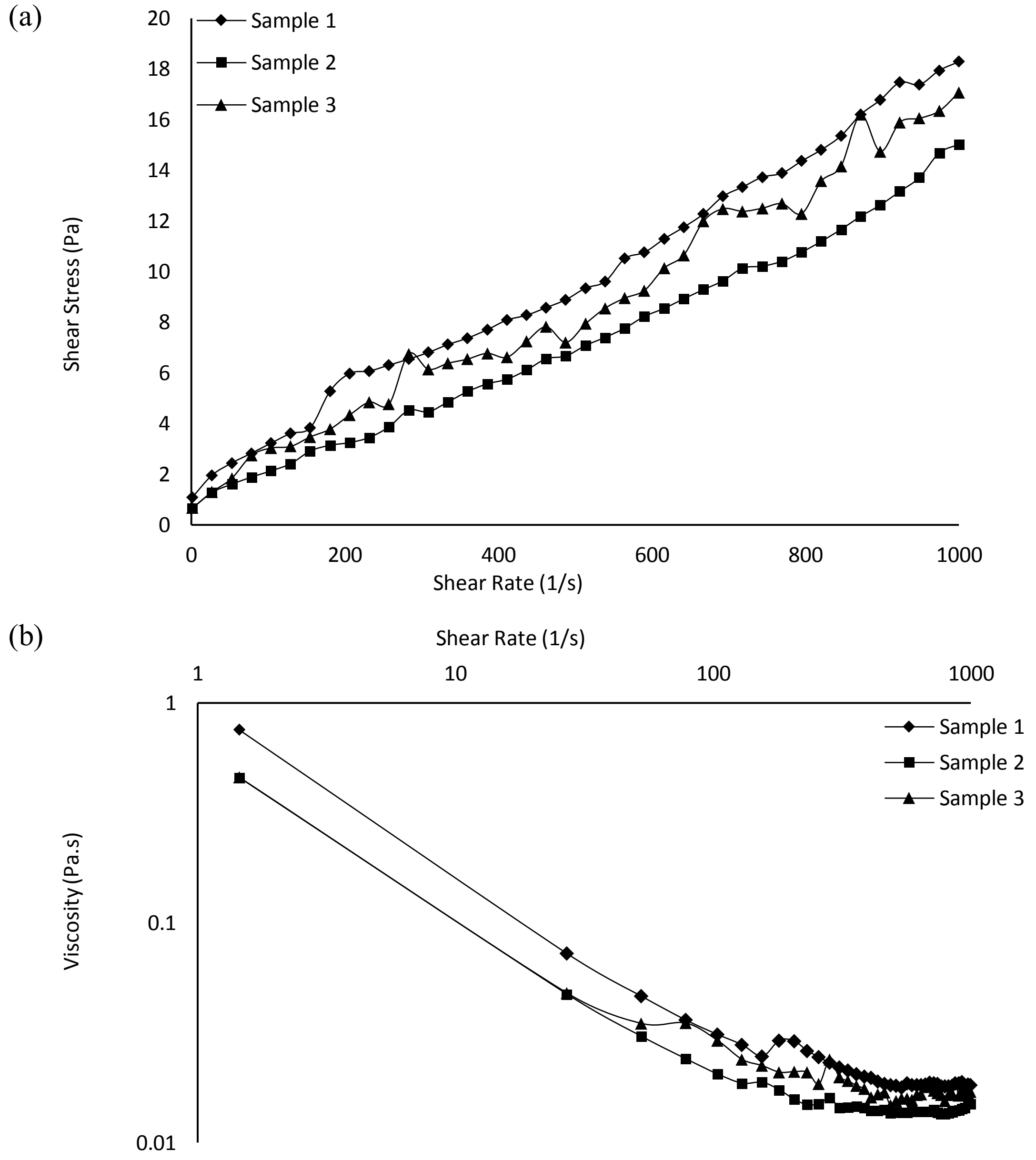


Fig. 6.20 (a) shear stress-shear rate curves and (b) viscosity-shear rate curves for different digested sludge at different storage time where Sample 1 is the fresh sample, Sample 2 have been stored for 8 days and Sample 3 have been stored for 22 days.

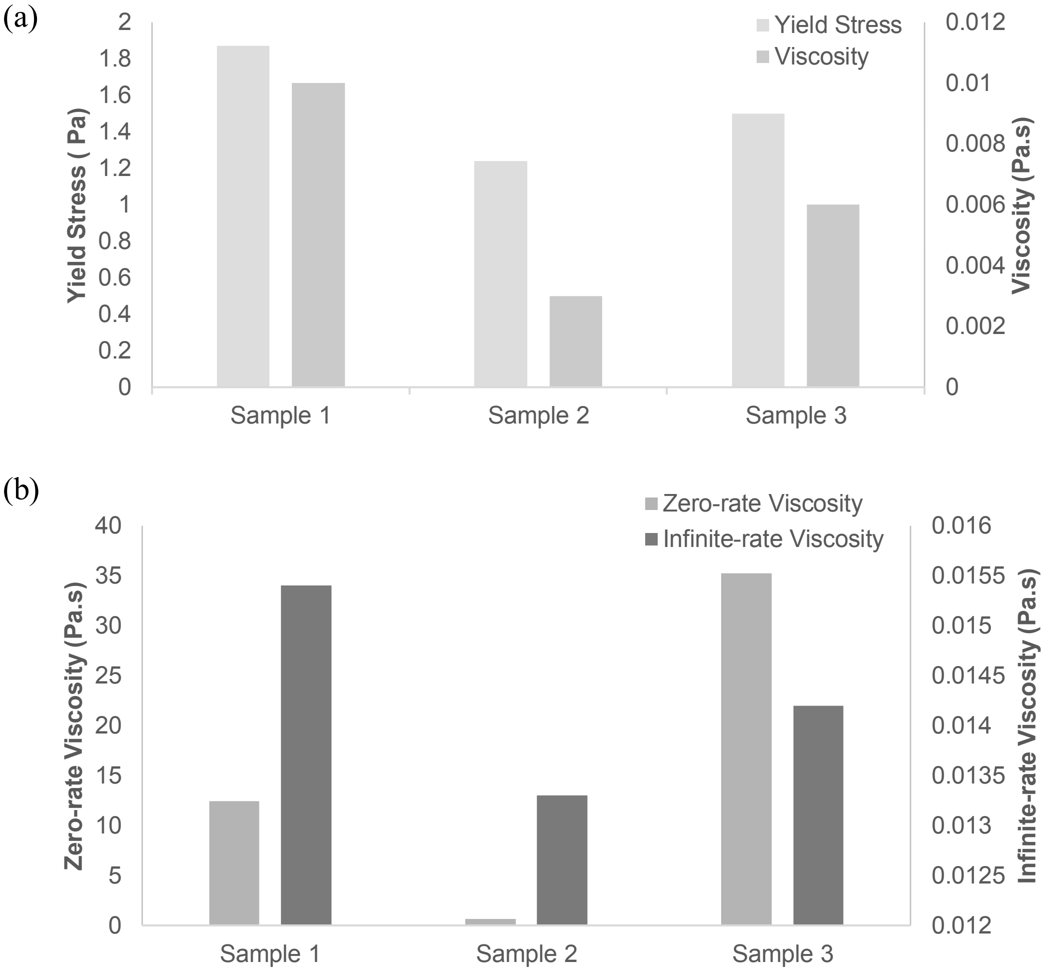


Fig. 6.21 Rheological model based parameters for different digested sludge at different storage time (a) yield stress & viscosity (Herschel-Bulkley), (b) zero-rate viscosity & infinite-rate viscosity (Cross) where Sample 1 is the fresh sample, Sample 2 have been stored for 8 days and Sample 3 have been stored for 22 days.

6.3.10 Relationship between digested sludge rheology and biosolid capture rate.

The relationship between rheological and physico-chemical characteristics of digested sludge, centrate and biosolid were also investigated in this study. The relationship between volatile solid content of digested sludge and biosolid capture rate shows that there is an interesting inverse relationship between volatile solid content of digested sludge fed to centrifuge and total solid content of biosolid as presented in Fig. 6.22 (a). The volatile organic solid content of digested sludge is mainly due to constituents like polysaccharides and proteins which significantly affect the network strength and the bound water content of the floc particles during the flocculation process in the presence of polymer as shown on the FTIR peaks of Fig. 6.1 (Mori et al. 2006). The relationship between yield stress and viscosity of digested sludge and its volatile solid concentration also confirms this fact that the network strength of the digested sludge flocs increases with increasing volatile solid concentration resulting in the increase of yield stress and viscosity as shown in Fig. 6.22 (b) and Fig. 6.22 (c) (Yin et al. 2004). These trends provide useful information for the monitoring and control of dewatering performance and biosolid capture rate using rheological parameters like yield stress and viscosity.

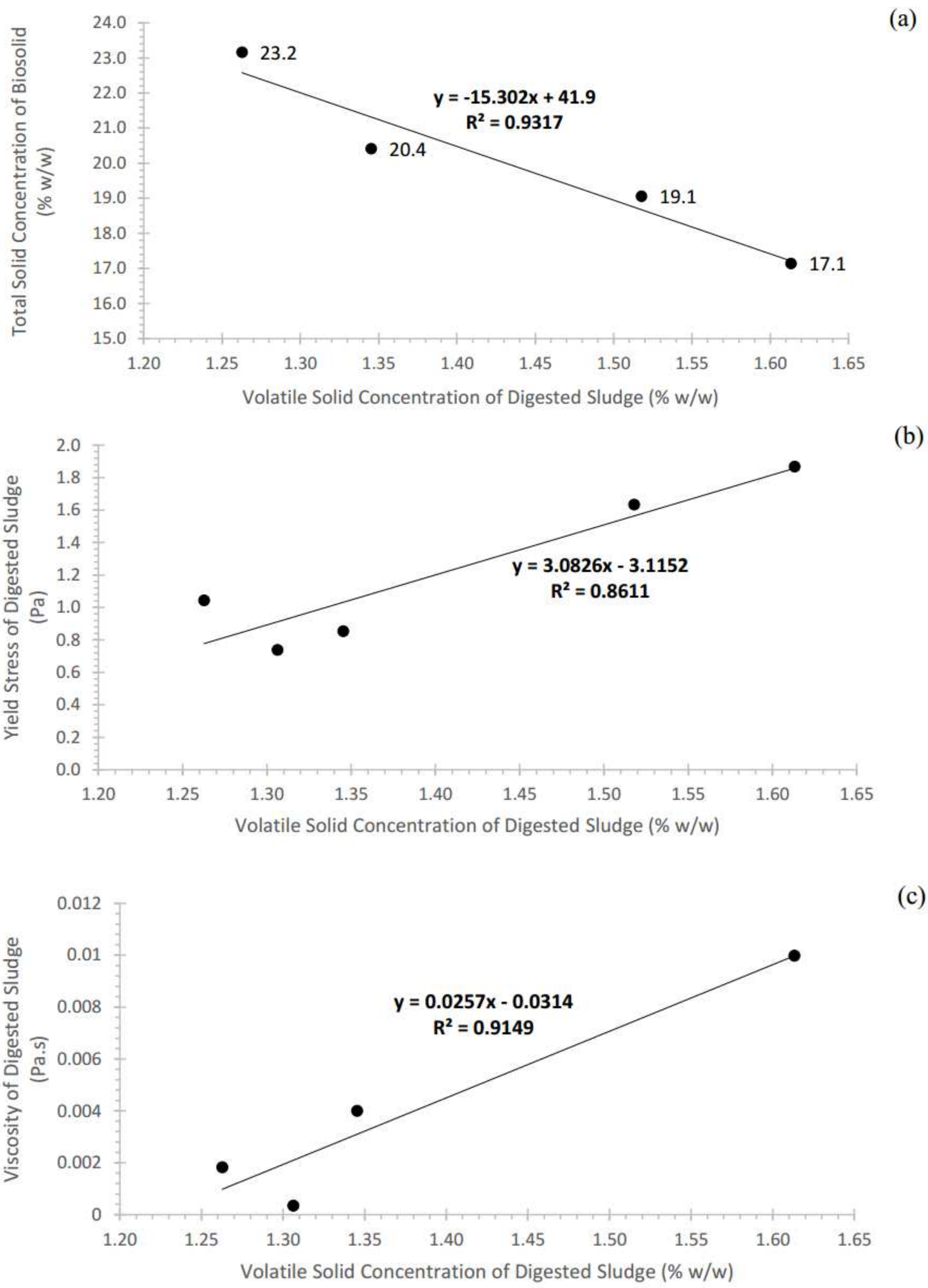


Fig. 6.22 Impact of digested sludge volatile solid concentration on (a) biosolid quality (total solid concentration of biosolid, (b) yield stress of digested sludge and (c) viscosity of digested sludge

Impacts of total solid concentration and volatile solid concentration of digested sludge on biosolid capture rate is presented in Fig. 6.23. The trend shown in Fig. 6.23 supports the relationship between biosolid capture rate and volatile solid content of digested sludge presented in Fig. 6.22 (a). The highest total solid content of biosolid of 23.2% w/w was achieved for the digested sludge sample with minimum volatile solid concentration of 1.26% w/w. The total solid content of the digested sludge sample which provided better biosolid capture rate is relatively low, 1.7% w/w as shown in Fig. 6.23. Interestingly, there are two samples with the same total solid content of 1.7% w/w but with different volatile solid contents. The digested sludge sample with lower volatile solid content of 1.26% w/w produced biosolid of better quality. This implies that lower total solid content and more importantly lower volatile solid content of digested sludge improves the dewaterability of digested sludge resulting in reduced polymer consumption and increased quality of biosolid (Yin et al. 2004, Yeneneh et al. 2016). Investigations conducted on the impact of change in total solid concentration of digested sludge on the rheological behaviour of digested sludge showed that an increase in total solid concentration from 1.6% w/w to 2.0% w/w resulted in the increase of yield stress from 0.7Pa to 1.9Pa as shown in Fig. 6.24. Further thickening of the digested sludge into biosolid resulted in a significant increase of yield stress to 83.5Pa as described in section 3.3. Yield stress can be used to calculate pipe friction and head losses and to optimize the polymer dose as the yield stress has direct relationship with total solid concentration. Automated online measurement techniques can also be devised to measure viscosity and yield stress and adjust the polymer dose accordingly (Mori et al. 2006). Fig. 6.25 shows the relationship between volatile solid content and COD of digested sludge and the effects on total solid concentration of biosolid. COD, an indicator of the total organic content of the digested sludge, is proportional of the volatile solid content of the digested sludge sample. Hence, lower COD favours the dewatering process in the same way as lower volatile solid content. Yield stress of digested sludge as function of its COD follows the same trend as volatile solid concentration of the digested sludge as shown in Fig. 6.26. Therefore, an increase in the performance of anaerobic digesters in terms of volatile solid removal and COD reduction contributes to the improvement of the rheological flow behaviour and dewaterability of the digested sludge and the biosolid capture rate (Houghton et al. 2002, Farno et al. 2016). Thus, COD of the digested sludge can also be used as a tool to indirectly determine the volatile solid of digested sludge, which could potentially be used to determine the polymer dose required to achieve desired biosolid capture rate.

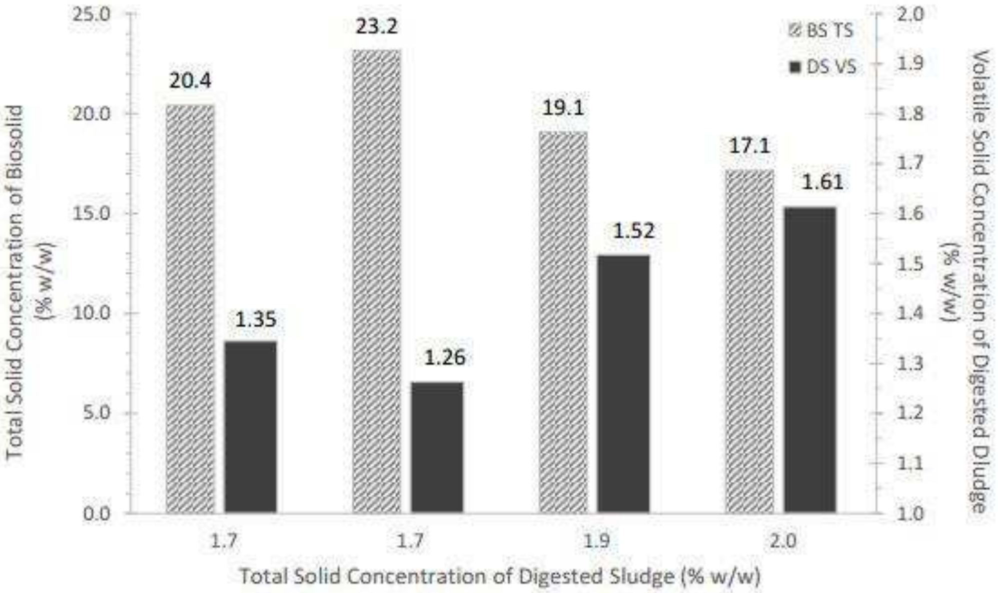


Fig. 6.23 Impact of total solid concentration of digested sludge on biosolid total solid concentration and digested sludge volatile solid concentration

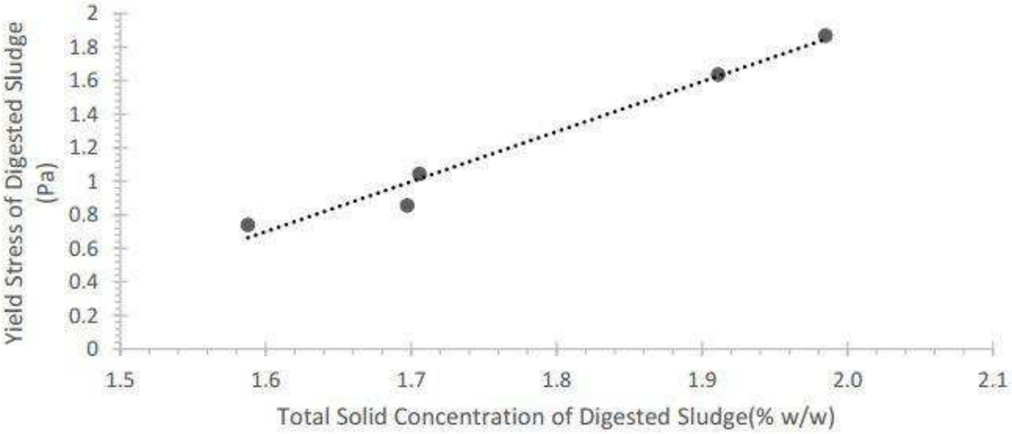


Fig. 6.24 Impact of digested sludge total solid concentration on yield stress

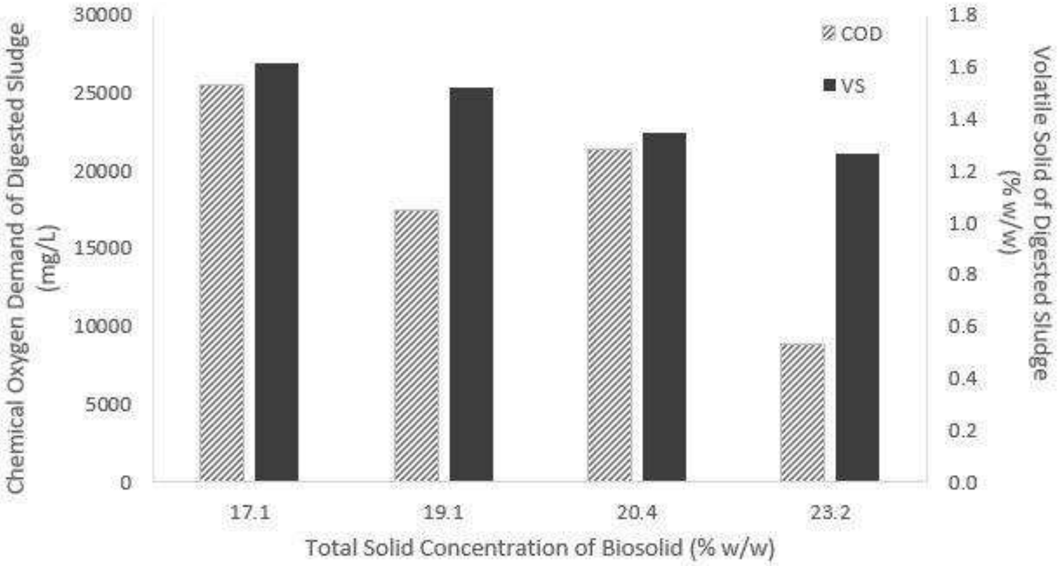


Fig. 6.25 The relationship of chemical oxygen demand and volatile solids concentration of digester sludge with biosolid total solid concentration

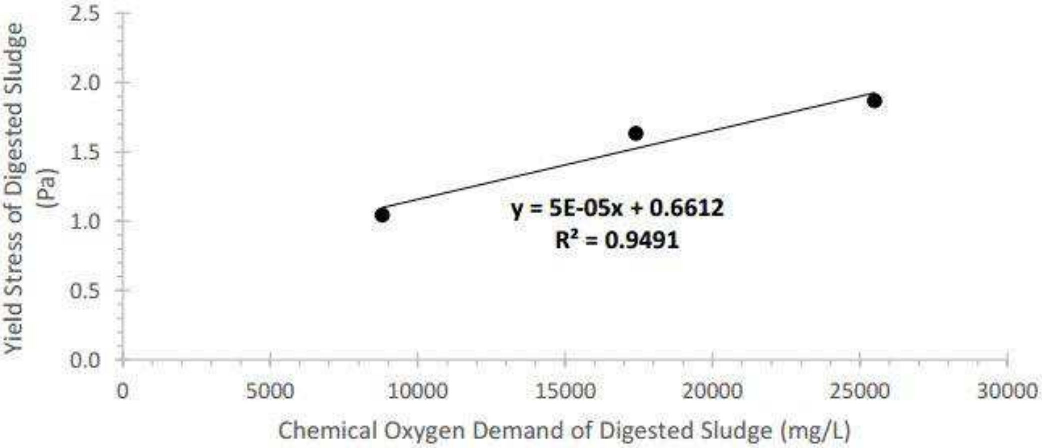


Fig. 6.26 Impacts of chemical oxygen demand of digester sludge on its yield stress

6.3.11 Relationship between centrate rheology and biosolid capture rate

The relationships between physico-chemical and rheological characteristics of the filtrate (centrate) and biosolid (cake) coming out of the centrifuge were also investigated. Fig. 6.27 shows the distribution of solids between the cake and the filtrate. An increase in the total solid concentration of the centrate indicates deterioration in dewatering performance or decrease in solid capture rate and vice versa. Yield stress of centrate in the same way as the digested sludge exhibited an increasing trend with the increase of its corresponding total solid concentrations, volatile solid concentrations and COD as shown in Fig. 6.28 (a), Fig. 6.28 (b) and Fig. 6.28 (c). Hence, totals solid concentration or volatile solid concentration or COD of centrate and/or the corresponding yield stress values can be used as indicators of the biosolid capture rate or performance of the dewatering unit. Continuous monitoring of these parameters can be used as a tool to control the quality of the biosolid (Girovich 1996, Wang et al. 2009, Farno et al. 2016).

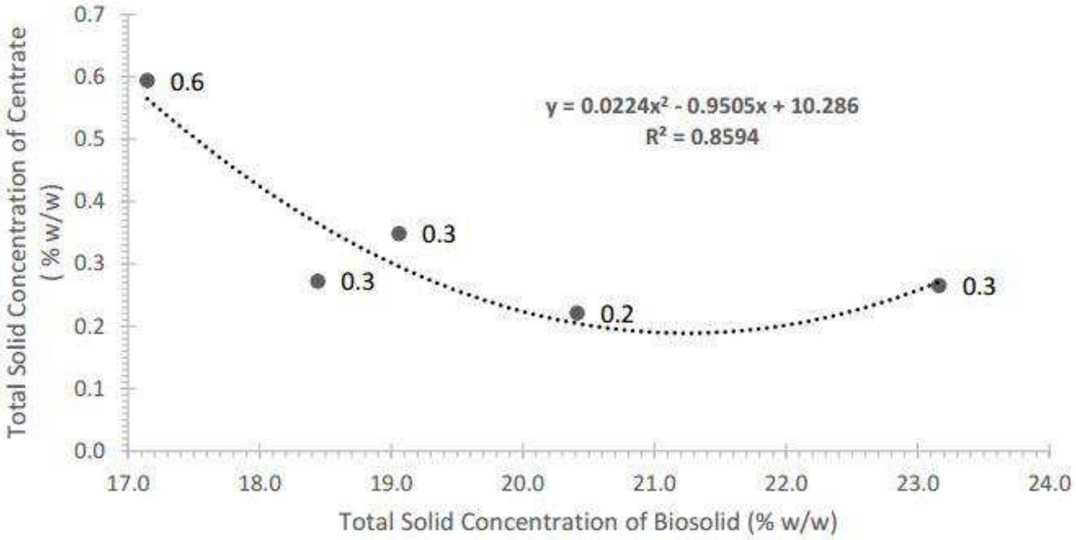


Fig. 6.27 The relationship between total solid concentration of centrate and the effects on biosolid capture rate

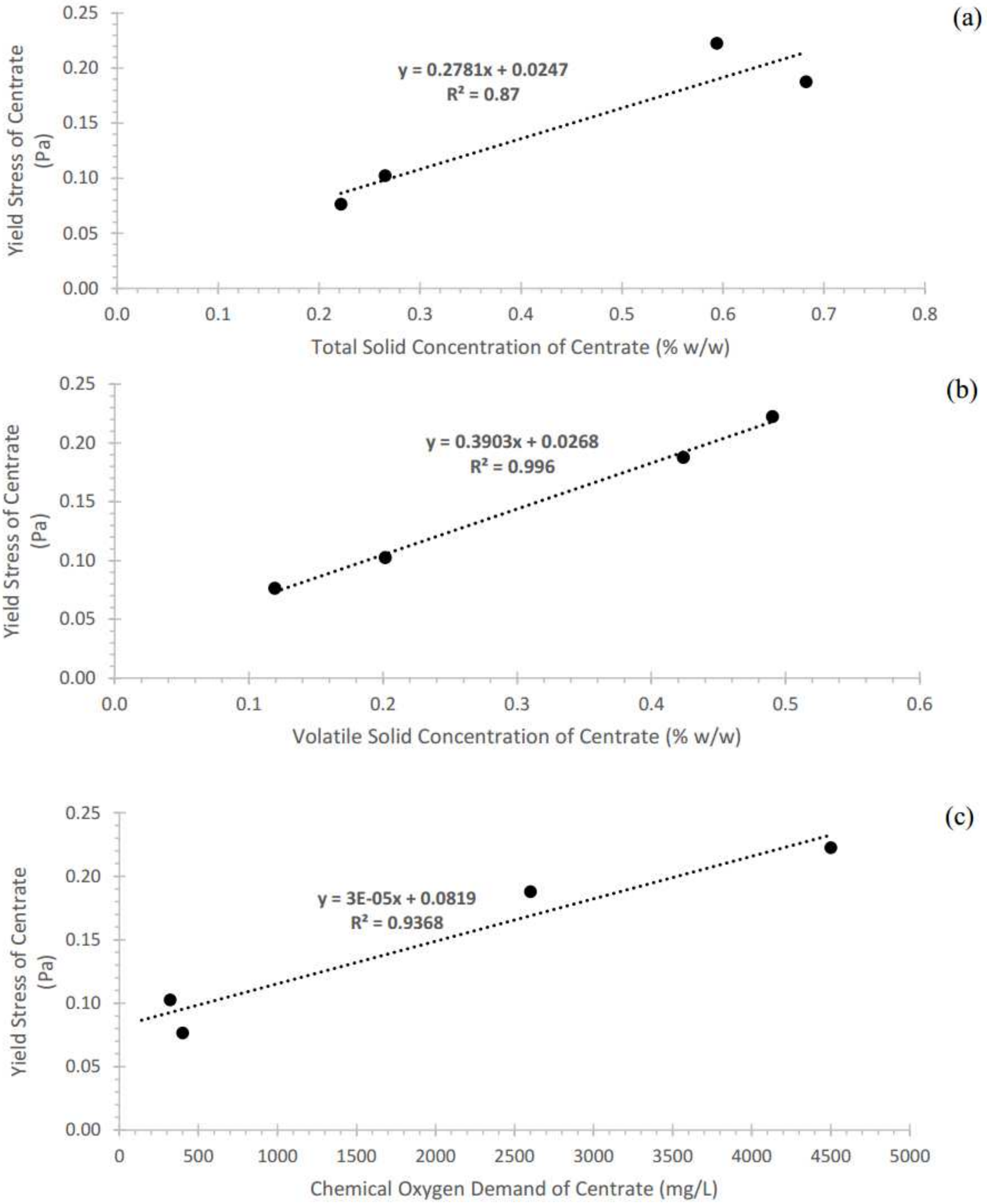


Fig. 6.28 The relationship between yield stress of centrate and (a) total solid concentration (b) volatile solid concentration (c) chemical oxygen demand

6.3.12 Rheology as a tool to optimize polymer dose and biosolid capture rate (relationship between Biosolid capture rate and polymer dose)

The relationship between total solid concentrations of biosolid and reclaimed effluent diluted polymer dose is presented in Fig. 6.29. Based on the practice in BWWTP, WA, the emulsion polymer used for flocculation is diluted by reclaimed effluent. The polymer and the diluting reclaimed effluent are mixed online at the inlet of the centrifuge. The polymer flow rate is mostly kept constant. The increase in total flow rate of the mixture of polymer and the diluting effluent is exclusively due to the increase in the flow rate of the diluting reclaimed effluent only as shown in Fig. 6.29. Hence, more diluted polymer resulted in better dewatering performance by enhancing the solid capture rate as shown in Fig. 6.30. Less diluted polymer samples resulted in lower total solid concentration of biosolid. The addition of effluent for dilution decreases the bicarbonate alkalinity of the sludge, which in turn reduces the consumption of the flocculation polymer (Ayol et al. 2006, Mowla et al. 2013). This result has significant economic importance in terms of reducing polymer consumption. The trend in polymer dose versus biosolid total solid concentration profile shows that optimum total solid concentration of biosolid of 20.4% w/w was achieved for the most diluted polymer dose to digested sludge ratio of 0.19 as shown in Fig. 6.29.

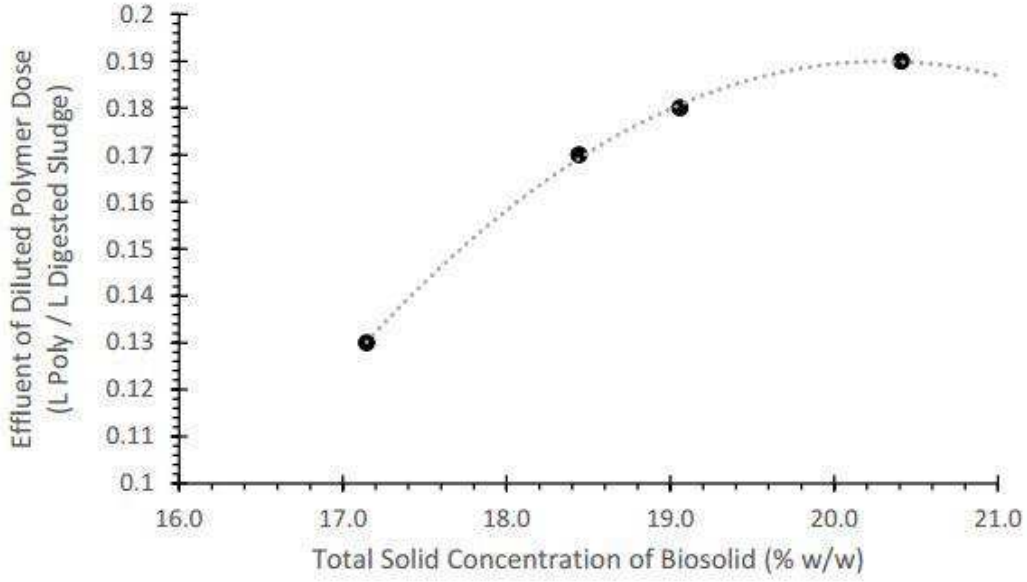


Fig. 6.29 Biosolid total solid concentration against effluent diluted polymer dose

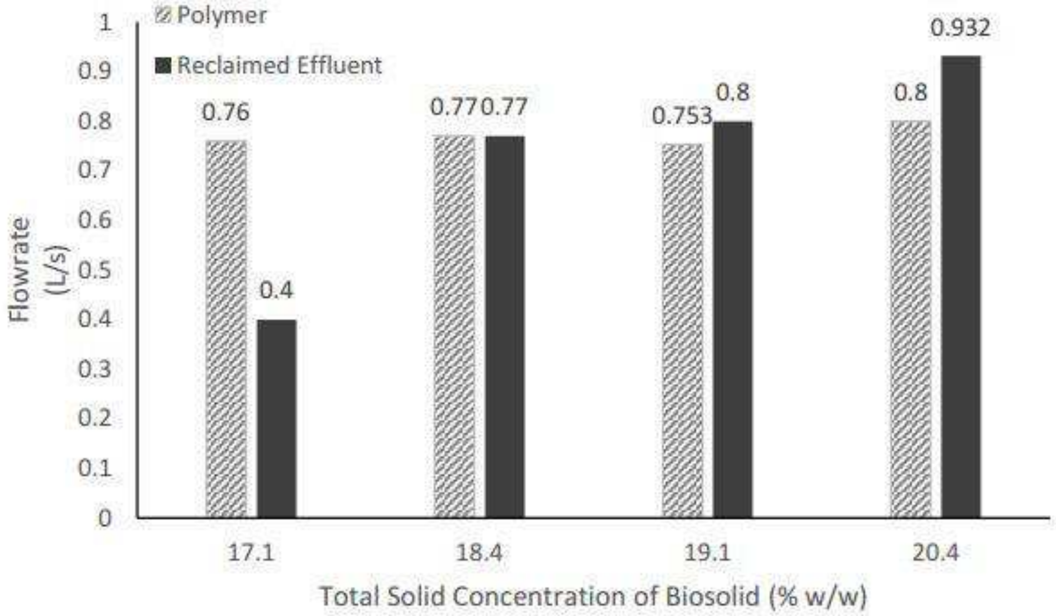


Fig. 6.30 Total solid concentration of biosolid with respect to flow rate of polymer and reclaimed effluent

6.3.13 The impacts of total solid concentration of digested sludge and polymer dose on dewaterability

The impacts of change in total solid concentration of the digested sludge and polymer dose on dewaterability and the rheological behaviour of digested sludge were also investigated in this work. The polymer doses and the total solid concentration were selected based on our previous research on polymer dose optimization for the same sludge type (Yeneneh et al. 2016). The experiments on the dewaterability of digested sludge for varying polymer dose and total solid concentration shows that optimum dewaterability was achieved for the lowest total solid concentration of 1.4% w/w and polymer dose of 15kg/t DS as shown in Table 6.6 and Fig. 6.31 respectively. Decrease in total solid concentration reduced the polymer consumption and improved the dewaterability of the digested sludge (Hou et al. 2003, Mowla et al. 2013). The rheological behaviour of polymer conditioned digested sludge in terms of yield stress for varying total solid concentration is also presented in Fig. 6.32. The increasing trend in yield stress from 0.36 Pa to 2.13 Pa with the increase of the total solid concentration of polymer conditioned digested sludge from 1.3- 2 %w/w comply with the trend reported in section 3.3. Hence, total solid concentration of digested sludge and its corresponding yield stress can be used to optimize polymer dose. Likewise, the viscosity of polymer conditioned digested sludge for varying polymer doses can also serve as a monitoring tool to optimize polymer dose as reported in our previous work (Yeneneh et al. 2016). Furthermore, the decreasing trend in TCOD with the reduction of total solid concentration shown in Table 6.6 and the resulting improvement in dewaterability justifies the results discussed in above sections.

Table 6.6 Characteristic of digested sludge with varying total solid concentration

Characteristic parameters	**Sample 1**	**Sample 2**	**Sample 3**
Total Solid Concentration (% w/w)	1.40	1.70	1.80
Temperature (˚C)	29	29	29
Conductivity (mS)	5.05	6.14	6.5
Total Chemical Oxygen Demand (ppm)	13900	16900	17900
Total Soluble Chemical Oxygen Demand (ppm)	1866	2266	2400

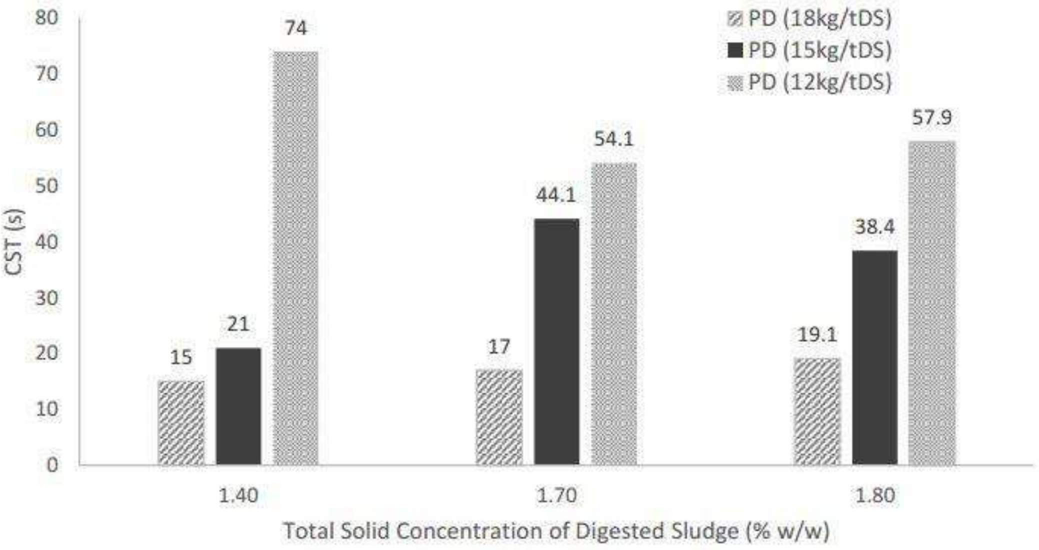


Fig. 6.31 Dewaterability of digested sludge for varying total solid concentration and polymer dose

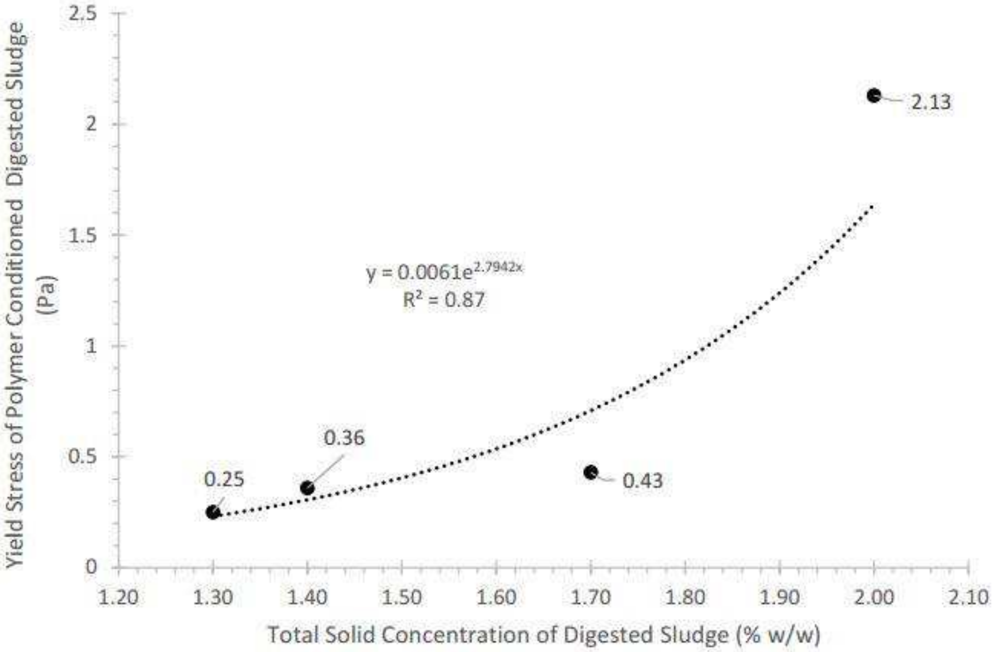


Fig. 6.32 Yield stress of polymer conditioned digested sludge for varying total solid concentration

6.4 Conclusion

In can be concluded that temperature, total solid concentration and polymer dose significantly affect the dewaterability and rheological behaviour of digested sludge. In this study, shear stress-shear rate and viscosity shear rate profiles were developed and the dewaterability and yield stress were determined for varying total solid concentration, temperature and polymer dose and the relationship between physico-chemical and rheological characteristics of digested sludge, centrate, and biosolid and the effects on dewatering performance and biosolid capture rate were investigated. Maintaining the temperature of the digested sludge at the digester operating condition of 35-36˚C was found to be beneficial to the dewatering process. The total solid content particularly the organic fraction of the solid which is composed of polymeric substances (protein, polysaccharides etc.) is responsible for the significant variation in the rheological property of digested sludge. The biodegradation of organics enhances the shear thinning behaviour; yield stress and viscosity reduce gradually over time which is because of the change in composition of key components like protein, lipid and carbohydrate with the age of the sludge and due to synthesis of volatile fatty acids. Digested sludge conditioning and flocculation process is also significantly affected by temperature and solid concentration; hence, polymer consumption can be reduced by operating the dewatering process at optimum temperature condition and varying the polymer dose as a function of total solid concentration of the digested sludge. The hysteresis test shows that digested sludge exhibits shear-thinning thixotropic behaviour in the hysteresis loop. In general, digested sludge, centrate and biosolid showed non-Newtonian rheological flow behaviour. Interesting inverse relationship was observed between volatile solid content of digested sludge fed to the centrifuge and biosolid capture rate that lower total and volatile solid content of digested sludge resulted in higher biosolid capture rate. The corresponding yield stress and viscosity of digested sludge showed an increasing trend with increasing total and volatile solid concentration. The decrease in COD of the digested sludge also improved the biosolid capture rate and the rheological flow behaviour of the digested sludge flocs. Rheological behaviour of digested sludge and polymer dose consumption were found to depend on total solid concentration, volatile solid concentration and COD of the digested sludge. Optimum dewaterability was achieved for the lowest total solid concentration of 1.4% w/w and polymer dose of 15kg/t DS. Likewise, physico-chemical and rheological properties of centrate were observed to vary proportionally with biosolid capture rate. Hence, analysis of total solid content, volatile solid content, COD and rheology of centrate can also be used as a tool to monitor dewatering performance. Moreover, dilution of digested sludge or the conditioning polymer by reclaimed effluent from the wastewater treatment plant helps to reduce polymer consumption. Polymer dose optimization and monitoring can be conducted by using rheological parameters like yield stress and viscosity, total solid concentration and volatile solid concentration or COD of the digested sludge or centrate. Direct or indirect online measurement of these parameters will help to make monitoring and control of dewatering performance more efficient.

Reference

[1] Abu-Jdayil, Basim, Fawzi Banat, and Mukheled Al-Sameraiy. 2010. "Steady Rheological Properties of Rotating Biological Contactor (RBC) Sludge." *Journal of Water Resource and Protection* no. 2 (1):1-7. doi: 10.4236/jwarp.2010.21001.

[2] Abu-Orf, M., and S. Dentel. 1999. "Rheology as Tool for Polymer Dose Assessment and Control." *Journal of Environmental Engineering* no. 125 (12):1133-1141. doi: doi:10.1061/(ASCE)0733-9372(1999)125:12(1133).

[3] Abu-Orf, Mohammad M., and Banu Örmeci. 2005. "Measuring Sludge Network Strength Using Rheology and Relation to Dewaterability, Filtration, and Thickening—Laboratory and Full-Scale Experiments." *Journal of Environmental Engineering* no. 131 (8):1139-1146. doi: 10.1061/(ASCE)0733-9372(2005)131:8(1139).

[4] Ayol, A., A. Filibeli, and S.K. Dentel. 2006. "Evaluation of conditioning responses of thermophilic-mesophilic anaerobically and mesophilic aerobically digested biosolids using rheological properties." *Water Science and Technology* no. 54 (5):23-31. doi: 10.2166/wst.2006.543.

[5] Baroutian, Saeid, Nicky Eshtiaghi, and Daniel J. Gapes. 2013. "Rheology of a primary and secondary sewage sludge mixture: Dependency on temperature and solid concentration." *Bioresource Technology* no. 140:227-233. doi: http://dx.doi.org/10.1016/j.biortech.2013.04.114.

[6] Baudez, J. C., F. Markis, N. Eshtiaghi, and P. Slatter. 2011. "The rheological behaviour of anaerobic digested sludge." *Water Research* no. 45 (17):5675-5680. doi: http://dx.doi.org/10.1016/j.watres.2011.08.035.

[7] Baudez, Jean-Christophe. 2008. "Physical aging and thixotropy in sludge rheology." *Applied Rheology* no. 18:1123-1139.

[8] Baudez, Jean-Christophe, and Philippe Coussot. 2001. "Rheology of aging, concentrated, polymeric suspensions: Application to pasty sewage sludges." *Journal of Rheology* no. 45 (5):1123-1140. doi: 10.1122/1.1392298.

[9] Campbell, H.W., and P.J. Crescuolo. 1983. Assessment of sludge conditionability using rheological properties. Paper read at E.E.C. Workshop Methods of Characterization of Sewage Sludge, at Dublin, Ireland.

[10] Eshtiaghi, Nicky, Flora Markis, Shao Dong Yap, Jean-Christophe Baudez, and Paul Slatter. 2013. "Rheological characterisation of municipal sludge: A review." *Water Research* no. 47 (15):5493-5510. doi: http://dx.doi.org/10.1016/j.watres.2013.07.001.

[11] Farno, Ehsan, Jean Christophe Baudez, Rajarathinam Parthasarathy, and Nicky Eshtiaghi. 2016. "Impact of thermal treatment on the rheological properties and composition of waste activated sludge: COD solubilisation as a footprint of rheological changes." *Chemical Engineering Journal* no. 295:39-48. doi: http://dx.doi.org/10.1016/j.cej.2016.03.022.

[12] Farno, Ehsan, Rajarathinam Parthasarathy, Jean Christophe Baudez, and Nicky Eshtiaghi. 2013. Effect of Thermal History on Municipal Digested Sludge Rheology: Experimental and Modeling. In *Chemeca 2013*.

[13] Forster, CF. 1981. "Preliminary studies on the relationship between sewage sludge viscosities and the nature of the surfaces of the component particles." *Biotechnology Letters* no. 3 (12):707-712.

[14] Girovich, Mark J. 1996. *Biosolids Treatment and Management: Processes for Beneficial Use*: CRC Press.

[15] Hasar, Halil, Cumali Kinaci, Ayhan Ünlü, Hasan Toğrul, and Ubeyde Ipek. 2004. "Rheological properties of activated sludge in a sMBR." *Biochemical Engineering Journal* no. 20 (1):1-6. doi: http://dx.doi.org/10.1016/j.bej.2004.02.011.

[16] Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016a. "Rheological characteristics of mixture of raw primary and thickened excess activated sludge: impact of mixing ratio, solid concentration, temperature and sludge age." *Desalination and Water Treatment* no. 57 (44):20726-20737. doi: 10.1080/19443994.2015.1115374.

[17] Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016b. "Rheological characteristics of municipal thickened excess activated sludge (TEAS): impacts of pH, temperature, solid concentration and polymer dose." *Research on Chemical Intermediates* no. 42 (8):6567–6585. doi: 10.1007/s11164-016-2482-2.

[18] Hou, Chia-Hung, and Kung-Cheh Li. 2003. "Assessment of sludge dewaterability using rheological properties." *Journal of the Chinese Institute of Engineers* no. 26 (2):221-226. doi: 10.1080/02533839.2003.9670772.

[19] Houghton, Jennifer I., and Tom Stephenson. 2002. "Effect of influent organic content on digested sludge extracellular polymer content and dewaterability." *Water Research* no. 36 (14):3620-3628. doi: http://dx.doi.org/10.1016/S0043-1354(02)00055-6.

[20] Khalili Garakani, A. H., N. Mostoufi, F. Sadeghi, M. Hosseinzadeh, H. Fatourechi, M. H. Sarrafzadeh, and M. R. Mehrnia. 2011. "Comparison Between Different Models for Rheological Characterization of Activated Sludge." *Iranian Journal of Environmental Health Science & Engineering* no. 8 (3):255-264.

[21] Lay, Jiunn-Jyi, Young-Joon Lee, and Tatsuya Noike. 1999. "Feasibility of biological hydrogen production from organic fraction of municipal solid waste." *Water Research* no. 33 (11):2579-2586. doi: http://dx.doi.org/10.1016/S0043-1354(98)00483-7.

[22] Lotito, V., L. Spinosa, G. Mininni, and R. Antonacci. 1997. "The rheology of sewage sludge at different steps of treatment." *Water Science and Technology* no. 36 (11):79-85. doi: http://dx.doi.org/10.1016/S0273-1223(97)00672-0.

[23] Lotito, Vincenzo, and Adriana Maria Lotito. 2014. "Rheological measurements on different types of sewage sludge for pumping design." *Journal of Environmental Management* no. 137 (0):189-196. doi: http://dx.doi.org/10.1016/j.jenvman.2014.02.005.

[24] Markis, Flora, Jean-Christophe Baudez, Rajarathinam Parthasarathy, Paul Slatter, and Nicky Eshtiaghi. 2014. "Rheological characterisation of primary and secondary sludge: Impact of solids concentration." *Chemical Engineering Journal* no. 253 (0):526-537. doi: http://dx.doi.org/10.1016/j.cej.2014.05.085.

[25] Mori, M., I. Seyssiecq, and N. Roche. 2006. "Rheological measurements of sewage sludge for various solids concentrations and geometry." *Process Biochemistry* no. 41 (7):1656-1662. doi: http://dx.doi.org/10.1016/j.procbio.2006.03.021.

[26] Mowla, D., H. N. Tran, and D. Grant Allen. 2013. "A review of the properties of biosludge and its relevance to enhanced dewatering processes." *Biomass and Bioenergy* no. 58:365-378. doi: http://dx.doi.org/10.1016/j.biombioe.2013.09.002.

[27] Neyens, Elisabeth, Jan Baeyens, Raf Dewil, and Bart De heyder. 2004. "Advanced sludge treatment affects extracellular polymeric substances to improve activated sludge dewatering." *Journal of Hazardous Materials* no. 106 (2–3):83-92. doi: http://dx.doi.org/10.1016/j.jhazmat.2003.11.014.

[28] Örmeci, Banu. 2007. "Optimization of a full-scale dewatering operation based on the rheological characteristics of wastewater sludge." *Water Research* no. 41 (6):1243-1252. doi: http://dx.doi.org/10.1016/j.watres.2006.12.043.

[29] Piani, Luciano, Claudia Bruna Rizzardini, Adriano Papo, and Daniele Goi. 2014. "Rheology Measurements for Online Monitoring of Solids in Activated Sludge Reactors of Municipal Wastewater Treatment Plant." *The Scientific World Journal* no. 2014:6. doi: 10.1155/2014/590961.

[30] Raszka, Anna, Monika Chorvatova, and Jiri Wanner. 2006. "The role and significance of extracellular polymers in activated sludge. Part I: Literature review." *Acta hydrochimica et hydrobiologica* no. 34 (5):411-424. doi: 10.1002/aheh.200500640.

[31] Ratkovich, N., W. Horn, F. P. Helmus, S. Rosenberger, W. Naessens, I. Nopens, and T. R. Bentzen. 2013. "Activated sludge rheology: A critical review on data collection and modelling." *Water Research* no. 47 (2):463-482. doi: http://dx.doi.org/10.1016/j.watres.2012.11.021.

[32] Sanin, F. Dilek. 2002. "Effect of solution physical chemistry on the rheological properties of activated sludge." *Water SA* no. 28 (2):207-212.

[33] Seyssiecq, Isabelle, Jean-Henry Ferrasse, and Nicolas Roche. 2003. "State-of-the-art: rheological characterisation of wastewater treatment sludge." *Biochemical Engineering Journal* no. 16 (1):41-56. doi: http://dx.doi.org/10.1016/S1369-703X(03)00021-4.

[34] Show, Kuan-Yeow, Taohong Mao, and Duu-Jong Lee. 2007. "Optimisation of sludge disruption by sonication." *Water Research* no. 41 (20):4741-4747. doi: http://dx.doi.org/10.1016/j.watres.2007.07.017.

[35] Sun, Yongjun, Huaili Zheng, Jun Zhai, Houkai Teng, Chun Zhao, Chuanliang Zhao, and Yong Liao. 2014. "Effects of Surfactants on the Improvement of

Sludge Dewaterability Using Cationic Flocculants." *PLoS ONE* no. 9 (10):e111036. doi: 10.1371/journal.pone.0111036.

[36] Wang, L.K., N.K. Shammas, and Y.T. Hung. 2009. *Biosolids Engineering and Management*: Humana Press.

[37] Wang, YL, and SK Dentel. 2010. "The effect of high speed mixing and polymer dosing rates on the geometric and rheological characteristics of conditioned anaerobic digested sludge (ADS)." *Water research* no. 44 (20):6041-6052.

[38] Yang, Fei, Amos Bick, Semion Shandalov, Asher Brenner, and Gideon Oron. 2009. "Yield stress and rheological characteristics of activated sludge in an airlift membrane bioreactor." *Journal of Membrane Science* no. 334 (1–2):83-90. doi: http://dx.doi.org/10.1016/j.memsci.2009.02.022.

[39] Yen, Pei-Shan, L. C. Chen, C. Y. Chien, Rome-Ming Wu, and D. J. Lee. 2002. "Network strength and dewaterability of flocculated activated sludge." *Water Research* no. 36 (3):539-550. doi: http://dx.doi.org/10.1016/S0043-1354(01)00260-3.

[40] Yeneneh, Anteneh Mesfin. 2014. *Study on performance enhancement of anaerobic digestion of municipal sewage sludge*. PhD Thesis, Chemical Engineering Department, Curtin University, Perth, Australia.

[41] Yeneneh, Anteneh Mesfin, Eugene Hong, Tushar Kanti Sen, Ahmet Kayaalp, and Ha Ming Ang. 2016. "Effects of Temperature, Polymer Dose, and Solid Concentration on the Rheological Characteristics and Dewaterability of Digested Sludge of Wastewater Treatment Plant (WWTP)." *Water, Air, & Soil Pollution* no. 227 (4):119. doi: 10.1007/s11270-016-2820-4.

[42] Yeneneh, Anteneh Mesfin, Ahmet Kayaalp, Tushar Kanti Sen, and Ha Ming Ang. 2015. "Effect of Combined Microwave-Ultrasonic Pretreatment of Real Mixed Sludge on the Enhancement of Anaerobic Digester Performance." *Water, Air, & Soil Pollution* no. 226 (9):1-14. doi: 10.1007/s11270-015-2586-0.

[43] Yin, Xuan, Pingfang Han, Xiaoping Lu, and Yanru Wang. 2004. "A review on the dewaterability of bio-sludge and ultrasound pretreatment." *Ultrasonics Sonochemistry* no. 11 (6):337-348. doi: http://dx.doi.org/10.1016/j.ultsonch.2004.02.005.

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CHAPTER 7

ANFIS BASED MODELLING OF DEWATERING PERFORMANCE AND POLYMER DOSE OPTIMIZATION IN A WASTEWATER TREATMENT PLANT

Abstract

Anaerobic digestion coupled with dewatering is a common and widely used sludge treatment methods in a wastewater treatment plants (WWTP). Many researchers have employed adaptive neuro-fuzzy logic inference system (ANFIS) successfully to optimize the output of anaerobic digesters. However, there is no published work on the application of ANFIS to optimize the performance of the dewatering section of a WWTP. In this study, ANFIS was applied to model the relationship between biosolid quality (total solid content in biosolid) to total solid, volatile solid content, volatile fatty acid of digested sludge and polymer dose. Historical data on various physico-chemical process parameters such as total solid, volatile solid, volatile fatty acid content of digested sludge, total solid content of biosolid and polymer dose from the dewatering section of a WWTP over a period of four years was used for the analysis. Approximately 500 data points were selected from the historical data. The modelling study showed that the optimum total solid content (DS TS) was in the lower DS TS range of 1.3-1.5% w/w and the optimum volatile solid content (DS VS) was also in the lower DS VS range of 70-75% of TS of the digested sludge. The Optimum polymer dose was determined to be in the lower polymer dose range of 20 to 60 kg/ton of dry solid (kg/TDS) showing better biosolid capture compared to higher polymer dose ranges for the same total solid and volatile solid content. Generally, it can be observed that lower total solid and volatile solid concentration coupled with relatively low polymer dose corresponds to relatively higher biosolid capture rate. The relationships between biosolid capture rate, total solid concentration, volatile solid concentration, volatile fatty acid content and polymer dose can be effectively established and useful predictions and optimization can be made using ANFIS.

Ref: Hong, Eugene, Anteneh Mesfin Yeneneh, Tushar Kanti Sen, Ahmet Kayaalp, and Ha Ming Ang. n.d. "ANFIS based modelling of dewatering performance and polymer dose optimization in wastewater treatment plant" Journal of Environmental Chemical Engineering

7.1 Introduction

One of the most common and widely used sludge treatment methods in a wastewater treatment plants (WWTP) is anaerobic digestion coupled with dewatering (Husain 1998, Park 2011). This method commonly involves anaerobic digestion of thickened activated sludge to form digested sludge followed by centrifugal dewatering. Conventionally, excess activated sludge (EAS) thickened with dissolved air flotation thickeners will be mixed with RPS and the mixture is fed to the anaerobic digesters and ultimately processed in the dewatering centrifuges. The dewatering process depends on many process parameters including conditioning agent dose, temperature, total solid content, pH and much more (Clauss et al. 1998, Ratkovich et al. 2013). According to Gerber et al. (2008) and Yeneneh (2014), modelling of the anaerobic digestion process in WWTPs has been well investigated from design, operation and control point of view. However, there are no or few published literature on modelling of the relationship between physico-chemical characteristics of digested sludge to dewatering performance. Modelling of the dewatering system is important, as it enables a better understanding, simulation and prediction of the sludge behaviour within the dewatering unit and is also a key factor to further improve the efficiency in sludge management while maintaining lower operational cost (Heddam et al. 2012).

In this study, adaptive neural fuzzy inference systems (ANFIS) prediction tool in MATLAB was used. Several researchers have shown that this method can be employed successfully to predict and control product quality upstream and downstream of WWTPs. They also proposed that the performance of the dewatering unit and the quality of biosolid and conditioning agent dose (polymer) can be well predicted and optimized using the ANFIS modelling (Tay et al. 1999, Mjalli et al. 2007, Wu et al. 2008, Heddam et al. 2012, Atasoy et al. 2013, Ay et al. 2014). However, there is no published work on the use of ANFIS modelling for the optimization of the performance dewatering process based on the physico-chemical characteristic of digested sludge such as total solid and volatile solid content.

ANFIS would interpret the input vector and assign an output value utilizing fuzzy If-Then rule. This process involves a method which is based on hybrid learning or back propagation algorithm commonly known as a first-order Sugeno-fuzzy model which has the adaptive capabilities similar to neural network integrated into its qualitative logic (Perendeci et al. 2008). Furthermore, ANFIS method can be applied to different parameter of nonlinear relationship with different inputs and outputs in various areas while producing good predictive results. ANFIS model is also simpler to construct when compared to other modelling techniques used for similar applications. ANFIS can be trained with new data with varying changes allowing flexibility and adaptability in a manner that the model can be continuously updated (Turkdogan-Aydınol et al. 2010).

Hence, the main objective of this work is to utilize ANFIS model for the application and development of rules that will relate physico-chemical characteristics of digested sludge to biosolid capture rate and polymer dose within the dewatering process. Four years historical data from Beenyup WWTP were used for training, testing, and predictions in this modelling study. The data was normalized before running the simulation for prediction. The model output was compared against the actual training data and the error was minimized to obtain the optimum operational points.

7.2 Material and Method

As the dewatering unit is the process of reducing sludge volume or converting liquid digested sludge feed to biosolid cake, physico-chemical characteristic such as total solid and total volatile content of the feed and product are frequently monitored. For quality purposes, it is essential to understanding the connection between the input variables and output variables to determine the ideal operating conditions and to better understand the relationship between all key performance parameters involved in the process (Perendeci et al. 2007, Erdirencelebi et al. 2011). Therefore, historical data from the dewatering unit of Beenyup WWTP, Western Australia over a period of four years were collected and used for the analysis. Physico-chemical characteristic of digested sludge, centrate and biosolid data were collected every day during this period. From the raw historical data, the total solid and total volatile content of both digested sludge and biosolid were normalized between 0 and 1 and managed in Excel. Furthermore, to increase the accuracy of the model generated, the quality of both training and validation database is vital. Therefore, a preprocessing stage was conducted on the raw data where some and not all redundant data were removed to better describe the system (Tay et al. 2000, Erdirencelebi et al. 2011). Although there were some discrepancies present within the data, the trend between of actual and predicted data were comparable to one another. Considering the fluctuation in the digested sludge physico-chemical characteristic, the predicted output performances were evaluated separately with different combination of input parameters.

Approximately a total of 500 data points were obtained from the historical data. Using software such as Excel, 350 data points were randomly picked and used for training the ANFIS Sugeno model, and remaining points were used for testing and validation purpose. MATLAB with the inbuilt fuzzy logic toolbox was used to analyse and derive the model and functions necessary for the generation of the results. The function 'genfis2' was used to generate the FIS which generated different input and output parameters. Furthermore, minimizing the prediction errors was necessary for the generation of an accurate and representative model for the system. The relationships between the different inputs and outputs were investigated to determine trends and optimum working conditions for the system under investigation.

In this study, the physico-chemical properties of digested sludge were taken as input variables and the biosolid quality (total solid concentration) was the output parameter in this model prediction. 78 nodes with 108 linear and 18 nonlinear parameters were the condition used to define the model structure. A total of 27 fuzzy rules were used to establish the model with three Gaussian member functions as the input member functions with 100 epoch used to evaluate the data. The architecture of the ANFIS test is shown in Fig. 7.1. The model analysis was undertaken for one input one output structure and three input one output structure.

The normalized data set of four years historical data from Beenyup WWTP were used for the prediction model. The normalization was carried out using Equation 7-1. The statistical distribution of the normalized input, output parameters, and the maximum and minimum values of each variable within this study are presented in Table 7.1. The variables used for this analysis are total solid content (TS), volatile solid content (VS) and polymer dose. These parameters were divided into input and output parameters to predict the influence of one parameter to the others. The historical data were normalized after determining the maximum and minimum values for each variable to avoid discrepancies during the model training and prediction. The normalized data set is shown in Fig. 7.2.

The prediction capability of ANFIS model has to be assessed and verified. Mean square error (MSE), root mean square normalized error (RMSE) and correlation coefficients (R-squared) are commonly used as performance indicators to verify and assess ANFIS model prediction capability. The equation for Mean square error (MSE) and root mean square normalized error (RMSE) are shown in Equation 7-2 and 7-3 respectively. The minimum RMSE between the training database and predicted model output was 0.09 with a reasonably good average error for both training and validation database as shown in Fig. 7.3. While the MSE and R-squared values are discussed below.

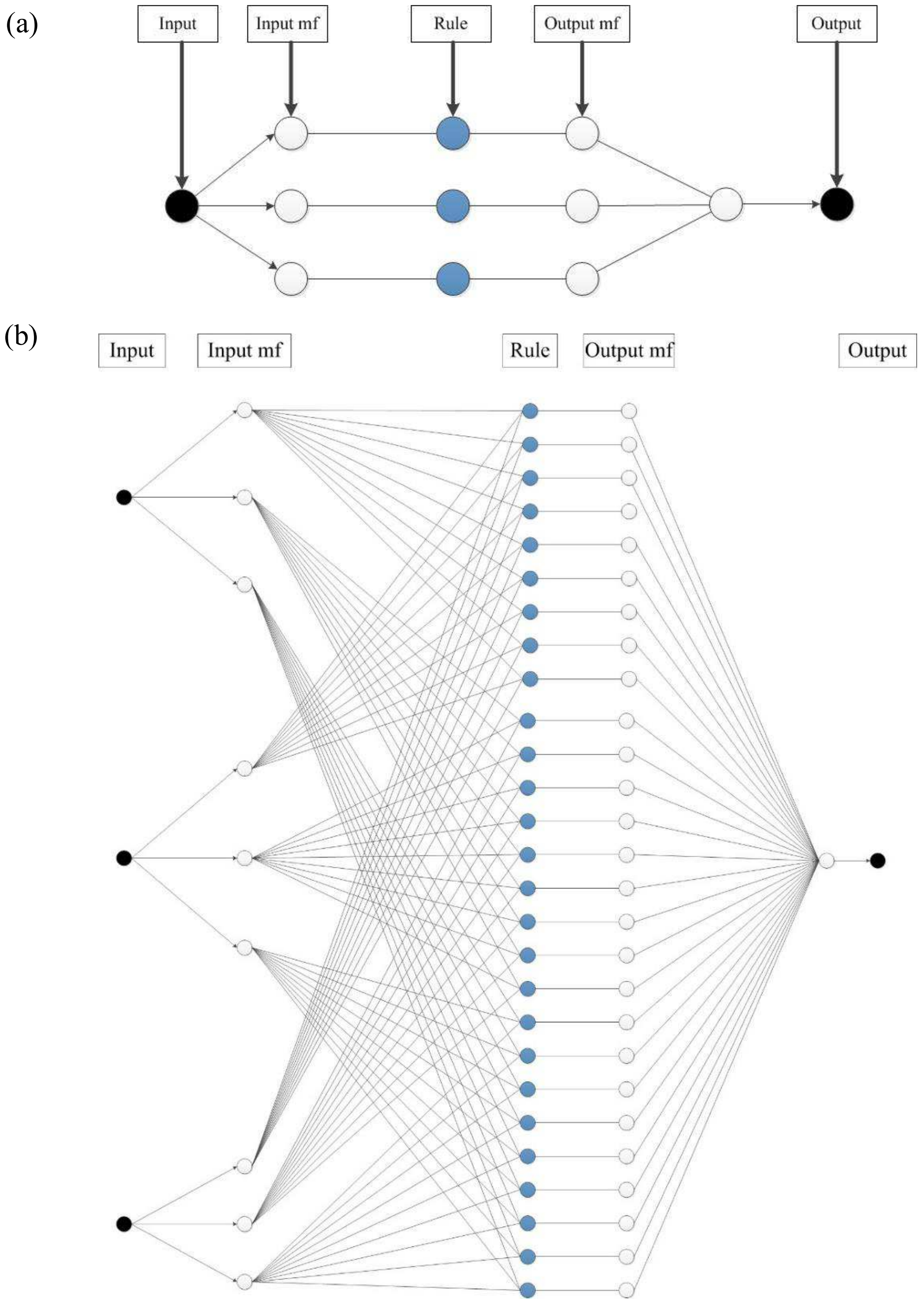

Fig. 7.1 (a) Generic model structure for the prediction one input one output system and (b) model structure of the Fuzzy logic inference model for the prediction of biosolid total solid concentration with three input and three Gaussian member functions.

Table 7.1 Statistical distribution of the normalized operational data used in the building of the ANFIS model.

	Digested Sludge TS (% w/w)	**Digested Sludge VS (% DS TS)**	**Digested Sludge VFA (mg/L)**	**Biosolid TS (% w/w)**	**Polymer Dose (kg/TDS)**
Minimum	1.2	68.9	3.5	11.1	13.1
Maximum	2.3	80.9	77.3	21.5	181.1
Mean	1.8	77.4	12.9	17.7	46.6
Mode	1.66	77.7	7.0	17.8	60.0
Standard Deviation	0.27	1.07	7.45	0.98	20.1
Median	1.8	77.4	11.8	17.7	44.0

$$\text{Normalized value} = \frac{(\text{actual value} - \text{minimum value})}{(\text{maximum value} - \text{minimum value})} \quad (7\text{-}1)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{N}(\tau_{expt,i} - \tau_{pred,i})^2 \quad (7\text{-}2)$$

$$RMSE = (\frac{1}{N} * \sum_{i=1}^{N}[(\tau_{expt,i} - \tau_{pred,i})^2])^{\frac{1}{2}} \quad (7\text{-}3)$$

Where N is the number of data points, $\tau_{expt,i}$ is the experimental data for shear stress and $\tau_{pred,i}$ is the predicted model data.

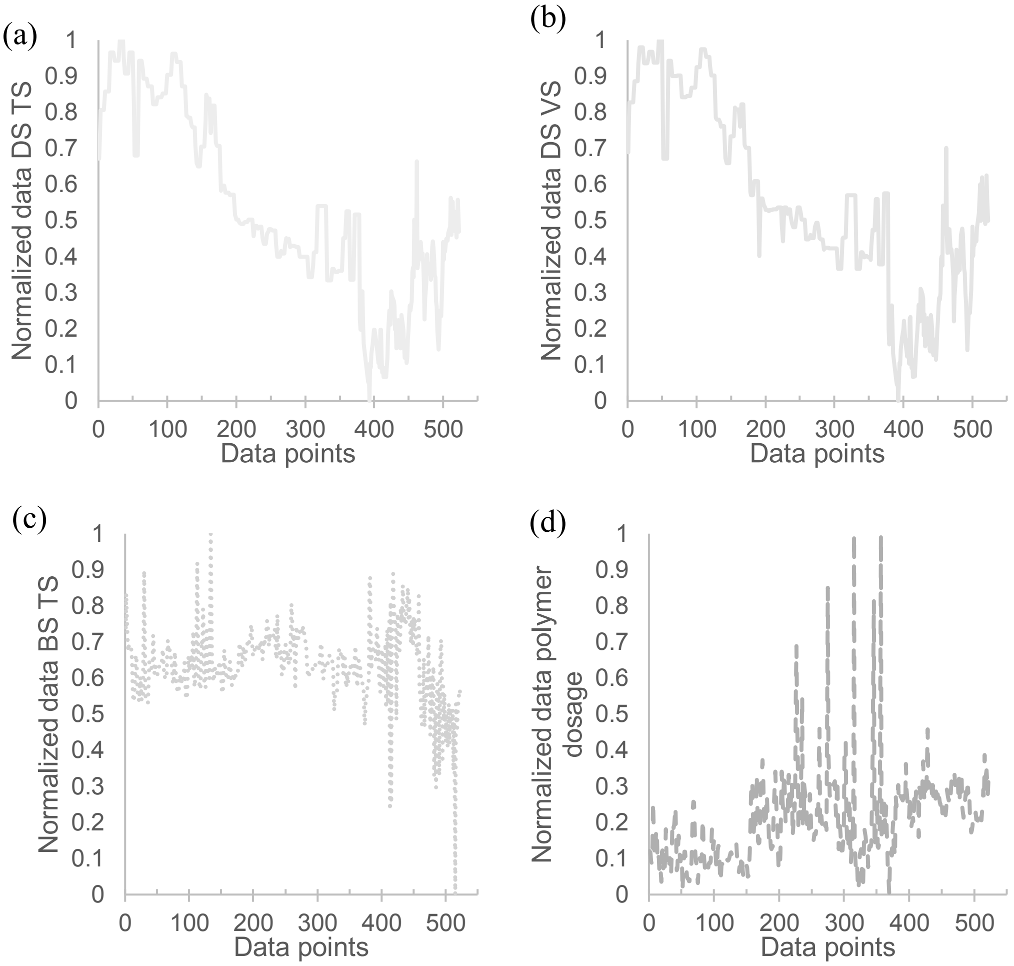

Fig. 7.2 Plot of normalized historical data for (a) digested sludge total solid, (b) digested sludge volatile solid, (c) biosolid total solid content and (d) polymer dosage.

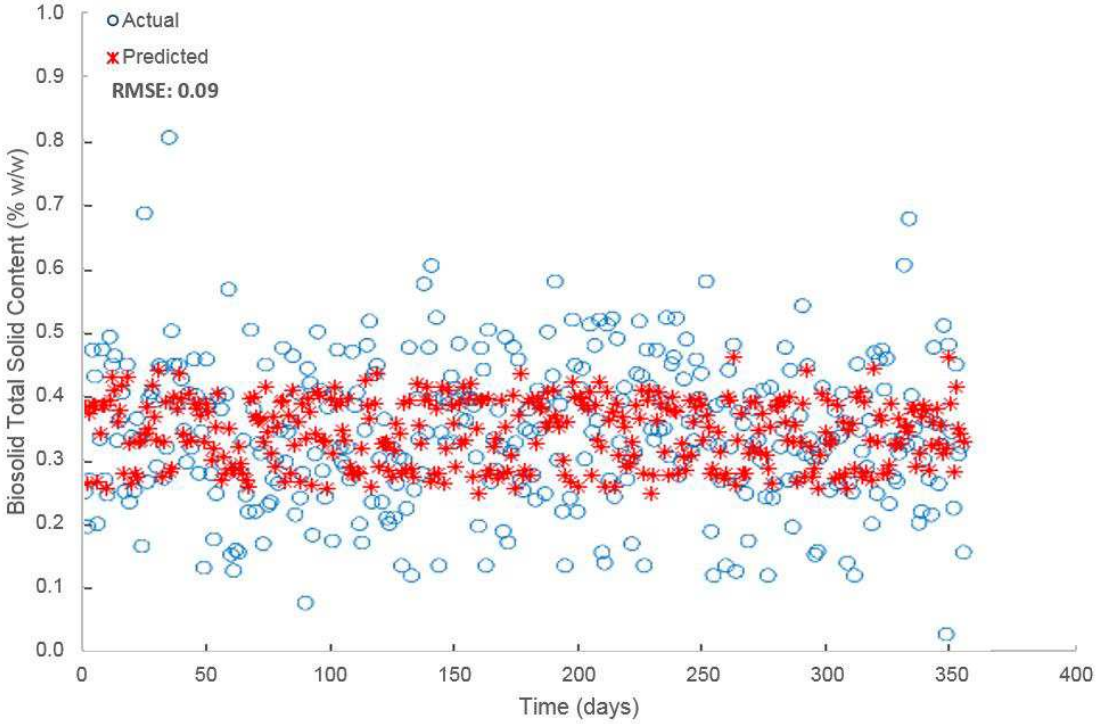

Fig. 7.3 Time plot of actual and predicted data (FIS generated output)

7.3 Results and Discussion

7.3.1 Model based prediction of biosolid capture rate based on digested sludge physico-chemical characteristics.

In this section, the effect of digested sludge total solid, volatile solid and volatile fatty acid content on biosolid capture rate was investigated. The modelling investigation confirmed that significant reduction in total solid and volatile solid concentrations of digested sludge resulted in better quality biosolid (higher total solid concentration in biosolid) as shown in Fig. 7.4(a) and Fig. 7.4(b). This trend provides the advantage of optimizing polymer dose based on the totals solid and volatile solid content of the digested sludge for enhanced dewatering performance and higher biosolid capture rate. Using the model trend and results from digested sludge rheological studies, a correlation equation could potentially be developed to predict the required optimum polymer dose for a desired biosolid capture rate (Yeneneh et al. 2016, Hong et al. 2017). The predicted results generated from the model were compared graphically to the actual data results as shown in Fig. 7.5. Fig. 7.5 indicates that there is a reasonable agreement between model prediction data and actual plant data. Both total solid concentration of digested sludge versus biosolid total solid concentration and the total volatile concentration of digested sludge versus biosolid total solid concentration displayed an R-squared value of 0.78 and 0.81 respectively and MSE value of 0.0054 and 0.0051 respectively. Based on the model, it can be seen that the optimum value for total solid and volatile solid content are within the range of 1.35-1.45% w/w and volatile solid content in the range of 74-75% as also shown in Fig. 7.4.

The other very important operational parameter that is included in the ANFIS prediction is the volatile fatty acid content of the digested sludge. Volatile fatty acid content of the digested sludge indicates the performance of the anaerobic digesters and the quality of the digested sludge (Franke-Whittle et al. 2014). In the historical data analysis, it was observed that increase in volatile fatty acid content corresponds to higher biosolid capture rate as shown in Fig. 7.6(a). This may be related to the effect of volatile fatty acid content on the surface charge distribution of the digested sludge where an increase in the negative charge of the sludge surface enhances the floc formation and dewaterability ultimately resulting in higher cake solid concentration of the biosolid. The predicted results generated from the model were compared graphically to the actual data results as shown in Fig. 7.6(b). It can be seen from Fig. 7.6(b) that the plots of actual and predicted data show an R-squared value of 0.89 and MSE value of 0.004. Based on the model, it can be seen that relatively high biosolid capture rate can be obtained for high volatile fatty acid content (above 70mg/L) as it can be seen in Fig. 7.6(a).

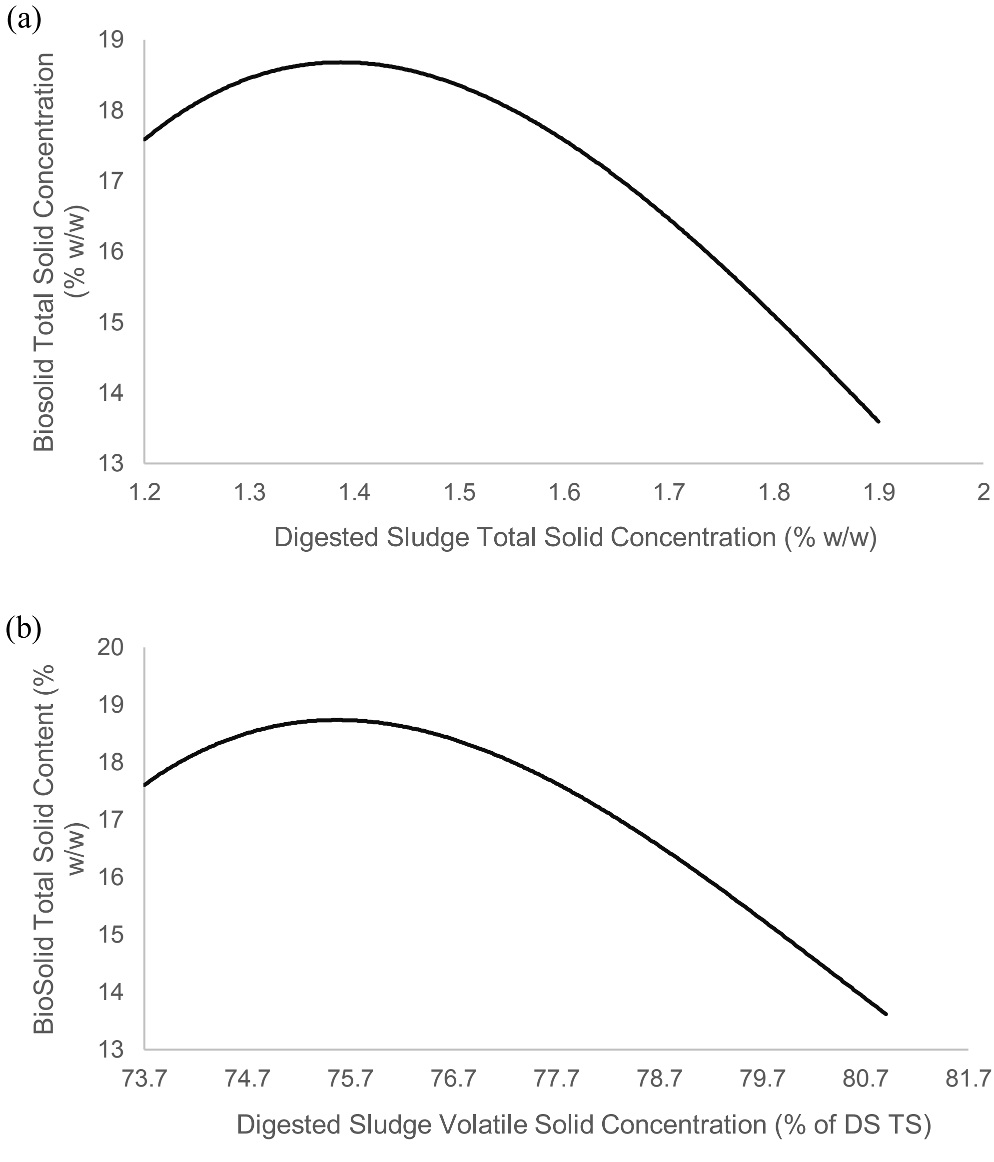

Fig. 7.4 ANFIS based prediction of biosolid total solid concentration for varying (a) total solid concentrations of digested sludge and (b) volatile solid concentrations of digested sludge

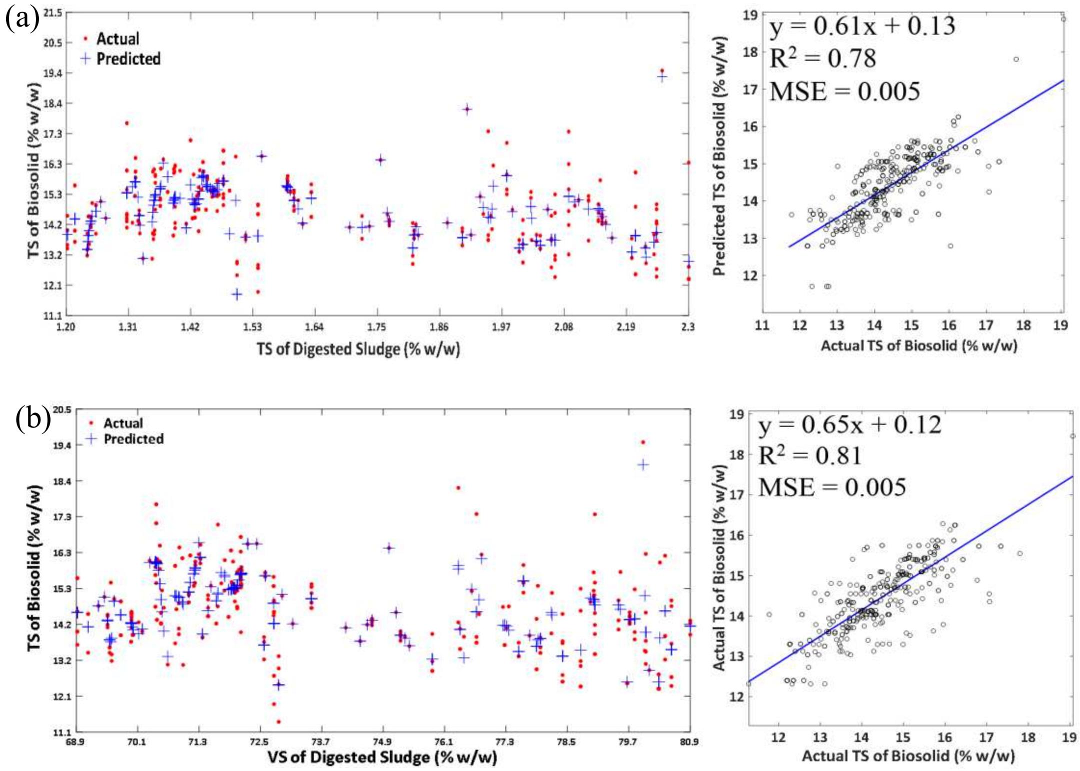

Fig. 7.5 Actual and predicted biosolid total solid concentration based on (a) digested sludge total solid concentration and (b) digested sludge volatile solid concentration.

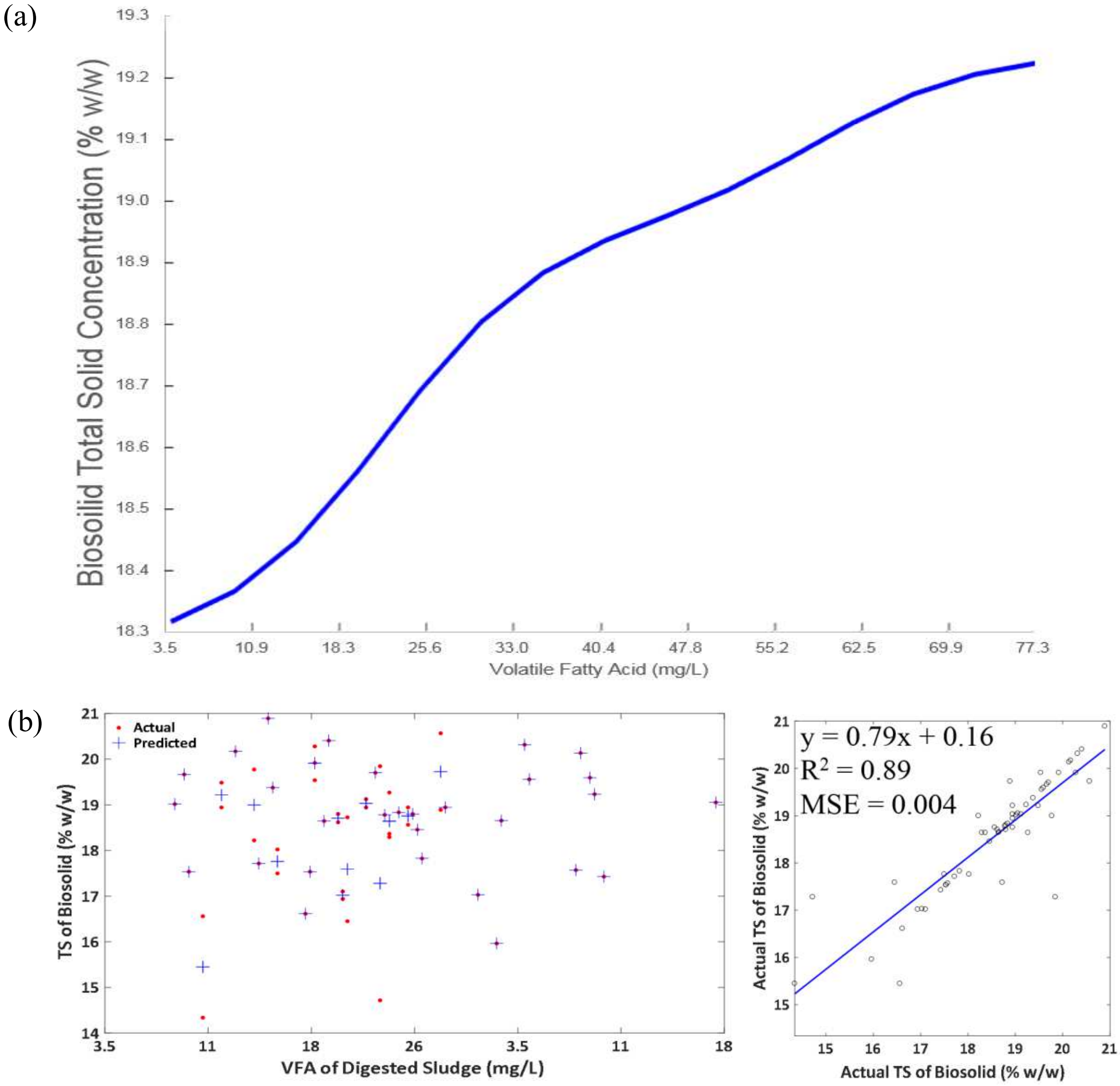

Fig. 7.6 (a) ANFIS based prediction of biosolid total solid concentration for varying volatile fatty acid content of digested sludge and (b) actual and predicted biosolid total solid concentration based on volatile fatty acid content

The effect of two input parameters, total solid and volatile solid concentration of digested sludge on biosolid capture rate was considered for further analysis. The surface response plot in Fig. 7.7 shows a combination of the two inputs, total and volatile solid concentration of digested sludge against cake solid content of the biosolid. The model structure for the surface response is as depicted in Fig. 7.1(b) with the training data set against the predicted plots shows an error of 0.121. Generally lower volatile solid and total solid content results higher biosolid totals solid concentration and higher dewatering performance. Therefore, higher volatile solid removal from the digested sludge during the anaerobic digestion process significantly reduces polymer consumption and enhances biosolid capture rate. Likewise, lower total solid content of digested sludge shows enhanced performance of anaerobic digesters and dewatering unit ultimately resulting in higher biosolid capture rate. Furthermore, it can be seen from Fig. 7.7 that the optimum value for total solid and volatile solid content are within the lower range (0.1-0.4) which correspond to 1.3-1.5% w/w and 70-75% of DS TS supporting the results shown in Fig. 7.4.

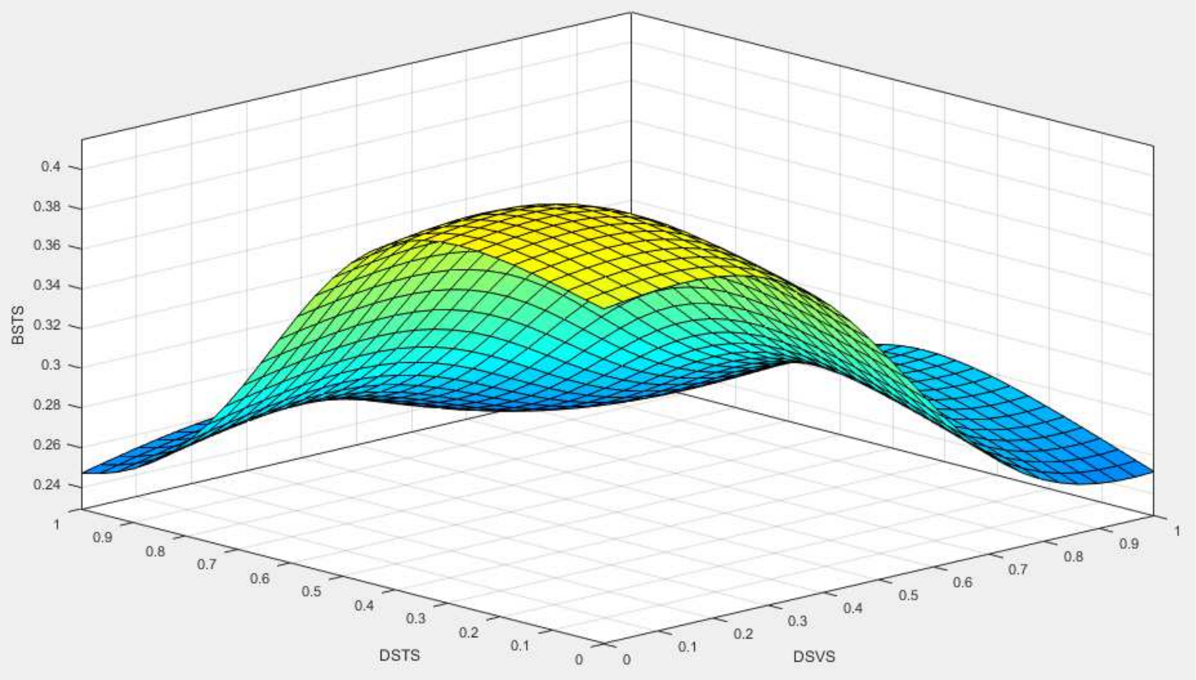

Fig. 7.7 Surface response for digested sludge total solid content (DSTS) and volatile solid and content (DSVS) as an input and biosolid total solid concentration (BSTS) as an output.

7.3.2 ANFIS model prediction for polymer dose optimization on biosolid capture rate

In this section, the effect of polymer dose on biosolid capture rate was investigated. The modelling investigation confirmed that polymer dose in the range between 20 to 60 kg/TDS provided relatively high biosolid capture rates as shown in Fig. 7.8(a). The polymer dose prediction and optimization is of great importance as it helps to manage and optimize polymer consumption for enhanced dewatering performance and improved WWTP economy. Fig. 7.8(a) shows that optimizing the polymer consumption to the lower polymer dose range between 20 to 60 kg/TDS would show better biosolid capture when compared to higher dose ranges. The predicted results generated from the model were compared graphically to the actual dataset as shown in Fig. 7.8(b). It can be seen from Fig. 7.8(b) that the plots of actual and predicted data show that the model performances are overall acceptable with an R-squared value of 0.77 and MSE value of 0.008. Similarly, Yeneneh et al. (2016) and Hong et al. (2017), conducted experimental investigations on digested sludge from the same WWTP and developed correlation equations that relate the physico-chemical characteristics of digested sludge, polymer consumption, biosolid capture rate with rheological properties of digested sludge. The trends observed in the experimental investigations exactly portray similar trend and can ultimately be used to determine the optimum polymer dosage as a function of the physico-chemical properties of digested sludge. The surface response plot for total solid and volatile solid concentration combined with polymer dose on biosolid capture rate is shown as Fig. 7.9. The training dataset resulted in an error of 0.098. Generally, it can be seen that lower total solid and volatile solid concentration coupled with relatively low polymer dose correspond to relatively higher biosolid capture rate. Fig. 7.9 also shows that a digested sludge sample with a total solid concentration of 1.6%w/w and volatile solid concentration of 1.1%w/w is predicted to generate biosolid with a low total solid content of 15%w/w when the polymer dose varies from 86kg/TDS up to 165kg/TDS. From this result, it can be seen that overdosing results in deteriorated dewaterability and low biosolid capture rate.

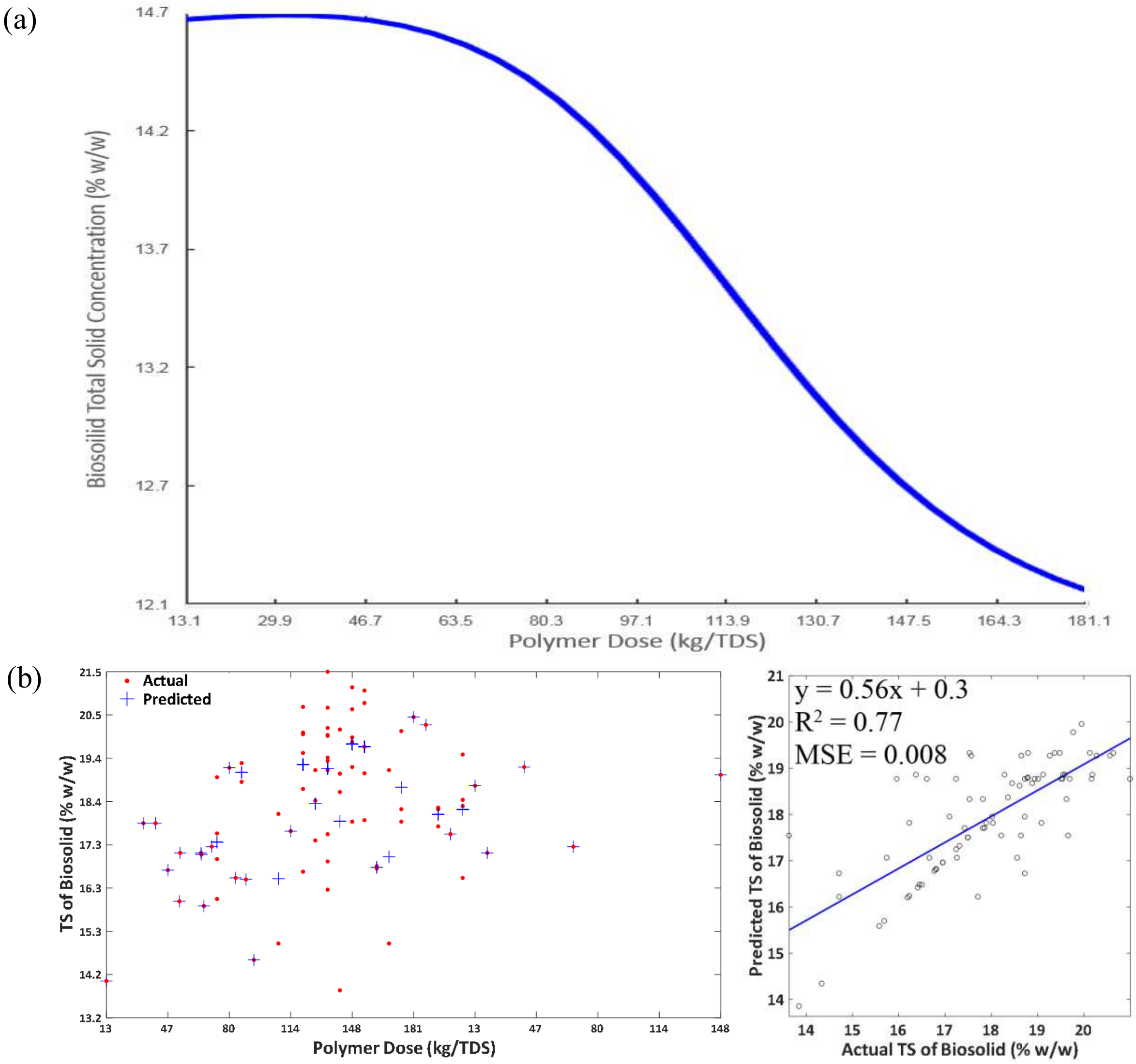

Fig. 7.8 (a) ANFIS based prediction of biosolid total solid concentration for polymer dose and (b) actual and predicted biosolid total solid concentration based on polymer dose

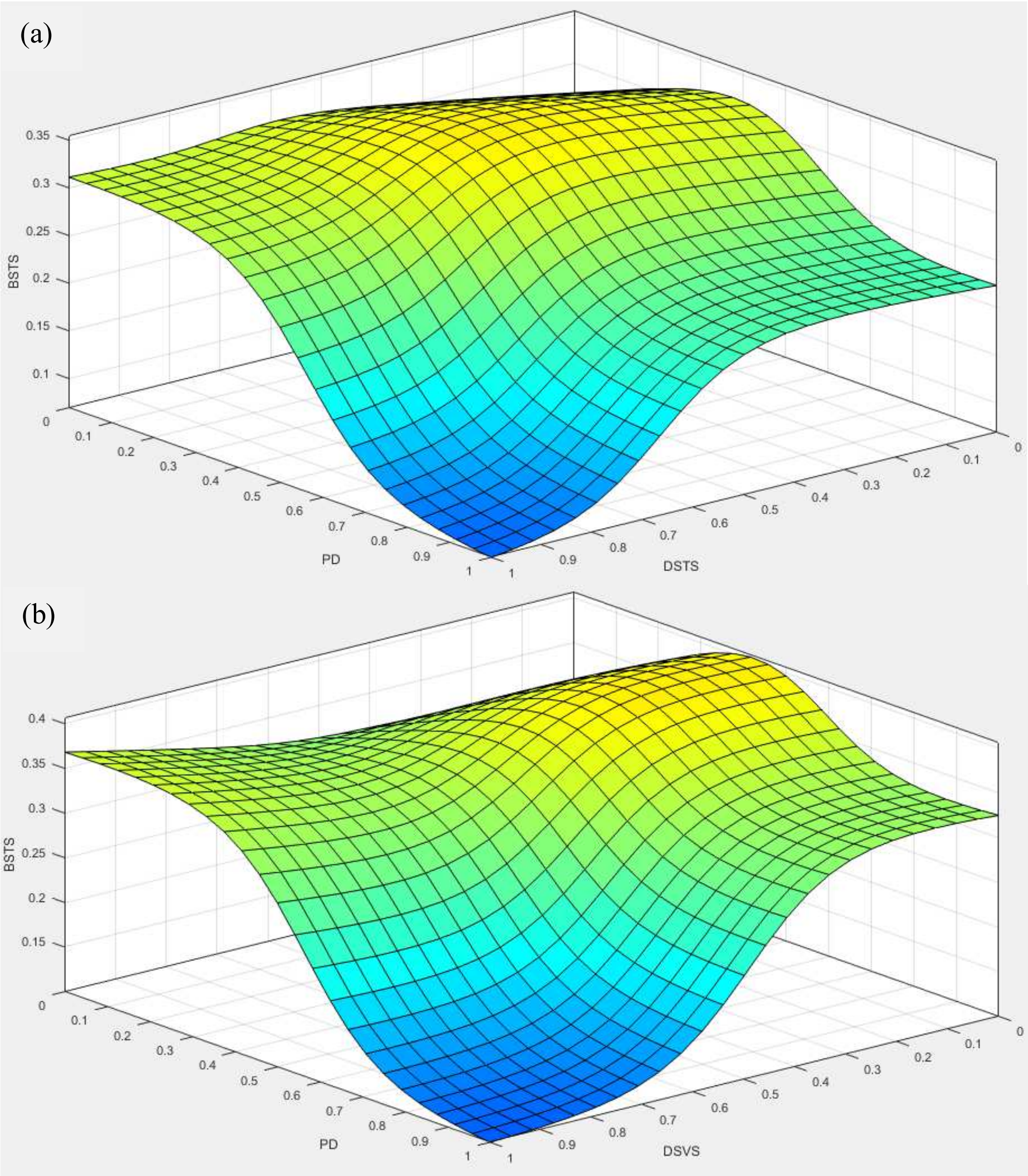

Fig. 7.9 Surface response for (a) digested sludge total solid content (DSTS) and polymer dose (PD) as an input and biosolid total solid concentration (BSTS) as an output and (b) volatile solid and content (DSVS) and polymer dose (PD) as an input and biosolid total solid concentration (BSTS) as an output.

7.4 Conclusion

ANFIS was applied to understand the relationship between the biosolid capture rate, volatile solid and total solid content of digested sludge and polymer dose. It was found that the ANFIS model based prediction helps to understand the impact of physico-chemical properties of digested sludge on cake solid content of biosolid and polymer consumption. The historical data used for this study was obtained from Beenyup WWTP. The data were normalized and used to train and test and validate the ANFIS model to predict the optimum polymer dose and optimum biosolid capture rate. The modelling investigation confirmed that significant reduction in total solid and volatile solid concentrations of digested sludge resulted in better quality biosolid while reducing polymer dosing. From the results of this study, it can be seen that the optimum total solid and volatile solid content were determined to be in the lower range 1.3-1.5% w/w and 70-75% of DS TS respectively. The Optimum polymer dose was determined to be in the lower polymer dose range of 20 to 60 kg/ton of dry solid (kg/TDS) showing better biosolid capture compared to higher polymer dose ranges for the same total solid and volatile solid content. Generally, it can be seen that lower total solid and volatile solid concentration coupled with relatively low polymer dose corresponds to relatively higher biosolid capture rate. The other very important operational parameter that is included in the ANFIS prediction is the volatile fatty acid content of the digested sludge. It was observed that increase in volatile fatty acid content corresponds to higher biosolid capture rate. Volatile fatty acid content of the digested sludge has an effect on the surface charge distribution of the digested sludge. It potentially enhances floc formation as it increases the negative charge of the surface of the floc particles resulting in better dewatering or higher total solid content of the biosolid. To conclude, improving the performance of the anaerobic digesters and optimizing the polymer dose based on total and volatile solid concentration of the digested sludge will have a significant impact on the economy of sludge treatment process. Furthermore, using the results from this work and results from digested sludge rheological studies, a correlation could be developed to predict the required optimum polymer dose for a desired biosolid capture rate.

Reference

[1] Abu-Jdayil, Basim, Fawzi Banat, and Mukheled Al-Sameraiy. 2010. "Steady Rheological Properties of Rotating Biological Contactor (RBC) Sludge." *Journal of Water Resource and Protection* no. 2 (1):1-7. doi: 10.4236/jwarp.2010.21001.

[2] Abu-Orf, M., and S. Dentel. 1999. "Rheology as Tool for Polymer Dose Assessment and Control." *Journal of Environmental Engineering* no. 125 (12):1133-1141. doi: doi:10.1061/(ASCE)0733-9372(1999)125:12(1133).

[3] Abu-Orf, Mohammad M., and Banu Örmeci. 2005. "Measuring Sludge Network Strength Using Rheology and Relation to Dewaterability, Filtration, and Thickening—Laboratory and Full-Scale Experiments." *Journal of Environmental Engineering* no. 131 (8):1139-1146. doi: 10.1061/(ASCE)0733-9372(2005)131:8(1139).

[4] Ayol, A., A. Filibeli, and S.K. Dentel. 2006. "Evaluation of conditioning responses of thermophilic-mesophilic anaerobically and mesophilic aerobically digested biosolids using rheological properties." *Water Science and Technology* no. 54 (5):23-31. doi: 10.2166/wst.2006.543.

[5] Baroutian, Saeid, Nicky Eshtiaghi, and Daniel J. Gapes. 2013. "Rheology of a primary and secondary sewage sludge mixture: Dependency on temperature and solid concentration." *Bioresource Technology* no. 140:227-233. doi: http://dx.doi.org/10.1016/j.biortech.2013.04.114.

[6] Baudez, J. C., F. Markis, N. Eshtiaghi, and P. Slatter. 2011. "The rheological behaviour of anaerobic digested sludge." *Water Research* no. 45 (17):5675-5680. doi: http://dx.doi.org/10.1016/j.watres.2011.08.035.

[7] Baudez, Jean-Christophe. 2008. "Physical aging and thixotropy in sludge rheology." *Applied Rheology* no. 18:1123-1139.

[8] Baudez, Jean-Christophe, and Philippe Coussot. 2001. "Rheology of aging, concentrated, polymeric suspensions: Application to pasty sewage sludges." *Journal of Rheology* no. 45 (5):1123-1140. doi: 10.1122/1.1392298.

[9] Campbell, H.W., and P.J. Crescuolo. 1983. Assessment of sludge conditionability using rheological properties. Paper read at E.E.C. Workshop Methods of Characterization of Sewage Sludge, at Dublin, Ireland.

[10] Eshtiaghi, Nicky, Flora Markis, Shao Dong Yap, Jean-Christophe Baudez, and Paul Slatter. 2013. "Rheological characterisation of municipal sludge: A review." *Water Research* no. 47 (15):5493-5510. doi: http://dx.doi.org/10.1016/j.watres.2013.07.001.

[11] Farno, Ehsan, Jean Christophe Baudez, Rajarathinam Parthasarathy, and Nicky Eshtiaghi. 2016. "Impact of thermal treatment on the rheological properties and composition of waste activated sludge: COD solubilisation as a footprint of rheological changes." *Chemical Engineering Journal* no. 295:39-48. doi: http://dx.doi.org/10.1016/j.cej.2016.03.022.

[12] Farno, Ehsan, Rajarathinam Parthasarathy, Jean Christophe Baudez, and Nicky Eshtiaghi. 2013. Effect of Thermal History on Municipal Digested Sludge Rheology: Experimental and Modeling. In *Chemeca 2013*.

[13] Forster, CF. 1981. "Preliminary studies on the relationship between sewage sludge viscosities and the nature of the surfaces of the component particles." *Biotechnology Letters* no. 3 (12):707-712.

[14] Girovich, Mark J. 1996. *Biosolids Treatment and Management: Processes for Beneficial Use*: CRC Press.

[15] Hasar, Halil, Cumali Kinaci, Ayhan Ünlü, Hasan Toğrul, and Ubeyde Ipek. 2004. "Rheological properties of activated sludge in a sMBR." *Biochemical Engineering Journal* no. 20 (1):1-6. doi: http://dx.doi.org/10.1016/j.bej.2004.02.011.

[16] Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016a. "Rheological characteristics of mixture of raw primary and thickened excess activated sludge: impact of mixing ratio, solid concentration, temperature and sludge age." *Desalination and Water Treatment* no. 57 (44):20726-20737. doi: 10.1080/19443994.2015.1115374.

[17] Hong, Eugene, Anteneh Mesfin Yeneneh, Ahmet Kayaalp, Tushar Kanti Sen, Ha Ming Ang, and Mehlika Kayaalp. 2016b. "Rheological characteristics of municipal thickened excess activated sludge (TEAS): impacts of pH, temperature, solid concentration and polymer dose." *Research on Chemical Intermediates* no. 42 (8):6567–6585. doi: 10.1007/s11164-016-2482-2.

[18] Hou, Chia-Hung, and Kung-Cheh Li. 2003. "Assessment of sludge dewaterability using rheological properties." *Journal of the Chinese Institute of Engineers* no. 26 (2):221-226. doi: 10.1080/02533839.2003.9670772.

[19] Houghton, Jennifer I., and Tom Stephenson. 2002. "Effect of influent organic content on digested sludge extracellular polymer content and dewaterability." *Water Research* no. 36 (14):3620-3628. doi: http://dx.doi.org/10.1016/S0043-1354(02)00055-6.

[20] Khalili Garakani, A. H., N. Mostoufi, F. Sadeghi, M. Hosseinzadeh, H. Fatourechi, M. H. Sarrafzadeh, and M. R. Mehrnia. 2011. "Comparison Between Different Models for Rheological Characterization of Activated Sludge." *Iranian Journal of Environmental Health Science & Engineering* no. 8 (3):255-264.

[21] Lay, Jiunn-Jyi, Young-Joon Lee, and Tatsuya Noike. 1999. "Feasibility of biological hydrogen production from organic fraction of municipal solid waste." *Water Research* no. 33 (11):2579-2586. doi: http://dx.doi.org/10.1016/S0043-1354(98)00483-7.

[22] Lotito, V., L. Spinosa, G. Mininni, and R. Antonacci. 1997. "The rheology of sewage sludge at different steps of treatment." *Water Science and Technology* no. 36 (11):79-85. doi: http://dx.doi.org/10.1016/S0273-1223(97)00672-0.

[23] Lotito, Vincenzo, and Adriana Maria Lotito. 2014. "Rheological measurements on different types of sewage sludge for pumping design." *Journal of Environmental Management* no. 137 (0):189-196. doi: http://dx.doi.org/10.1016/j.jenvman.2014.02.005.

[24] Markis, Flora, Jean-Christophe Baudez, Rajarathinam Parthasarathy, Paul Slatter, and Nicky Eshtiaghi. 2014. "Rheological characterisation of primary and secondary sludge: Impact of solids concentration." *Chemical Engineering Journal* no. 253 (0):526-537. doi: http://dx.doi.org/10.1016/j.cej.2014.05.085.

[25] Mori, M., I. Seyssiecq, and N. Roche. 2006. "Rheological measurements of sewage sludge for various solids concentrations and geometry." *Process Biochemistry* no. 41 (7):1656-1662. doi: http://dx.doi.org/10.1016/j.procbio.2006.03.021.

[26] Mowla, D., H. N. Tran, and D. Grant Allen. 2013. "A review of the properties of biosludge and its relevance to enhanced dewatering processes." *Biomass and Bioenergy* no. 58:365-378. doi: http://dx.doi.org/10.1016/j.biombioe.2013.09.002.

[27] Neyens, Elisabeth, Jan Baeyens, Raf Dewil, and Bart De heyder. 2004. "Advanced sludge treatment affects extracellular polymeric substances to improve activated sludge dewatering." *Journal of Hazardous Materials* no. 106 (2–3):83-92. doi: http://dx.doi.org/10.1016/j.jhazmat.2003.11.014.

[28] Örmeci, Banu. 2007. "Optimization of a full-scale dewatering operation based on the rheological characteristics of wastewater sludge." *Water Research* no. 41 (6):1243-1252. doi: http://dx.doi.org/10.1016/j.watres.2006.12.043.

[29] Piani, Luciano, Claudia Bruna Rizzardini, Adriano Papo, and Daniele Goi. 2014. "Rheology Measurements for Online Monitoring of Solids in Activated Sludge Reactors of Municipal Wastewater Treatment Plant." *The Scientific World Journal* no. 2014:6. doi: 10.1155/2014/590961.

[30] Raszka, Anna, Monika Chorvatova, and Jiri Wanner. 2006. "The role and significance of extracellular polymers in activated sludge. Part I: Literature review." *Acta hydrochimica et hydrobiologica* no. 34 (5):411-424. doi: 10.1002/aheh.200500640.

[31] Ratkovich, N., W. Horn, F. P. Helmus, S. Rosenberger, W. Naessens, I. Nopens, and T. R. Bentzen. 2013. "Activated sludge rheology: A critical review on data collection and modelling." *Water Research* no. 47 (2):463-482. doi: http://dx.doi.org/10.1016/j.watres.2012.11.021.

[32] Sanin, F. Dilek. 2002. "Effect of solution physical chemistry on the rheological properties of activated sludge." *Water SA* no. 28 (2):207-212.

[33] Seyssiecq, Isabelle, Jean-Henry Ferrasse, and Nicolas Roche. 2003. "State-of-the-art: rheological characterisation of wastewater treatment sludge." *Biochemical Engineering Journal* no. 16 (1):41-56. doi: http://dx.doi.org/10.1016/S1369-703X(03)00021-4.

[34] Show, Kuan-Yeow, Taohong Mao, and Duu-Jong Lee. 2007. "Optimisation of sludge disruption by sonication." *Water Research* no. 41 (20):4741-4747. doi: http://dx.doi.org/10.1016/j.watres.2007.07.017.

[35] Sun, Yongjun, Huaili Zheng, Jun Zhai, Houkai Teng, Chun Zhao, Chuanliang Zhao, and Yong Liao. 2014. "Effects of Surfactants on the Improvement of Sludge Dewaterability Using Cationic Flocculants." *PLoS ONE* no. 9 (10):e111036. doi: 10.1371/journal.pone.0111036.

[36] Wang, L.K., N.K. Shammas, and Y.T. Hung. 2009. *Biosolids Engineering and Management*: Humana Press.

[37] Wang, YL, and SK Dentel. 2010. "The effect of high speed mixing and polymer dosing rates on the geometric and rheological characteristics of conditioned anaerobic digested sludge (ADS)." *Water research* no. 44 (20):6041-6052.

[38] Yang, Fei, Amos Bick, Semion Shandalov, Asher Brenner, and Gideon Oron. 2009. "Yield stress and rheological characteristics of activated sludge in an airlift membrane bioreactor." *Journal of Membrane Science* no. 334 (1–2):83-90. doi: http://dx.doi.org/10.1016/j.memsci.2009.02.022.

[39] Yen, Pei-Shan, L. C. Chen, C. Y. Chien, Rome-Ming Wu, and D. J. Lee. 2002. "Network strength and dewaterability of flocculated activated sludge." *Water Research* no. 36 (3):539-550. doi: http://dx.doi.org/10.1016/S0043-1354(01)00260-3.

[40] Yeneneh, Anteneh Mesfin. 2014. *Study on performance enhancement of anaerobic digestion of municipal sewage sludge*. PhD Thesis, Chemical Engineering Department, Curtin University, Perth, Australia.

[41] Yeneneh, Anteneh Mesfin, Eugene Hong, Tushar Kanti Sen, Ahmet Kayaalp, and Ha Ming Ang. 2016. "Effects of Temperature, Polymer Dose, and Solid Concentration on the Rheological Characteristics and Dewaterability of Digested Sludge of Wastewater Treatment Plant (WWTP)." *Water, Air, & Soil Pollution* no. 227 (4):119. doi: 10.1007/s11270-016-2820-4.

[42] Yeneneh, Anteneh Mesfin, Ahmet Kayaalp, Tushar Kanti Sen, and Ha Ming Ang. 2015. "Effect of Combined Microwave-Ultrasonic Pretreatment of Real Mixed Sludge on the Enhancement of Anaerobic Digester Performance." *Water, Air, & Soil Pollution* no. 226 (9):1-14. doi: 10.1007/s11270-015-2586-0.

[43] Yin, Xuan, Pingfang Han, Xiaoping Lu, and Yanru Wang. 2004. "A review on the dewaterability of bio-sludge and ultrasound pretreatment." *Ultrasonics Sonochemistry* no. 11 (6):337-348. doi: http://dx.doi.org/10.1016/j.ultsonch.2004.02.005.

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CHAPTER 8
CONCLUSION AND RECOMMENDATION

8.1 Conclusion

In this research the rheological and flow behaviour of raw primary sludge, excess activated sludge, thickened excess activated sludge, mixed sludge, digested sludge, and biosolid were investigated under the influence of different operating parameters. The operating parameters that were investigated include total solid concentration, temperature, pH, mixing ratio and polymer dose. The relationship between rheological and operational parameters were also established and options for the applicability of rheological parameters as indicators for monitoring and control of different treatment processes/units in a WWTP were devised.

The following conclusions were made from the intensive experimental and model based investigations on rheological characteristic of WWTP sludge and process.

- The rheological behaviour of different sludge types within the WWTP were observed to be affected by total solid concentration, temperature, mixing ratio and polymer conditioning.
- Yield stress was found to increase with increasing solid concentration for all sludge types.
- Viscosity showed a decreasing trend with decreasing total solid concentration
- Temperature showed an inverse relationship with yield stress and viscosity.
- Viscosity was observed to decrease with the decrease in pH due to the change in surface charge and ionic strength of the sludge particles.
- Studies on the relationship between rheological characteristics of digested sludge and dewatering performance particularly on rheology as an indicator or monitoring tool of dewatering performance are only emerging very recently.
- Rheological parameter can be used to monitor the dewaterability of digested sludge as sludge viscosity and rheogram peaks are potential indicators of the dewaterability of digested sludge.
- Volatile solid content and chemical oxygen demand (COD) of digested sludge and centrate showed inverse relationship with biosolid capture rate.

- Yield stress and viscosity of digested sludge and centrate were observed to change proportionally with total solid concentration, volatile solid content and COD.
- Improving the total solid, volatile solid and COD reduction by enhancing the performance of anaerobic digesters or by using other digested sludge conditioning methods will significantly improve the flow behaviour of digested sludge and its dewaterability.
- Rheological investigations for varying polymer dose as a function of the digested sludge and biosolid characteristics provides more reliable results compared to dewaterability test on the digested sludge alone.
- Polymer dose can be reduced by operating the dewatering process at optimum temperature condition and varying the polymer dose as a function of the total solid concentration, volatile solid concentration, COD and viscosity of the digested sludge.

8.2 Recommendation

Based on the findings of this study the following research directions are recommended for further investigations in the future.

- Investigating the microscopic characteristic and composition of sludge and their influence on the rheological behaviour of sludge and identifying the specific constituent which greatly affects sludge rheology.
- Investigating relationship between rheology and conditioning agents at microscopic level and optimizing the conditioner dose based on mechanistic understanding of the flocculation process in relation to rheology and dewatering.
- Investigating the dynamic rheological response of sludge in anaerobic digestion unit and the applicability of rheology in monitoring and controlling the performance of digesters.
- Investigating the applicability of sludge rheology in monitoring and control of the performance of aeration unit and establish the relationship between sludge rheology and aerobic degradation of sludge or the performance of the activated sludge process.

- Investigating the effectiveness of different alternative digested sludge conditioning methods including ultrasonic treatment, advanced oxidation by hydrogen peroxide and ozone, mono valent divalent and trivalent metal cation conditioning, chemical (synthetic) and biopolymer (chitosan) based conditioning and a combination of these techniques for optimization of dewatering performance. And investigating the effect of such pretreatment techniques on sludge rheology and determining the optimum doses and corresponding rheological conditions.
- Investigating the effect of polymer shearing conditions, injection point, and polymer solution strength and polymer dilution on the dewaterability and rheological properties of sludge.
- Developing a method to evaluate and obtain rheological information of sludge for online monitoring and controlling of operating parameters for a WWTP.
- Developing a generic rheological map for the entire WWTP applicable for any wastewater and sludge processing facility.