The Impact of Selected Water and Wastewater Treatment Process Variables on Sludge Dewaterability

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The Impact of Selected Water and Wastewater Treatment Process Variables on Sludge Dewaterability

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Journal Paper

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Abstract

The most significant operational cost in a treatment plant is related to the dewatering and disposal of sludge. Coagulation is the most common process in water and wastewater treatment plants and produces sludge as a by-product. The influence of different important coagulation factors has been investigated in this study to assess corresponding impacts on sludge dewaterability. The CST (Capillary Suction Time) apparatus was used as the main tool to measure sludge dewaterability, followed by the turbidimeter, the particle size analyzer, and the SRF (Specific Resistance to Filtration) as a comparison and also for verification.

The CST results indicate that the magnetic stirrer produces the lowest CST values, while the other four shapes of mixers produced similar but higher trends. Rapid mixing velocity and rapid mixing time have varying degrees of influence on the CST value and hence on sludge dewaterability. Rapid mixing velocity seems to have a more significant impact on the CST value than rapid mixing time. The coagulants aluminium sulphate and ferric chloride have similar effects on CST values. The performance of aluminium sulphate and *Moringa oleifera* are affected by temperature, but the performance of coagulant ferric chloride was hardly impacted. Different synthetic water samples do not significantly affect the CST value.

The turbidity result correlates well with the CST value. Observations using the particle size analyzer indicate that, in general, the floc size has a direct correlation with the CST value. The larger the floc size, the lower the CST value. Floc size distribution results show that synthetic raw water has a narrow particle size distribution; synthetic domestic wastewater produced a wider distribution than synthetic raw water. The comparison between the CST and SRF results indicates that the CST and SRF are well correlated if different methods (rapid mixing velocity and rapid mixing time) are used, but uncorrelated if different materials (mixers, coagulants, temperature and water samples) are used.

Based on the results of this investigation, the working of the magnetic stirrer should be investigated further in order to implement this mixer in the treatment process. The magnetic stirrer does not only produce the lowest CST value but is also the only mixer that produces different CST values significantly. This is because it produces the optimum G value for sludge formation. The implementation of rapid mixing velocity is more important than rapid mixing time in the operation of a treatment plant. Due to its correlation with temperature, ferric chloride is the most appropriate coagulant among the three types of coagulants used in the treatment plant to reduce sludge dewaterability. Based on the results using different water samples, all of these factors can be used for both inorganic and organic water and wastewater to produce lower sludge dewaterability.

Abbreviations

CST	Capillary Suction Time
COD	Chemical Oxygen Demands
CFD	Computational Fluid Dynamics
G	Velocity Gradient
PIV	Particle Image Velocimetry
SRF	Specific Resistance to Filtration
SS	Suspended Solids

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter will discuss the background to this research, specific aims and objectives of the research, research methodology and limitations of the research. It will also explain the importance of the coagulation process and the impact of important variables on sludge production and sludge dewaterability.

1.2 Background to Research

Sludge is an inevitible by-product of the water and wastewater treatment process; indeed, water and wastewater treatment plants produce large volumes of sludge every day, and dewatering and disposal of sludge accounts for approximately 40% of the treatment costs of a typical treatment plant (Hernando et al., 2010). Globally, in modern society, the quantity of sludge increases annually because of increasing population and greater access to sewage and water treatment. Quantity and quality of sludge are dependent on the treatment process in the wastewater plant (Sanin et al., 2011). Table 1 shows the projection of sludge generation in the United States (US EPA, 1999).

Table 1. Projection of Sludge Generation in the United States (US EPA, 1999)

Year	Total (million dry metric tons)
1998	6.3
2000	6.5
2005	6.9
2010	7.5

For the UK alone, sludge production in 2001 was 1,186,615 metric tons of dry matter; it increased to 1,360,366 metric tons of dry matter in 2003 (Sanin et al., 2011) as can be seen in Table 2 which presents figures for the EU. As a consequence, sludge and the management of sludge is a significant problem in water and wastewater treatment plants.

Table 2. Sludge Production in the European Union in 2001 and 2003 (Sanin et al., 2011)

	Sludge Produced (metric tons of dry matter)	
Member state	**2001**	**2003**
Austria	96,110	115,448
Belgium Flemish	81,352	76,072
Belgium Walloon	18,514	23,520
Denmark	158,017	140,021 (2002)
Finland	159,900	150,000
France	893,252	910,255 (2002)
Germany	2,300,686	2,172,196
Greece	67,755	79,757
Ireland	33,559	42,147
Italy	884,964	905,336
Luxembourg	NA	7,750
Netherlands	536,000	550,000
Portugal	209,014	408,710 (2002)
Spain	892,238	1,012,157
Sweden	220,000	220,000
UK	1,186,615	1,360,366
Total	**7,737,975**	**8,173,735**

Dewatering of sludge is considered to be one of the most significant problems associated with sludge management, as well as being the most costly process in water and wastewater treatment plants (Katsiris & Katsiri, 1987; Jin et al., 2004). The dewaterability of sludge is fundamentally determined by the chemical composition and physical configuration of the flocs or solid particles that make up the sludge (Verrelli et al., 2009). In water and wastewater treatment plants a number of process stages are employed to treat water in order to remove contaminants. Zhan et al. (2011) identified coagulation as one of the key elements within the treatment process, whilst research conducted by Diaz et al. (2011) and Verrelli et al. (2009) highlighted the importance of coagulation in influencing both the production and the dewaterability of sludge.

The coagulation process produces purified water and sludge (floc) as a by-product (Byun et al., 2005; Gray, 2005; Diaz et al., 2011). In this process, small contaminants, which have a diameter less than 1µm, attach themselves to one another to produce an agglomeration and, as a result, the initially small contaminant can be removed from water as part of a much larger agglomeration (AWWA, 1999). Sludge properties, such as the volume, strength, size and dewaterability, will influence the method of dewatering and disposal (Tchobanoglous et al., 2003; Razi & Molla, 2007). In order to improve the conditions for coagulation, rapid mixing is employed. Rapid mixing is the first of two stages of the mixing process (Gray, 2005) and is an essential part of the coagulation process (Mhaisalkar et al., 1991; Dharmappa et al., 1993). It is recognized that this rapid mixing phase is crucial throughout the coagulation process and equally important in the formation of sludge. The main purpose of rapid mixing is to effectively disperse a coagulant in the water; however, it also establishes the formation of coagulant hydrolysis products. Precipitate formation of coagulant hydrolysis products is the agent that has the responsibility not only to destabilize the contaminant, but also to determine sludge production (Wang et al., 2008; AWWA, 1999).

According to AWWA (1999), coagulation is complex, involving physical, chemical and also mass transfer processes. The main processes in coagulation are coagulant formation, particle destabilization, and inter-particle collisions. Coagulant formation, destabilization and the reaction between contaminant/coagulant occur during and immediately after the rapid mixing process. In addition, inter-particle collisions that cause aggregation begin to develop during rapid mixing and form, predominantly, during the coagulation process. Coagulation processes in water and wastewater treatment plants usually produce bulk contaminant or sludge. The amount and properties of the sludge depend on the coagulant used. The greater the volume of sludge, the more processing is required and the costs of dewatering and disposal increase. The effectiveness of coagulation depends on many factors such as rapid mixing, coagulant characteristics, pH, alkalinity, temperature and contaminant characteristics. Of these factors, the most important is rapid mixing (Maishalkar et al., 1991; Dharmappa et al., 1993).

In water and wastewater treatment plants, rapid mixing can be carried out with a wide range of mixers and reactor configurations, any of which will produce different shearing rates, different flocculant aggregate sizes and hence different rates of flocculant agglomeration. Much work has been published in the area of rapid mixing in relation to the coagulation process, however, the influence of different shapes of mixer on floc formation and stability has been neglected. Initial findings show that different shapes of mixer produce different coagulation efficiency (Leentvaar & Ywema, 1980; McConnachie, 1989; Spicer et al., 1996; Kim et al., 2006; Wu, 2010). This is due to different shear rates influencing the rate of floc agglomeration. Serra et al. (2008), who investigated the efficiency of different shear devices on flocculation, concluded that different shapes of mixer produce different sized aggregates during flocculation. The different shapes of mixer produced different shear rates, thus influencing the rate of floc agglomeration. At low mixing or low shear rates with a mixing velocity gradient less than $20s^{-1}$($G < 20s^{-1}$), floc diameter increased with increasing shear rates and aggregation dominated over break up. Intermediate shear rates ($20s^{-1}<G<30s^{-1}$) produced the largest flocs because flow rates were maximized. At high shear rates ($G>30s^{-1}$), the shear rate was such that the maximum floc sizes were smaller due to the dominance of particle break up, rather than aggregation.

Park et al. (2003) investigated the effect of hydraulic turbulence in rapid mixers on turbidity removal. The research was conducted at laboratory scale using wet tests, Computing Fluid Dynamics (CFD) simulation and Particle Image Velocimetry (PIV) analysis, using three different shapes of jar: a circular jar with squared baffles, a circular jar without baffles and a Hudson jar. The authors concluded that for designing and operating rapid mixing, rapid mixing intensity, defined as the product of velocity gradient (G) value and mixing time (t), was inadequate due its inability to reflect important hydraulic conditions in the coagulation process, such as turbulence. In the most effective turbidity removal processes non-identical impeller rotating speeds and G values in different shapes of jar have been found. Park et al. emphasized that in determining the performance of a rapid mixer the most important factor is turbulent fluid conditions, including distribution of turbulence and formation of dead zones.

In this research, the behaviour of different shapes of mixer is examined and their influence on sludge formation analyzed. Research was carried out through a rigorous programme of laboratory testing, examining a range of parameters that are considered to affect the coagulation process, using the Capillary Suction Time (CST) as the main sludge dewaterability measurement apparatus. In order to compare and verify the CST results, particle size analysis, a turbidimeter and SRF (Specific Resistance to Filtration) were also employed as additional measures of sludge dewaterability.

Although a number of studies have been carried out with regards to rapid mixing and its influence on sludge dewaterability, comprehensive studies of specific aspects of this relationship are still required. It is believed that further research can provide insights into the increase in sludge dewaterability in water and wastewater treatment systems.

1.3 Specific Aims and Objectives of the Research

The principal aim of this research is to contribute to the development of sludge dewatering techniques by critically evaluating the influence of a number of essential variables on the coagulation process, which is a critical element in sludge dewatering. The objectives of this research are therefore to investigate the influence of the following important factors on the coagulation process during sludge dewatering:

- Mixer shape
- Rapid mixing velocity
- Rapid mixing time

- Coagulant type
- Temperature
- Water composition

The influence of these parameters has been examined based on the results of experimental work, and modifications to existing dewatering processes are suggested which aim to improve the efficiency and efficacy of water and wastewater treatment.

1.4 Research Methodology

The research methodology focused on collecting and analyzing experimental data acquired through a programme of experiments relating to the interaction of a range of different variables and their influence on the coagulation process. In order to do this, the researcher identified a number of key challenges:

1. Data analysis – the programme generates a large body of data. Detailed quantitative analysis of this experimental data was required, informed by appropriate statistical methodologies;
2. Sludge production mechanisms – many aspects affect sludge production, including the shape of mixers, coagulants and contaminants in water. The mechanisms were investigated and analyzed based on the results of experimental laboratory work;
3. Quantitative measurement of sludge dewaterability – a number of methods were available to evaluate sludge dewaterability, including the CST, turbidimeter, particle size analyzer and SRF. These were critically reviewed and evaluated in

the context of this study. Clearly, a key element of the experimental work is to evaluate the method by which sludge dewatering was assessed;

4. Chemistry of sludge/wastewater – one of the key aspects in understanding the processes in water and wastewater treatment plants is the chemistry of the water or wastewater. In this research, the chemistry studied was based on the coagulant and the water sample used in the experiment.

1.5 Limitations of the research

The principal limitations of this research have been identified as:

1. The selection of mixer shapes used in this research to represent the real mixer shapes in the industry. Many shapes are used in water and wastewater treatment plants. This research cannot use all of them, so to overcome this problem the selection was based on information provided by companies producing and/or selling standard mixers used by the water and wastewater industry.

2. In order to obtain a sample with consistent water quality characteristics for laboratory tests, synthetic raw water and synthetic domestic water was used (at least for benchmarking purposes) in all experiments. The use of synthetic water minimizes differences in experimental conditions, which are particularly important for most laboratory-scale tests. The properties of ‘natural’ or ‘real’ water samples can often be highly variable and very dynamic. These properties depend on the treatment plant operational conditions and may change over time during transport, handling and storage. It was an initial requirement of this work to obtain appropriate synthetic water and wastewater recipes. There are no

standard water and wastewater formulas. In order to address this problem, the researcher carried out an extensive literature review.

1.6 Chapter Summary

Sludge dewatering and disposal is a very expensive process. Sludge production is increasing every year, not only in the UK but also globally. As one of the essential processes in water and wastewater treatment plants, coagulation impacts sludge conditions and sludge dewaterability. Coagulation uses different shapes of mixer, and research findings show that different mixer shapes produce different degrees of coagulation. Based on these facts, it might be valuable to seek a correlation between different shapes of mixer and other important variables in the coagulation process on sludge dewaterability. A contribution to increasing sludge dewaterability should result from this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Chapter 2 presents the literature review, which has an important role in supporting this research. Sludge problems in water and wastewater treatment plants, and correlation between the coagulation process and important variables in sludge dewaterability will be discussed in detail. The role of floc size on sludge dewaterability and sludge dewaterability measurement will also be considered.

2.2 Sludge Problems in Water and Wastewater Treatment Plants

Generally, the water content in sludge is approximately 95%, which needs to be reduced prior to disposal and this saccounts for almost half of the treatment costs of dewatering and disposal (Chen et al., 2010). Reduction of sludge volume by separating water from sludge (solid) has become the most important part of the sludge treatment process (Qi et al., 2011). However, although sludge dewatering is considered to be one of the most expensive elements of the treatment process, it is also one of the least well understood (Bruus et al., 1992) and one of the more complex and difficult processes in water and wastewater treatment (Lee & Wang, 2000). The cost and difficulty of sludge handling are directly correlated with the amount of water remaining in the sludge after the dewatering process (Dentel et al., 2000).

For example, Di Iaconi et al. (2010) compared the costs of ozone-enhanced biological degradation and conventional processes for tannery wastewater treatment. The authors stated that of the 0.9€/m^3 total cost for ozone treatment, 0.07€/m^3 (8%) is for sludge treatment and disposal. For biological units, of the 2.4€/m^3 total cost, 0.7€/m^3 (29%) is for sludge treatment and disposal. For wastewater treated by the Fenton process, of the 1.45€/m^3 total cost, 0.8€/m^3 (56%) is for sludge treatment and disposal. The sludge treatment and disposal costs were determined by the quantity of sludge, where the larger the volume of sludge, the more costly is the sludge treatment and disposal process. The data above shows that every water and wastewater treatment process produces different volumes of sludge, and this affects the cost of sludge treatment and sludge disposal.

Razi and Molla (2007) stated that sludge dewatering performance is dependent on the composition and physical properties of the sludge, such as particle size, density, porosity as well as settling velocities. Besra et al. (2000) also found sludge dewaterability to be very much dependent on particle size and its distribution, sphericity of the particles, bed porosity, water retention capacities and variation in the dispersion properties. The composition of sludge is highly dependent on the treatment process and the water or wastewater composition (Gale & Baskerville, 1970; Wang et al., 2009; Zhang et al., 2004).

In water and wastewater treatment plants many processes can be used to separate contaminants from water, including physical, chemical and biological processes. Almost every stage of the treatment produces sludge (Figure 1), and of all of these stages, coagulation, which is one of the primary treatment processes in water and wastewater treatment plants, most influences sludge production (Diaz et al., 2011). Lin et al. (2008), investigating the effect of Al(III) speciation on coagulation of highly turbid water, found that sludge characteristics are dependent on coagulation mechanisms. Furthermore, sludge dewaterability is very dependent on sludge/floc characteristics, in particular size distribution and the presence of small particles (Jin et al., 2004), which are determined by the specific coagulation process mechanism.

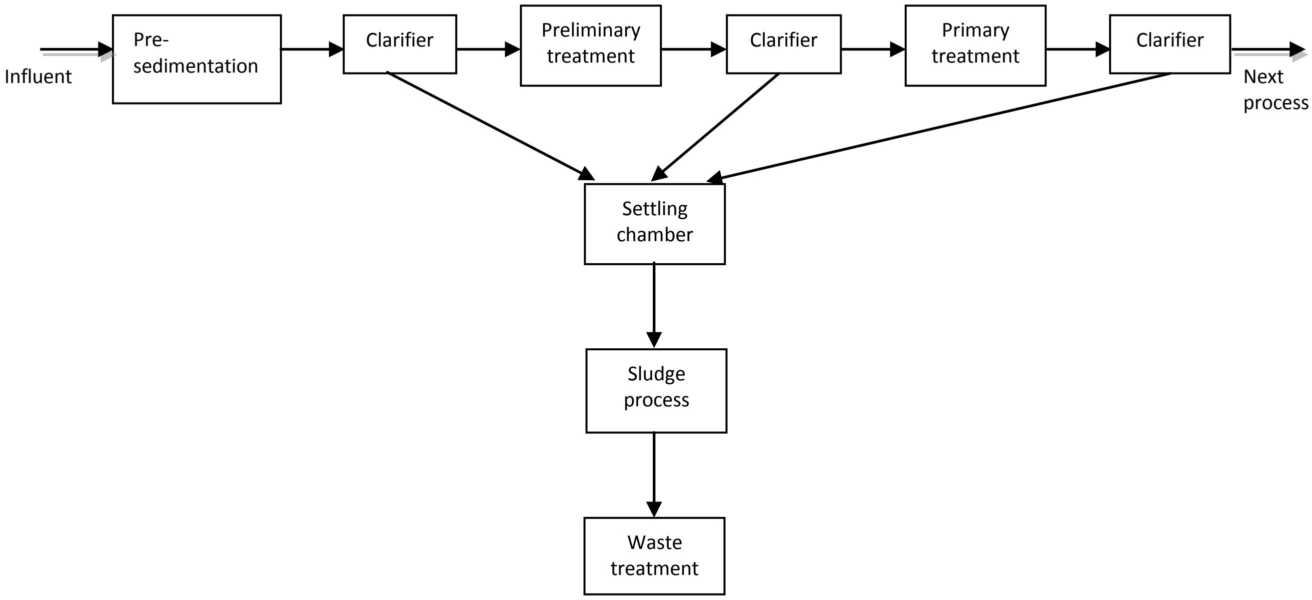


Figure 1. Generic sludge production and treatment process (after Tchobanoglous et al., 2003)

2.3 Relationship Between Coagulation and Sludge Dewaterability

Coagulation is a process in which all the reactions and mechanisms have the purpose of producing an agglomeration of contaminants or particles (AWWA, 1999; Gray, 2005). The coagulation process consists of two-stage mixing processes: rapid mixing (coagulation) and slow mixing (flocculation). Rapid mixing is employed at the first stage to disperse the coagulant in the water. Slow mixing is used as a second stage to stimulate the agglomeration of particles and to encourage sedimentation (Figure 2). The agglomeration itself is an essential process because its purpose is to produce a larger size of floc. Larger and denser floc seems preferable since these will settle more easily and dewater more readily (Larue & Vorobiev, 2003).

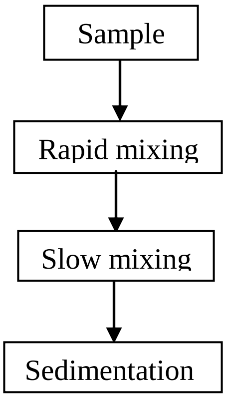


Figure 2. Flow Chart of Coagulation Process

(after AWWA, 1999)

Coagulation is an important process and is used worldwide in sequential processes in water and wastewater treatment plants (Bhatia et al., 2007). In water treatment, coagulation processes followed by a treatment step for liquid and solid separation are the most commonly used processes to remove particles and particulates from the water (Byun et al., 2005; Slavik et al., 2012). In addition, Byun et al. (2005) stated that the coagulation process is not just effective for treating drinking water but it is also economical. This is due to the coagulation process being fast, so it can avoid lengthy power consumption and minimize energy costs. The coagulation process does not need an excess dose of coagulant to remove the contaminant from water. Charge neutralization is a coagulation mechanism which produces good contaminant removal but does not need an excessive coagulant dose (AWWA, 1999).

Coagulation is an old process thought to date back to ancient Egypt, circa 1500 BC (Jiang, 2001). At that time, the Egyptians used aluminum salt to encourage the settlement of particles, much as we do today. The modern history of coagulation started some 100 years ago with the first use of ferric and aluminum salts in a complete water treatment plant (Jiang, 2001). Much experimental work has been undertaken to examine the influence of coagulation factors such as the type of coagulant, physical-chemical processes, contaminants, and many other factors on the efficiency of the process (eg. Black et al., 1933; Jiang, 2001; Kan et al., 2002; Bektas et al., 2004; Bhatia et al., 2007; Barbot et al., 2008; Gao et al., 2008; Almubaddal et al., 2009). However, not many investigations have been undertaken into rapid mixing and sludge dewaterability (Appendix 1), even though among all of the processes in coagulation, rapid mixing is considered by Dharmappa et al. (1993) and Mhaisalkar et al. (1991) to be the most important factor in removing the contaminant from water.

The coagulation process comprises complex mechanisms which include adsorption, neutralization of colloid charges and the entrapment of colloids by the coagulant (Gray, 2005). Adsorption occurs when the contaminant particle is adsorbed or attached to the surface of coagulant hydrolysis products. Neutralization of colloid charges is a process where a positive charge of coagulant hydrolysis products destabilizes the negative charge of colloids. As the net charge of the colloid reduces, it becomes easier for the colloid to make contact with others. Excess coagulant dosage will entrap the contaminant and cause it to settle down. The presence of these mechanisms is dependent on the rapid mixing intensity (AWWA, 1999; Kim et al., 2006). These mechanisms affect sludge characteristics and sludge dewaterability (Jin et al., 2004; Lin et al., 2008). This is a consequence of the range of floc sizes produced by different coagulation mechanisms (Wang et al., 2009). Gao et al. (2008), who observed the size and coagulation behaviour of a novel composite inorganic-organic coagulant, found further evidence that the coagulation mechanism determines sludge characteristics. They stated that when the coagulation pathway or mechanism changes, such as from bridge to charge neutralization, this affects significantly floc growth rate, floc size and floc size variance.

2.3.1 The Role of Mixer Shape and Type on the Coagulation Process and Sludge Dewaterability

The mixer is needed to mix the water and produce a good contact between the coagulant and the contaminant. To produce mixing in a coagulation chamber, the mixer has two actions, circulation and shearing the fluid (Tchobanoglous et al., 2003). The mixer transfers energy into the water to produce water turbulence. The greater the turbulence, the better the mixing. Hydraulic turbulence is a hydrodynamic condition indicated by the presence of recirculation, eddies, apparent randomness and a Reynold's number typically more than 10,000 (Tcobanoglous, 2003). Relating to the coagulation process, the hydraulic turbulence determines the dispersion of coagulant in the water (Oldsue, 1983) and also the strength of the floc (Jarvis et al., 2005). Park et al. (2003) confirmed that the intensity of hydraulic conditions is dependent on the pattern of energy dissipation from the mixer. This energy dissipation pattern relates to the mixer type. Even though the same mechanical energy has been employed, different water mixing will be produced if a different mixer type is used.

Different types of mixer are used in water and wastewater treatment plants for the rapid mixing process. According to Tchobanoglous et al. (2003), the principal types of mixer used for rapid mixing in the wastewater treatment plant are static mixers, in-line mixers, high speed induction mixers, pressurized water jets and turbine and propeller mixers. Turbine and propeller mixers are the most commonly used mixer types in wastewater treatment plants. They use a paddle or a propeller as a tool to produce a movement in the fluid and have many shapes of propeller. According to A.T.E. (2011) and Chemineer (2004) the most commonly used mixers in water and wastewater treatments are those with axial, radial and marine style propellers.

Different shapes and types of mixer and mixer chamber have been shown to influence removal efficiency in coagulation (Leentvaar & Ywema, 1980; McConnachie, 1989; Spicer & Pratsinis, 1996; Kim et al., 2006; Wu, 2010). The different types of mixer produce different shear rates, different hydraulic conditions, different distribution of mixing and different formation of dead zones. The difference in hydraulic conditions affects the dispersion of mixing in the fluid, the formation of coagulant hydrolysis products, contact efficiency between the coagulant and the contaminant, the agglomeration process and finally the floc properties. The greater the mixing distribution in the fluid, the better the coagulant distribution (Tchobanoglous et al., 2003). The coagulant hydrolysis products are formed very quickly after dissolution in water, usually less than 7s (Amirtharajah & Mills, 1982), so a high mixing intensity is required to disperse the coagulant and produce contact between the coagulant and the contaminant.

Rossini et al. (1990) observed the impact of different rapid mixing velocities and times on coagulation efficiency. They compared the removal efficiency produced by different mixers, and found that the different mixers can make a difference in removal efficiency of 12% to 80%. Some mixer shapes give better outcomes than others; for example, the Rushton mixer which has a 6-blade turbine (Figure 3), produced a larger floc than other mixer shapes in the coagulation process examined by Spicer et al. (1996). This is due to the greater distribution of turbulence in water mixing and this result demonstrates that different shapes of mixer can affect the performance of coagulation. The selection of the right propeller for the mixing process is crucial in determining the quality of the treated water, because of the different mixing produced, as well as the quantity and quality of the residual sludge generated in the process (Torres et al., 1997). Mixer shapes influence the mixing pattern of fluids and the fluid mixing conditions.

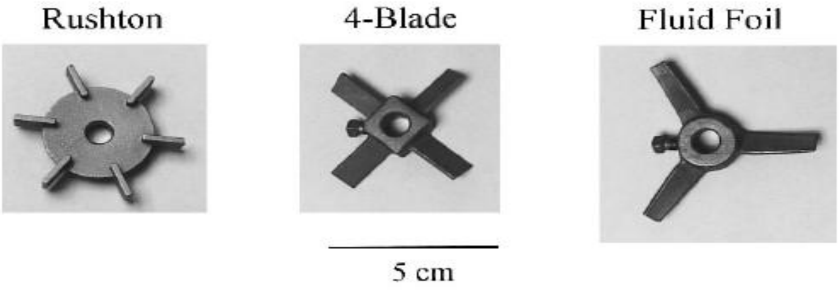


Figure 3. Examples of tested shapes of mixers (Spicer et al., 1996)

Even though many researchers (Leentvaar & Ywema, 1980; McConnachie, 1989; Spicer & Pratsinis, 1996; Kim et al., 2006; Wu, 2011) have demonstrated that different mixer shapes result in different removal efficiency, there is still no published research which explains the correlation between different shapes of mixer and sludge dewaterability. In water and wastewater treatment plants, many shapes of mixers are used (Tchobanoglous et al., 2003). The literature suggests that different shapes and types of mixer produce different coagulation efficiency, which can be indicated by the removal of turbidity and contaminant in water. There has been no investigation to date of the influence of different mixer shapes on sludge dewaterability. Thus, experimental data that might be used to inform decisions about mixer shape is important and a key outcome of this research.

2.3.2 The Influence of Rapid Mixing Velocity on the Coagulation Process and Sludge Dewaterability.

At a fundamental level, the rapid mixing velocity provides interaction between molecules and particles in the water and a coagulant (Amirtharajah & Jones, 2000). This interaction is controlled by the hydrodynamic parameters and geometry of the mixer, molecular properties of the source water, and the kinetics of the coagulation reactions. For mechanical mixing, such as with an impeller or paddle, the mixing causes circulation and shear of the fluid. Mixing effectiveness can be roughly determined by the power input per unit volume of liquid and is characterized by power input or velocity gradient (G) (Park et al., 2003).

Previous research has examined the relationship between factors such as rapid mixing velocity, rapid mixing time and the type of impeller and floc or sludge formation. The results show that all of these factors have a significant impact on sludge formation (Black & Rice, 1933; Clark & Flora, 1991; Leentvaar & Ywema, 1980; Li et al., 2006; Yu et al., 2011). Different rapid mixing velocities, different rapid mixing times and different types of impeller change the floc conditions. These factors determine the formation of the floc and the floc size. Rapid mixing velocity and rapid mixing time have their own optimum values to produce the best floc formation (Rossini et al., 1999).

In the coagulation process, the contaminant can be removed from the water by either sweep flocculation or adsorption-destabilization processes. Sweep flocculation is the condition where the coagulant dose exceeds the optimum value, due to the need for an excessive coagulant dose to entrap the colloid. In this process, high, intense rapid mixing is not used because the entrapment process will not occur properly in the presence of high mixing intensity. High, intense rapid mixing will disturb the entrapment of contaminant by the coagulant. For adsorption-destabilization processes, the coagulation dose is lower but it needs immediate rapid mixing velocity application, so increasing the rapid mixing velocity will enhance the contribution of this stage of the coagulation process (Rossini, 1998). Kim et al. (2006) observed the effect of different initial mixing conditions on the fouling of filtration membranes in the coagulation process and found that rapid mixing intensities affect the formation of coagulation species. Furthermore, Kan et al. (2002b), who investigated the effect of rapid mixing velocity on the coagulation process of highly turbid water, stated that the rapid mixing velocity affected the aggregation degree of flocs. A poor rapid mixing velocity is not able to produce sufficient conditions to support the aggregation process, so it produces small flocs, reduces the ability of flocs to settle down and ultimately inhibits the reduction of water turbidity.

As the most important factor, rapid mixing velocity influences all of the stages in this process and the formation of sludge (Zhan et al., 2011) and the result of the whole treatment depends on this stage (Rossini et al., 1999). Guan et al. (2005), showed that different rapid mixing velocities have various impacts on contaminant removal while using alum sludge to remove particulate content from sewage. The hydraulic velocity gradient also has an important role in the aggregation; Li et al. (2006) stated that the floc size, which is impacted by the aggregation process, decreases with the average hydraulic gradient. Moreover, Amirtharajah and Mills (1982) stated that rapid mixing velocity does make a significant difference in the quality of the settled water produced for a specific region of the alum stability diagram.

Following the addition of the coagulant and employment of rapid mixing velocity, the hydrolysis products of coagulants such as alum or Fe (III) are produced in 10^{-4} to 1sec. Aluminium hydroxide starts to precipitate in about 7sec. The coagulant hydrolysis product species is an important factor influencing sludge structure, determining the structure of the floc (Wang et al., 2008). As mentioned previously, the floc structure is one of the factors that affects sludge dewaterability.

Rapid mixing velocity affects floc size, where floc size decreases if the rapid mixing velocity increases (Bouyer et al., 2005). Rapid mixing velocity influences floc formation due to its intensity or quality to disperse the coagulant into water and to determine the predominant reaction pathway (AWWA, 1999). Each pathway produces a different coagulant hydrolysis product and this affects floc formation due to the interaction between the coagulant and the contaminant. Figure 4 lists reaction pathways that the hydrolysis products may follow when a Hydrolyzing Metal Salt (HMS) coagulant is added to water that contains particles or Natural Organic Matter (NOM).

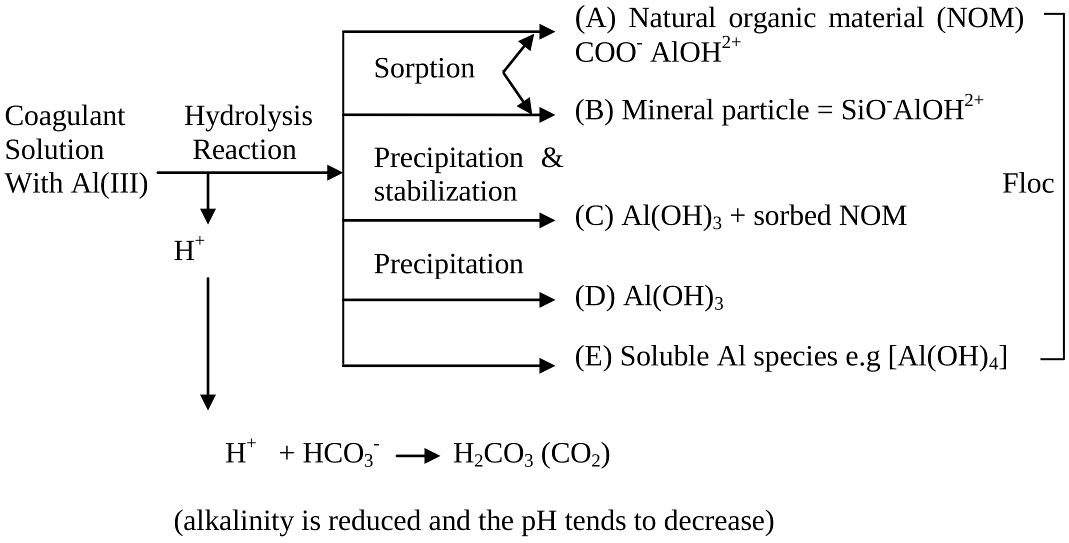


Figure 4. Pathway that hydrolysis products may follow when a coagulant is added to water with organic particles or NOM (AWWA, 1999)

For mechanical mixing, such as with an impeller or paddle, the mixing causes circulation and shearing of the fluid. Mixing effectiveness can be roughly determined by the power input per unit volume of liquid and is characterized by a velocity gradient (G). Camp and Stein in 1943 used Smoluchowski’s formula for flocculation in uniform laminar shear to derive a widely used flocculation rate equation for turbulent flow that can be used to calculate the velocity gradient (Tchobanoglous et al., 2003):

$$G = \sqrt{\frac{P}{\mu V}} \qquad (1)$$

Where G = average velocity, T^{-1}, 1/s

P = power requirement, W

μ = dynamics viscosity, N.s/m^2

V = flocculator volume, m^3

For use of the impeller, the formula to calculate P is:

$$P = Np\, \rho\, n^3 D^5 \qquad (2)$$

Where P = Power requirement, W

Np = power number of impeller, unitless

ρ = density of water kg/m^3

n = impeller speed (1/s)

D = diameter of impeller (m)

Although rapid mixing velocities have been proven to have an impact on the floc conditions (Kan et al., 2002b; Bouyer et al., 2005; Kim et al., 2006; Li et al., 2006), the correlation between rapid mixing velocity and sludge conditioning in the coagulation process are still uncertain. Sawalha (2010) and Wang (2010) observed that mixing without subsequent chemical addition influences sludge dewaterability where the better the mixing, the better the sludge dewaterability. To ensure high quality results in sludge dewaterability, sufficient mixing is needed. Based on the correlation between rapid mixing and sludge conditions, this raises a question about the effect of rapid mixing on sludge dewaterability. This research explores the influence of rapid mixing velocity on sludge dewaterability.

2.3.3 The Influence of Rapid Mixing Time on the Coagulation Process and Sludge Dewaterability

Rapid mixing time is the time needed to disperse a coagulant into water. Alongside the rapid mixing velocity, the rapid mixing time also has an important role in the coagulation process (Francois & Van Haute, 1984; Rossini et al., 1990; Kan et al., 2002a; Chakraborti et al., 2003; Zheng Yu et al., 2011). Rossini et al. (1990) and Mhaisalkar et al. (1991) have observed the impact of rapid mixing time on turbidity removal. The results showed that optimum rapid mixing produces better turbidity removal. Excess rapid mixing time is not favourable for contaminant settlement and coagulant efficiency, because increasing the rapid mixing time leads to a decrease in the final floc size (Zheng Yu, 2011). The excess of rapid mixing will erode and split the coagulant hydrolysis product, especially ferric, and form small particles (Rossini et al., 1990). Even though the formation of the floc occurs in the slow mixing process, the small particles from the rapid mixing process will end with even smaller particles.

Kan et al. (2002a) examined the time requirement for rapid mixing in the coagulation process. They proved that rapid mixing time has an important role in charge neutralization and sweep coagulation mechanisms. In the charge neutralization process, the rapid mixing time determines the size of the formed coagulant hydrolysis product. An excess of rapid mixing time breaks the hydrolysis products into smaller sizes. The small sized hydrolysis product has a lower positive charge. This influences its capacity to neutralize the negative charge of the contaminant and, as a result, the removal efficiency decreases. The sweep flocculation is not suitable for excessive rapid mixing time. The excessive rapid mixing time will disturb the entrapment process and produce small flocs and poor coagulation efficiency. The residual turbidity of charge neutralization results was similar or lower if rapid mixing time exceeded the optimum time. In contrast, the residual turbidity of sweep coagulation results increases if the rapid mixing time exceeded an optimum value. This is because the duration of rapid mixing affects the destabilization of the colloid and the downstream aggregation of particles. For example, with long duration rapid mixing, alum hydrolysis products break up and produce microfloc, which is not favourable for sedimentation and filtration processes (Rossini et al., 1990).

Rapid mixing time has an impact on floc breakage and recovery factors. Recovery factor is the degree of recovery of the ruptured flocs after the original velocity gradient is restored (Pawlowski et al., 1985). These factors have been calculated by Chakraborti et al. (2003) and both were found to decrease with increasing breakage time; thus increasing the rapid mixing time leads to a decrease in the final floc size For adsorption-destabilization mechanisms, the rapid mixing time should be sufficient for complete adsorption of the contaminant by the precipitate coagulant hydrolysis products (Zheng Yu et al., 2011). The precipitate coagulant hydrolysis product, aluminium hydroxide, has the ability to adsorb contaminants because it has a positive charge on its surface. These products need sufficient time to adsorb properly the contaminant onto its surface. Extended rapid mixing times give more limited floc growth, probably because small and compact aggregates are formed during rapid mixing, which leads to smaller flocs. With only a brief period of rapid mixing there is less chance of compact aggregates being formed and more open, larger flocs can grow. The onset of flocculation can occur several minutes after dosing and the overall time can be reduced by a longer period of rapid mixing.

Rapid mixing time influences floc size. Despite many investigations related to rapid mixing time, the investigation to see its influence on sludge dewaterability has not been done. More research is still needed in this area.

2.3.4 The Role of Coagulants on the Coagulation Process and Sludge Dewaterability

A coagulant is a chemical that is used in water treatment to destabilize contaminants and make their removal easier (AWWA, 1999). In water treatment, the removal of suspended solid content is very important and this process is strongly determined by the performance of the coagulant and the formation of floc with suitable properties (size and density) to settle down (Kim et al., 2001). The amount and type of coagulant affects the quantity, composition and physical properties of residue or sludge after the water treatment process. The costs associated with coagulation and the effectiveness of the process depend on the type and concentration of the coagulant, solution pH, ionic strength, as well as both concentration and nature of the organic residues in the effluent to be treated (Rodrigues et al., 2008).

An ineffective coagulation process is usually attributed to the restabilization of particles in the case of excessive coagulant dosage, or stabilization in the case of underdosage (Xiao et al., 2008). Coagulant concentration is determined as a function of raw water quality and can vary for each water coagulant (Barbot et al., 2008). The pH is another important factor in water coagulation (Kim et al., 2001; Canizares et al., 2008; Almubaddal et al., 2009; Canizares et al., 2009; Ghafari et al., 2009). The pH of the water represents the amount of H^+ ions in the solution. The pH has an essential role in determining the formation of coagulant hydrolysis products, where neutral pH produces a solid precipitate of coagulant hydrolysis products and acid or alkali pH produces soluble coagulant products. The solid precipitate coagulant hydrolysis product can adsorb the colloid particle onto its surface and destabilize the otherwise stable colloid charge (Kim et al., 2001; Canizares, 2009; Ghafari et al., 2009). Since a simple change in the water pH can result in a significant change in coagulation efficiency, pH must be set to an optimum value. For alum and ferric, Almubaddal et al. (2009) showed that the optimal pH is between 6 - 8. In this range, the coagulant forms solid precipitated hydrolysis products. This precipitate adsorbs and neutralizes the water and, as a result, the contaminant can be removed from the water.

Many coagulants are used in conventional waste water treatment plants (Boisvert et al., 1997). They can be inorganic (e.g. aluminium sulphate and ferric sulphate), synthetic organic (e.g. polyacrylamic derivatives), or naturally flocculant (microbial flocculant). These are used for different purposes depending on their chemical characteristics (Okuda et al., 1999). Alum and ferric-based salts such as alum, aluminium chloride, ferric chloride, ferric sulphate are commonly used coagulants (Bektas, 2004; Shi et al., 2007; Liang et al., 2009). Aluminium and iron salts are widely used as coagulants in water and waste water treatment for removing a broad range of impurities from effluent, including colloidal particles, and to dissolve organic substances.

Despite widespread use of alum as a coagulant, Ndabigengesere, (1995) stated about the adverse effect of introducing aluminium into the environment. Natural coagulants, such as *Moringa oleifera* can be used as an alternative coagulant without any of the perceived negative environmental side effects of metal salt-based coagulants and as a substitute therefore for alum and ferric. *Moringa oleifera* is a pan-tropical, multi-purpose tree, the seed from which contains a high quality edible oil (up to 40% by weight) and water soluble proteins that act as an active agent for water and wastewater treatment. Before the use of synthetic chemicals like alum and ferric salts, natural coagulants of vegetable and mineral origin like *Moringa oleifera* were used in water and wastewater treatments (Ndabingengesere & Narasiah, 1997). The further advantages of using *Moringa oleifera* include a safe, natural and environmentally friendly coagulant (Bhatia et al., 2007). It is also antibiotic-resistant and shows antimicrobial effects against bacteria (Ghebremichael, 2004).

The potential use of this natural coagulant material in water and wastewater treatment plants needs further investigation (Bhuptawat et al., 2007). It can be used in different ways in the water treatment process either as a primary source of activated carbon, and through seed extraction, the product of which works as a coagulant/flocculant agent. The last method is more effective and suitable to apply in developing countries because it does not need a complicated process to use, and also does not have a negative impact on health (Heredia et al., 2009).

Agrawal et al. (2007) compared the use of *Moringa oleifera* and alum as a coagulant in a coagulation process to remove turbidity. The results show that their performance is comparable, with the former decreasing the turbidity in water coagulation from 30 to 14.8NTU (50%) and the latter from 30 NTU to 11.6 NTU (60%) at the same concentration. Katayon et al. (2006) compared the efficiency of using *Moringa oleifera* and alum as a coagulant in a high rate settling pilot scale water treatment plant to reduce turbidity. At optimum dosage, alum effiency is slightly better than *Moringa oleifera*. Alum decreased turbidity from 201 NTU to 6.9 NTU and *Moringa oleifera* from 201 NTU to 13.9 NTU. They also found that *Moringa oleifera* can be used as a coagulant in a water treatment plant because the resulting turbidity is lower than the World Health Organization's guideline value of < 5NTU for drinking water.

Considerable research has been undertaken to explore the efficiency of alum, ferric and *Moringa oleifera* as coagulants, but most research projects used these coagulants in isolation, making it difficult to directly compare the relative performance of each. Some research has considered comparing alum and ferric, alum and *Moringa oleifera,* or ferric and *Moringa oleifera* (Musikavong et al., 2005; Balkan & Pala, 2009; Liang et al., 2009; Maleki et al., 2009; Karamany, 2010), but no research has compared alum, ferric and *Moringa oleifera* directly within a single project, or considered how they directly influence sludge dewaterability.

2.3.5 The Role of Temperature on Coagulation Process

Temperature is a crucial factor in the coagulation process. It can affect the metal ion hydrolysis reaction rate (Duan & Gregory, 2003). The reaction rate increases with increasing temperature and vice versa. Furthermore, in the coagulation process, the temperature determines the distribution of the coagulant (Duan & Gregory, 2003) and the formation of the hydrolysis products, which affect the coagulation and flocculation efficiency (Gao et al., 2005).

Low water temperature can result in poor coagulation due to inhomogeneous distribution of coagulation species because the reaction rate is poor. Not only does it have an effect on the performance of coagulation in general, but the water temperature also distinguishes the efficiency of different kinds of coagulant, where ferric has a better performance than alum under low temperature conditions (Moris & Knocke, 1984; Duan & Gregory, 2003). Furthermore, Kang & Cleasby (1995) stated that low water temperature also has a significant effect on flocculation kinetics by decreasing the minimum solubility of $Fe(OH)_3$ in water. Increasing the temperature and pH can accelerate the Fe (III) salt hydrolysis rate and decrease soluble polymeric iron species formation time (Flynn, 1984; Vander Woude & De Bruyn, 1983).

Morris and Knocke (1984) performed experimental research into temperature effects on the use of metal-ion coagulants for water treatment, and showed that water temperature has a substantial impact on turbidity removal. Low water temperature leads to a decrease in the efficiency of turbidity removal. In contrast, the precipitation temperature did not affect the rate of metal-ion precipitation. The authors also state that a range of temperature between 1 and

23ºC did not affect the precipitation of alum and Fe (III). Furthermore, Hanson et al. (1990) showed that for the temperature range 5-20ºC, coagulation kinetics when using ferric sulphate were nearly identical if the pOH of the solution was kept constant. Moris and Knocke (1984) argued that the effect of low temperatures in the coagulation process was related more to the sludge characteristics than to the reduction of the metal hydroxide precipitation rate. This is due to the fact that water temperature impacts the hydroxide precipitation rate and the establishment of equilibrium by the presence of dissolved coagulant hydrolysis in solution.

2.3.6 Composition of Water Sample

Large volumes of raw water and domestic wastewater are processed every day in water and wastewater treatment plants. In the US, the amount of wastewater is 1,409.68 m^3/s (Tchobanoglous et al., 2003). The treatment of raw water or reservoir water will produce tap water, while the treatment of domestic wastewater separates the contaminant from water and produces a better quality of water.

The quality of the raw water or drinking water source will determine the selection of the treatment process in the water treatment plant. Thus, the stages and the efficiency of the process will determine the quality of the resulting tap water. The quality of the drinking water source is dependent on natural geology, land use and pollution (Gray, 2005). The quality of treated water and the composition of sludge are dependent on the quality of the source water (AWWA, 1999; Jin et.al., 2004; Zhang et al., 2011). Furthermore, the efficiency of the dewatering process is highly dependent on the nature of the sludge (Jin et al., 2004). The presence of organic content and colloid material can cause a decrease in sludge dewaterability (Dulin & Knocke, 1989; Li et al., 2005; Qi et al., 2011). The organic content causes a reduction in sludge particle size and the fine size of colloid material can hinder the filterability which is not appropriate for the sludge dewatering process (Neyen et al., 2004).

For laboratory tests, synthetic raw water and domestic wastewater are used. The utilization of synthetic raw water and domestic wastewater is to prevent differences in experimental conditions, because for laboratory-scale tests the availability of certified samples and constant characteristics is required (Baudez et al., 2007). The properties of natural samples are variable and highly dynamic, depending on the operating conditions of the treatment plants and changes over time during transport, handling and storage.

Numerous studies have demonstrated that synthetic raw water and domestic wastewater may be used for experimental purposes (Page et al., 2002; Smith et al., 2002; Bracklow et al., 2007; Kuscu et al., 2009; Hu et al., 2011). The biggest challenge in using synthetic water is in determining the appropriate recipe to represent the raw water and domestic wastewater composition. Many aspects have been considered in previous studies to formulate synthetic raw water and synthetic domestic wastewater. For synthetic raw water, not many recipes have been published. Finding recipes focused on a particular contaminant that is the target to be removed from the water and wastewater. Smith et al. (2002) classified the quality of raw water as soft, hard and acid, and formulated recipes for each, because of common problems in preparing synthetic freshwater given that there is no standard chemical in raw water. Page et al. (2002) formulated a recipe for synthetic reservoir water, the composition including aqueous DOM (Dissolved Organic Matter) or leachates from vegetation and soils diluted in synthetic water, KCl (10mg/L), CaSO4 (35mg/L) and NaHCO3 (100mg/L). Powdered quartz (10mg/L) was also added to represent turbidity. Kaolin has also been used as the main ingredient combined with tap water to simulate synthetic turbid water (Ndabingengesere & Narasiah, 1997; Rossini et al., 1998; Zouboulis et al., 2008).

In relation to the use of kaolin, Bottero et al. (1993) observed that it seems that aggregates formed in turbid waters may have a structure similar to that formed by the precipitation of coagulant in pure water. Furthermore, Baudez et al. (2007) found that a combination of kaolin (90%), calcite (5%) and quartz sand (5%) was better able to describe the behaviour of real inorganic sludge (e.g waterworks sludge). Sun et al. (2012), Wang et al. (2012), Yang et al. (2010) and Zhao et al. (2011) used humic acid and kaolin as the main ingredients, as their research was focused on the removal of humic acid constituents from water. Based on these reviews, there appears to be no standard recipe for synthetic raw water. The selection of a recipe seems to be determined mainly by the aim of the research, that is by which ingredient is to be investigated. This research considers that kaolin can satisfactorily represent the conditions of real raw water, and so this will be used as the synthetic raw water ingredient.

For synthetic domestic wastewater, many recipes have been formulated by many researchers (eg. Bracklow et al., 2007; Kuscu et al., 2009; Hu et al., 2011). Each recipe represents the real condition of domestic wastewater with different ingredients to match the focus of investigation. For natural wastewater, Tchobanoglous et al. (2003) have created a list of common parameters to assess the constituents found in wastewater. The list considers physical characteristics, inorganic chemical characteristics, organic chemical characteristics and biological characteristics. Baudez et al. (2007) stated that organic sludge has fats, fibres, protein and sugar within its composition, varying with the age of the sludge.

From a study of synthetic domestic wastewater recipes, the recipe used by Hu et al. (2011) best represents the real condition of domestic wastewater. This is shown in Table 3. The composition is consistent with wastewater in term of physical characteristics, inorganic chemical characteristics, organic chemical characteristics and biological characteristics. All of the ingredients are prepared by dissolution in 1 l hot tap water.

Table 3. Synthetic domestic wastewater composition

No	Constituents	Concentration (mg/l)
1	Dextrin	150
2	Ammonium chloride	130
3	Yeast extract	120
4	Glucose	100
5	Soluble starch	100
6	Sodium carbonate	150
7	Detergent (commercial)	10
8	Sodium di-hydrogen orthophosphate	100
9	Potassium sulphate	8.3
10	Kaolin	10,000

2.3.7 The Role of Floc Size on Sludge Dewaterability

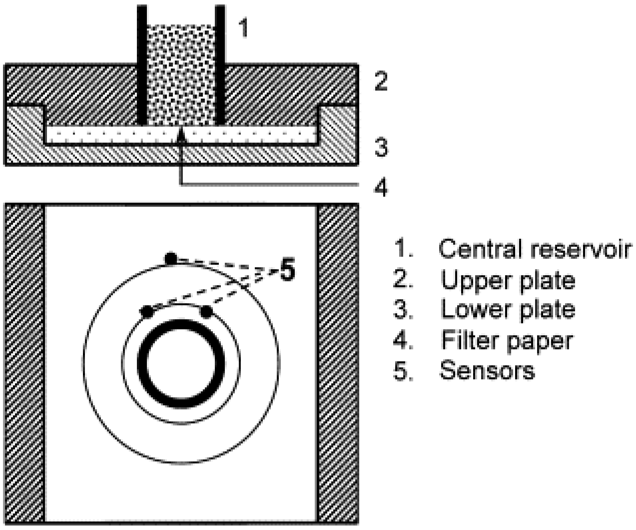
Coagulation mechanisms strongly influence floc size (Kim et al., 2001; Gao et al., 2008; Wang, 2009). Floc size also determines sludge dewaterability and plays an important role in sludge dewaterability processes (Lee & Liu, 2001; Zhao, 2003; Feng et al., 2009). Particle size in natural water is extremely variable, ranging from less than 1µm to 1.E+05µm (AWWA, 1999). Fine floc is not preferable because of its impact on the sludge dewatering process: the process can be reduced significantly by the presence of fine floc in the sludge, as this can cause clogging of the sludge cake pore structure and can also increase the bound water content in the sludge (Neyens et al., 2004).

In contrast to fine floc, large sized and dense floc is preferable because of their higher sedimentation rate and ease of dewatering (Larue & Vorobiev, 2003). Large sized and dense floc have higher mass and settle down more easily; large particles have larger floc porosity that easily releases water. Wen and Lee (1990) found an association between floc size and floc strength; larger flocs tend to have greater strength, and floc strength is recognized as an important element in sludge dewatering (Lee & Liu, 2001).

Floc size is also related to rapid mixing intensity: by increasing the slow stirring rate, the floc sizes will be decreased (Bouyer et al., 2005; Yu et al., 2011). As the coagulation mechanism is determined by rapid mixing intensity (AWWA, 1999; Byun et al., 2005) and since coagulant hydrolysis products (whose presence is specified by rapid mixing) determine the coagulated floc structure (Wang et al., 2008), it should be valuable in this research to observe the impact of the coagulation process on floc size and its role in sludge dewaterability.

2.4 Sludge Dewaterability Measurement

Dewaterability concerns the ease with which water is released from the sludge (Sanin et al., 2011). Capillary suction time (CST) and specific resistance to filtration (SRF) are widely accepted measurements of sludge dewaterability properties (Smollen, 1996; Chen et al., 2004; Dentel & Dursun, 2009). The CST measurement was devised by Baskerville and Gale in 1968. CST is obtained from two electrodes placed at a standard interval from the funnel. Sludge is exposed to an area at the centre of the CST filter paper and the filtrate from the sludge is absorbed by the CST paper (Figure 5). The time is recorded for the filtrate to travel between the two electrodes. The lower the CST value, the easier it is for the sludge to be filtered or dewatered (Besra et al., 2000).



Case dimensions : 33 x 26 x 5.5 cms

Figure 5. Diagram of capillary suction time test apparatus (Singh et al., 2006)

CST can be used to examine the impact of different rapid mixing velocities (Sawalha, 2010), different impellers on sludge dewaterability (Dentel et al., 2000) and is most commonly used for the rapid determination of flocculation dosages (Smollen, 1986). It is a valuable tool for characterizing biosolids pre-treatment for dewatering (Mayer, 2008).

The main use for CST is to determine filterability after the addition of coagulant aids (Scholz, 2005). The CST apparatus provides a simple, rapid, and inexpensive method to measure sludge dewaterability (Scholz, 2005, 2006). The test can be performed in any location by persons with little training because it does not require an external source of pressure or suction, and the automated CST test device is portable and easy to use. Baskerville and Gale (1968) and Sawalha and Scholz (2012) observed that the results of CST tests were sensitive to variations in temperature. The results tend to reduce with higher temperatures, which is probably due to the increase in filtrate viscosity with increasing temperature.

An alternative test, the SRF test, utilizes a Buchner funnel apparatus, with vacuum port and filter paper. The CST and SRF results usually correlate well (Scholz, 2005) and, for the same sludge sample, the CST and SRF values show a significant relationship (Sawalha & Scholz, 2010). The SRF test, however, is more difficult to execute, is time consuming, and expensive; no specific, standard device to measure SRF is available (Ayol & Dentel, 2005; Li et al., 2005; Teoh et al., 2006; Yukseler et al., 2007). Furthermore, SRF varies with pressure, area of filter paper, solid concentration and liquid viscosity (Sanin, 2011). Even differences in the apparatus and procedures used, e.g. the filter medium and the vacuum applied, have been found to cause variability in the results, reported by different workers (Smollen, 1986a;1986b).

The SRF equation was taken from Darcy’s law, which describes the flow of fluid through porous media. Sanin et al. (2011) explained the derivative equation taken from Chapman in 1933, who adapted Darcy’s equation to filtration; and from Coackley and Jones in 1956, who adapted Carman's theoretical analysis to filtration:

Darcy's law :

$$\frac{dV}{d\theta} = \frac{P}{\mu}\frac{\mathrm{AK}}{L} \tag{3}$$

where :

$\frac{dV}{d\theta}$ = rate of flow, volume (V) per time (ø)

P = pressure difference

A = area

μ = viscosity

K = permeability

L = thickness

if R (resistance) = 1/K then,

$$\frac{dV}{d\theta} = \frac{P}{\mu}\frac{\mathrm{A}}{LR} \tag{4}$$

in a filter, resistance is influenced by both the filter medium and the filter cake:

$$\frac{dV}{d\theta} = \frac{P}{\mu}\frac{\mathrm{A}}{(LR+Rf)} \tag{5}$$

Where Rf = resistance of filter medium

The volume of the cake can be expressed as: LA = υV

Where ν = volume of cake deposited per unit volume of filtrate

Substituting for L :

$$\frac{dV}{d\theta} = \frac{PA^2}{\mu(\mathrm{RvV+RfA})} \tag{6}$$

Cake is expressed as dry weight volume instead of volume of cake per volume of filtrate. And, R (resistance by unit volume) is replaced by r (resistance by unit weight), thus:

$$\frac{dV}{d\theta} = \frac{PA^2}{\mu(\mathrm{WrV+RfA})} \tag{7}$$

Where :

w = weight of dry cake solids per unit volume of filtrate

r = specific resistance

Assuming constant pressure over time,

$$\int_0^{\theta} d\theta = \int_0^{v} \left[\frac{\mu \mathrm{wrV}}{PA^2} = \frac{\mathrm{Rf}\mu}{\mathrm{PA}}\right] \mathrm{dv} \tag{8}$$

$$\theta = \frac{\mu wr\mathrm{V}^2}{2PA^2} + \frac{Rf\mu V}{PA} \text{ or } \frac{\theta}{\mathrm{V}} = \frac{\mu wr\mathrm{V}}{2PA^2} + \frac{\mu Rf}{PA} \tag{9}$$

Which is a straight line of type y = bx + a, where:

$$b = \frac{\mu wr}{2PA^2} \tag{10}$$

and

$$a = \frac{\mu Rf}{PA} \tag{11}$$

It should thus be possible to measure the volume of the filtrate, *V*, at various times, θ, plot these as θ/V vs *V*, and then obtain a straight line. The relationship of the slope of this line is calculated and since the slope b is equal to $\mu rw/2PA^2$, it is possible to calculate specific resistance, r, the only unknown, as:

$$\mathrm{r} = \frac{2\,PA^2 b}{\mu w} \tag{12}$$

Where:

r : the specific resistance to filtration (m/kg), P : the filtration pressure (N/m^2),

A : the filter area (m^2),

μ : the viscosity of the filtrate (Ns/m^2),

w : the weight of the cake solids per unit volume of filtrate (kg/m^3),

b : the slope of filtrate discharge curve (s/m^6).

According to Sawalha (2010), the results of the CST and SRF tests are interrelated. This means that the SRF value can be predicted from the CST test results. Thus, the CST and SRF apparatus are used in this research as a means of quantifying sludge dewaterability. The CST test is much easier and quicker than the SRF measurement (Tebbut, 1998). The CST is preferred because it is easy to use, results are obtained quickly, it is less expensive than SRF, and it has a standardized procedure. The SRF test is used as a verification tool for the CST results.

2.5 Chapter Summary

Much work has been undertaken on coagulation, but very little in the area of rapid mixing. The majority of the research into mixing has been carried out in the area of velocity, either in rapid mixing or slow mixing, and little research on rapid mixing time. In the mixing process, the mixer is needed to produce turbulence in the water. Different mixer geometries have been known to have different impacts on turbidity removal from water, but the influence of different mixer geometries in water treatment on sludge dewaterability still needs to be investigated. In industry, many types of mixer are used and a recommendation for the best mixer shape is still needed. The literature review of rapid mixing velocity and rapid mixing time shows that they have different impacts on contaminant removal from water. However, there has been no investigation into the impact of rapid mixing velocity and time in coagulation to sludge dewaterability. Alum and ferric are the most commonly used coagulants, but *Moringa oleifera* has also been used. Most research uses only one coagulant. And, occasionally for comparison, two or three coagulants are used simultaneously. However, comparison of alum, ferric and *Moringa oleifera* specifically has not been undertaken or documented. The distribution of the coagulant into water is also influenced by temperature, so that as well as the effect of different coagulants, the effect of different temperatures is investigated. The composition of the water sample also strongly influences the sludge dewaterability process. CST test apparatus and SRF methods are the most commonly used to measure sludge dewaterability.

Therefore, in this research, the influence of different mixer shapes with different rapid mixing velocities and times, different coagulants, different temperature and different water samples are investigated to ascertain their impact on sludge dewaterability, using the CST and SRF apparatus alongside the turbidimeter and particle size analyzer.

This research is based on experimental work, using many materials and several methods. The next chapter will discuss the materials and methodology of this study.

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

This section outlines the materials and specific test methods to be used in the primary testing phase. It also describes the results of preliminary tests carried out to establish the most appropriate test methodology.

3.2 Materials

3.2.1 Mixers

The Jar test is the most commonly used in coagulation studies. However, there is no internationally accepted standard procedure or equipment for this test (AWWA 2003). In this research, five shapes of mixer are used (radial, axial, wheel, magnetic and 3-blades) to disperse the coagulant into the water to be ‘treated’. The selected mixers are turbine and propeller, which use a paddle or propeller to produce movement in the water. The five shapes of mixer are used to investigate their influence on sludge dewaterability (Figure 6). The axial mixer represents the shape of a jar test paddle, whilst radial, wheel and 3-blades are common shapes produced and used in industry (A.T.E., 2011; Chemineer, 2004). The magnetic stirrer produces different conditions within the fluid to the other mixers, but is a common mixing apparatus in the laboratory. It operates at the base of the chamber whereas the other mixers operate at different elevations (1.5 cm) within the test chamber (6.5 cm internal diameter and 9 cm height) (Figure 6).

Diameter: 3 cm

Radial **Axial** **Wheel** **Magnetic** **3-blades**

Figure 6. Mixer types in experimental work

All of the mixer shapes have a diameter of 3 cm. The radial shape has two blades which are 1.2 cm in length, 0.8 cm in width and at a 45^{o} angle from the mixer's horizontal axis. The axial shape has two blades, 1.2 cm by 0.8 cm. The wheel shape is 1.7 cm high and at a 45^{o} angle from the mixer's horizontal axis. The magnetic stirrer is 3 cm by 0.5 cm. Finally, the blades of the 3-blade shape are 1.7 cm by 0.4 cm.

The radial, wheel and 3-blades mixer shapes were chosen based on the information provided by companies producing and/or selling standard mixers used by the water and wastewater industry, such as Chemineer Ltd. (Cranmer Road, Derby DE21 6XT, UK) and Promix Mixing Equipment and Engineering Ltd. (Columbus Road, Mississauga L5T 2G9, Canada).

The radial and axial mixers were obtained from Monmouth Scientific Ltd. (Units 5 and 6, Kilnside, East Quay, Bridgwater, Somerset TA6 4DB, UK). JP Accessories (J Perkins Distribution, Lenham, Kent ME17 2DL, UK) supplied the wheel mixer. The magnetic stirrer IKA REO was obtained from Sartorius Instrumental Ltd. (18 Avenue Road, Belmont, Surrey SM2 6JD, UK). The 3-blade mixer was manufactured in the engineering workshop at the University of Salford, based on designs obtained from Chemineer and Promix.

G calculation for every impeller used the formula in equation (1) and equation (2). Impeller power number (Np) is needed in this calculation and has the most important role because other elements in equation (2) are constant. Except magnetic stirrer, Np is provided by impeller company where for radial is 0.5 (Fusion Fluid Equipment Ltd), axial is 3 (Hayward Gordon Ltd), wheel is 0.35 (Dynamix Agitators Inc), magnetic is 0.958 (AWWA, 2000) and 3-blades is 0.32 (Fusion Fluid Equipment Ltd).

3.2.2 Coagulants

The coagulants investigated were Aluminum Sulphate $Al_2(SO_4)_3$ (alum) and Ferric Chloride ($FeCl_3$) (ferric) (from Sigma Aldrich Company Ltd., The Old Brickyard, New Road, Gillingham, Dorset SP8 4XT, UK), and *Moringa oleifera* (from Xiamen Tianzhu Ecological Agriculture and Forestry Science and Technology Co. Ltd., Haicang District, Xiamen City, Fujian Province, China).

Alum and ferric were prepared by diluting the concentrate with distilled water to obtain a 1000 mg/l concentration. The purpose of using distilled water was to avoid the addition of other ingredients which may affect the performance of the process. These solutions were renewed every three weeks in order to obtain a fresh solution. *Moringa oleifera* was prepared by grinding non-shelled seed with a blender into powder. This preparation process was based on the work by Ndabingengesere et al. (1995). The *Moringa oleifera* powder was mixed with distilled water using a magnetic stirrer for five minutes at 1200 rpm to obtain a 1000 mg/l *Moringa oleifera* solution. This solution was renewed every week to ensure that it was always fresh.

3.2.3 Temperature

The general temperature used for all investigations was room temperature (20°C±1°C) unless stated otherwise. This value reflects the general laboratory temperature present in temperate and oceanic regions; was kept constant with the intention of eliminating temperature effects on the CST measurements. In addition, temperatures of 16°C±1°C and 26°C±1°C were used to simulate field (i.e. outside) measurements in spring and autumn, and summer, respectively. These temperatures not only vary according to the location and time of the year, but 26°C±1°C also represents the optimum temperature for bacteria activity (25-30°C) and 16°C±1°C the temperature when methane-producing bacteria become inactive (Metcalf & Eddy 2003). The highest temperature may also reflect operating temperatures in laboratories located in warmer countries. All target temperatures were obtained by adjusting the temperature in the laboratory.

3.2.4 Water Samples

In this experimental study, synthetic raw water and synthetic domestic wastewater were used.

3.2.4.1 Synthetic Raw Water

Kaolin was the main ingredient for synthetic raw water because it was easy to obtain, inexpensive and it seems that aggregates formed in turbid waters may have a structure similar to that formed by the precipitation of coagulant in pure water (Bottero et al., 1993; Baudez et al., 1997). Furthermore, kaolin is commonly used to represent the TSS in raw water (Yang et al., 2010; Zhao et al., 2011; Sun et al., 2012; Wang et al., 2012).

3.2.4.2 Synthetic Domestic Wastewater

The synthetic domestic wastewater recipe followed that proposed by Hu et al. (2011) with the addition of kaolin as a suspended solid. This recipe was chosen because the composition represents the composition of domestic wastewater.

3.3 Coagulation Test

Most results presented in this research were obtained from three repeat coagulation experiments and from three readings. Some of the results presented are based on more than three readings, primarily due to high variability in the results.

3.3.1 Rapid Mixing Velocity

To investigate the influence of rapid mixing velocity on coagulant performance, a 100ml water sample was poured into a glass beaker followed by the addition of the coagulant. After adjusting the pH with sulphuric acid (H_2SO_4) or sodium hydroxide (NaOH) to reach a pH value of approximately 6.5, the fluid was mixed rapidly at a variable high rate (60, 65, 70, 75, 80, 85, 90, 95 and 100 rpm) for 60 s and then at a moderate rate of 50 rpm for 15 minutes to accommodate the agglomeration process.

3.3.2 Rapid Mixing Time

Tests to examine the influence of rapid mixing time utilized a 100 ml water sample contained within a glass beaker, to which was added H_2SO_4 or NaOH to adjust the pH. The coagulant was subsequently added to the water sample. Once a pH of 6.5 was reached, the sample was mixed rapidly at a range of times (10, 20, 30, 40, 50, 60, 70, 80, and 90 s) with a constant 100 rpm rapid mixing velocity, and then at a slower rate of 50 rpm for 15 minutes to accommodate the agglomeration of flocs.

3.4 CST Measurement

A Triton Type 304B Capillary Suction Timer apparatus and Whatman 17 chromatographic paper were used in this investigation (Triton Electronics Ltd., Bigods Lane, Great Dunmow, Essex CM6 3BE, UK). For the CST measurement, following the flocculation process, sedimentation was employed for 15 minutes. The sludge (floc) was carefully separated from the supernatant by discarding the supernatant so that only sludge remained in the coagulation chamber. After turning on the CST apparatus, the sludge was poured into the funnel. The CST is timed automatically as soon as the fluid reaches the first sensor circle and stops when the fluid reaches the second sensor circle. The measured time is referred to as the CST value. A lower CST value indicates good sludge dewaterability and a higher CST value indicates poor sludge dewaterability (Sanin et al., 2011).

3.5 Turbidity Measurement

The turbidimeter used in this investigation was a Lovibond (The Tintometer Ltd., Lovibond House, Solstice Park, Amesbury SP4 7SZ, UK). The turbidity measurement was perfomed on a sample of the supernatant taken during/after the sedimentation process. This sample was poured into the turbidimeter vial which was subsequently placed into the turbidimeter .

3.6 Floc Size Measurement

To determine the size of flocs produced during the coagulation process, a sample was obtained 15 minutes after the start of the sedimentation process following the flocculation process. The sludge sample was characterized by analyzing the distribution of particle sizes with a particle size analyzer (Horiba Laser Scattering Particle Size Analyzer LA-950 Horiba Instruments Inc., 34 Bunsen Drive, Insine, 92618, California, USA). The instrument calculates the correlation between the intensity and angle of light scattered from a particle, and subsequently determines the particle size based on Mie-scattering theory (scattering of electromagnetic radiation by a sphere). Floc size shearing was minimized during the experiment, by careful mixing during the measurement process. An overview of the detailed measurement procedure is outlined on the company website (http://www.horiba.com). In this study, particle size is synonymous with floc size.

3.7 Floc Density Measurement

To measure floc density, bulk of sludge after flocculation was poured on to filter paper. The filtration process took place for 24 hour. Then, filter paper was weighted by scale. The weight of floc is the difference between of filter paper weight after coagulation and before coagulation. Floc density is the result from the comparison between weight of floc and volume of floc/sludge after coagulation. To produce the result, 3 to 5 replicates have been used in the experiment.

3.8 Specific Resistance to Filtration (SRF)

There is no standard procedure for operating the SRF apparatus, especially for the intensity of vacuum pressure (Ayol & Dentel, 2005; Li et al., 2005; Teoh et al., 2006; Yukseler et al., 2007). The SRF method in this research followed the work of Bache and Papavasilopoulos (2003), who used it to investigate the dewatering of alumina-humic sludge. The SRF test was started by pouring the sample from the flocculation process into a Buchner funnel. A vacuum pressure of 80kPa was applied and a Whatman number 1 filter paper (Whatman International Ltd., Maidstore, 1 Rudolf Place, London SW8 1RP, UK) was used. The result is the relationship between the time needed to separate the water and the solid, and the filtrate volume. The filter was weighed to obtain the mass. Viscosity of the filtrate was measured using a viscosity meter. The SRF value was obtained from equation (12).

3.9 Preliminary testing

The purpose of laboratory preliminary testing is to obtain a preparation for the main experimental work, and to get early information about the influence of experimental parameters (mixer shape, coagulation velocity and time, coagulant and water sample) on sludge dewaterability. Most important is to determine the composition of the water sample, an optimum coagulant dose, the range of different rapid mixing velocity values, and the range of different rapid mixing time values. In this initial stage, laboratory work was performed with different shapes and types of mixer, and different rapid mixing velocities and times, to investigate their effects on sludge dewaterability.

3.9.1 Determination of Water Sample Composition

3.9.1.1 Synthetic Raw Water

The first step in the preliminary experimental work was to find water sample composition. For raw water preparation, kaolin (from Sigma Aldrich Company Ltd., The Old Brickyard, New Road, Gillingham, Dorset SP8 4XT, UK) was added to distilled water and stirred with a magnetic stirrer until well mixed (Zouboulis et al., 2008). In this research, mixing was done for five minutes at 1200 rpm. Initially, a series of experimental works were carried out to determine the optimum time and mixing intensity to produce a well mixed sample. The experiment started by using 1000 rpm mixing intensity for 60 s. The solution was not well mixed because the coarse unmixed kaolin was present at the bottom of the glass. By increasing the time to 120 s, 180 s, 240 s and 300 s, it was still not possible to produce a homogenous kaolin solution. The mixing intensity was then increased to 1100 rpm and 1200 rpm for 300 s. Finally, a 1200 rpm mixing intensity and 300 s mixing time produced a homogenous kaolin solution.

In addition to the rapid mixing intensity and rapid mixing time of the test, different kaolin dosages were examined to find the optimum dosage. The kaolin dosage was varied from 1 g, 2 g and 3.5 g kaolin per 100 ml distilled water. A comparison of the results showed a consistent trend among these concentrations (Figure 7). Considering the efficiency of using kaolin, 1g dose was chosen for this research. The concentration of SS was 1% in the synthetic raw water solution and became 5-30% for CST measurement, as a result of coagulation and sedimentation processes.

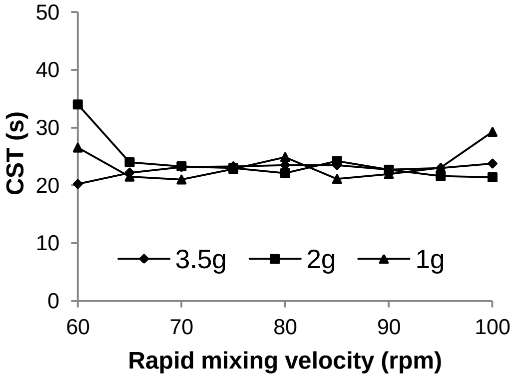


Figure 7. Comparison of different kaolin concentrations

3.9.1.2 Synthetic Domestic Wastewater

Raw water has different qualities from wastewater. Raw water has been identified as having a mainly inorganic content whilst domestic wastewater has a large organic content. This stage of the research investigated the impact of different wastewater composition on the coagulation process and on sludge dewaterability. Jin et al. (2004) believe that the nature of the (floc) sludge affects the efficiency of the dewatering process because every sludge has different characteristics, such as size distribution, surface properties and density, which determine the sludge dewaterability. Moreover, the wastewater composition determines the sludge composition (Zhang et al., 2004); for example, activated sludge has a complex and heterogeneous composition, which can be changed and finally affects the dewaterability (Jin et al., 2004). In this investigation, synthetic domestic wastewater was used.

The synthetic domestic wastewater recipe followed that proposed by Hu et al. (2011), with the addition of kaolin as a suspended solid. This recipe was chosen because the composition has represented the composition of domestic wastewater. The main purpose of using kaolin is to get 1% TSS (Total Suspended

Solid) concentration, which is similar to the suspended solid concentration of synthetic raw water. The sludge concentration at the bottom of the glass increased 5-30% due to coagulation and sedimentation processes. The solution was produced by adding the ingredients (Table 3), except that kaolin in 1 l hot tap water was followed by the addition of 10 g kaolin (well mixed by using 1200 rpm mixing intensity for 5 minutes). All chemicals were supplied by Sigma Aldrich Company Limited (The Old Brickyard, New Road, Gillingham, Dorset SP8 4XT, UK). This solution was prepared fresh everyday (or sometimes every two days) and was always stored in the fridge to avoid uncontrolled growth of microorganisms that might influence the wastewater quality.

The first investigation using synthetic domestic wastewater produced almost consistent results in terms of sludge dewaterability and turbidity with a change in rapid mixing velocity. In order to validate the recipe, other recipes for synthetic wastewater and natural domestic sludge were investigated and used as a comparison.

Another recipe was adopted from Sawalha (2010); it had been formulated to investigate the performance of the CST test under various conditions, such as different funnel geometries, different filter papers, different temperatures and different CST tests. The ingredients are 100 ml 85 mM sodium chloride solution, 3.33 % w/w kaolin clay, 1.67 % w/w bentonite clay, 10 mg/100 ml sodium alginate, 60 mg/100 ml cellulose fibrous and 548 mg/100 ml $CaCl_2$ $6H_2O$. Figure 8 shows the result of the different water samples comparison.

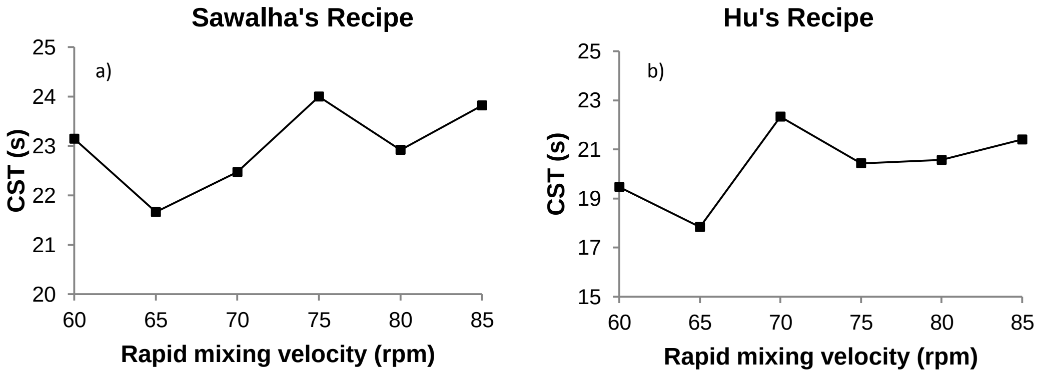


Figure 8. Investigation of synthetic domestic wastewater recipes

The two recipes show that different rapid mixing velocities using synthetic domestic wastewater as the water sample produce a fluctuating impact on sludge dewaterability. In general, increasing the rapid mixing velocity increases the CST value, although the trend is not always constant. For rapid mixing values of 60 rpm and 65 rpm, increasing the rapid mixing velocity causes a decrease in sludge dewaterability. At rapid mixing speeds higher than 65 rpm, as the velocity increases, sludge dewaterability reduces and finally increases again in response to the higher rapid mixing velocity.

Despite the level of sludge dewaterability value, the trends of rapid mixing velocity vs CST value from the two recipes are similar. The initial recipe proposed by Hu et al. produced experimental data that compares favourably with other published recipes for synthetic wastewater. The results of this sensitivity study therefore suggest that experimental results using Hu et al.'s recipe are likely acceptable, so this recipe can be used as a synthetic wastewater sample.

3.9.2 Determination of Optimum Coagulant Dosage

The correct coagulant dose is essential in the coagulation process as it determines the effectiveness of the process. It must be sufficient to destabilize the contaminant. A low dose results in an ineffective process because it cannot provide sufficient coagulant hydrolysis products to destabilize the contaminant. A high dose will remove the contaminant but may not be efficient or economic.

In order to obtain an optimum coagulant dose for this research, testing was done by adding different dosages from different coagulants to all the water samples, for subsequent dewaterability measurement with the CST apparatus. The magnetic stirrer was used as a mixer.

The test started by pouring a 100 ml sample into a glass beaker; H_2SO_4 or NaOH were added to adjust the pH. The coagulant was subsequently added to the water sample. Once a pH of 6.5 was reached, the sample was mixed rapidly for 1 minute with a constant 100 rpm rapid mixing velocity and then at a slower rate of 50 rpm for 15 minutes to accommodate the agglomeration of flocs. After 15 minutes' sedimentation, the sludge was separated carefully from the water by a decanting process. Then, the dewaterability of the sludge was measured using the CST apparatus. This experiment was performed several times with different coagulant doses, to produce the graphs in Figure 9.

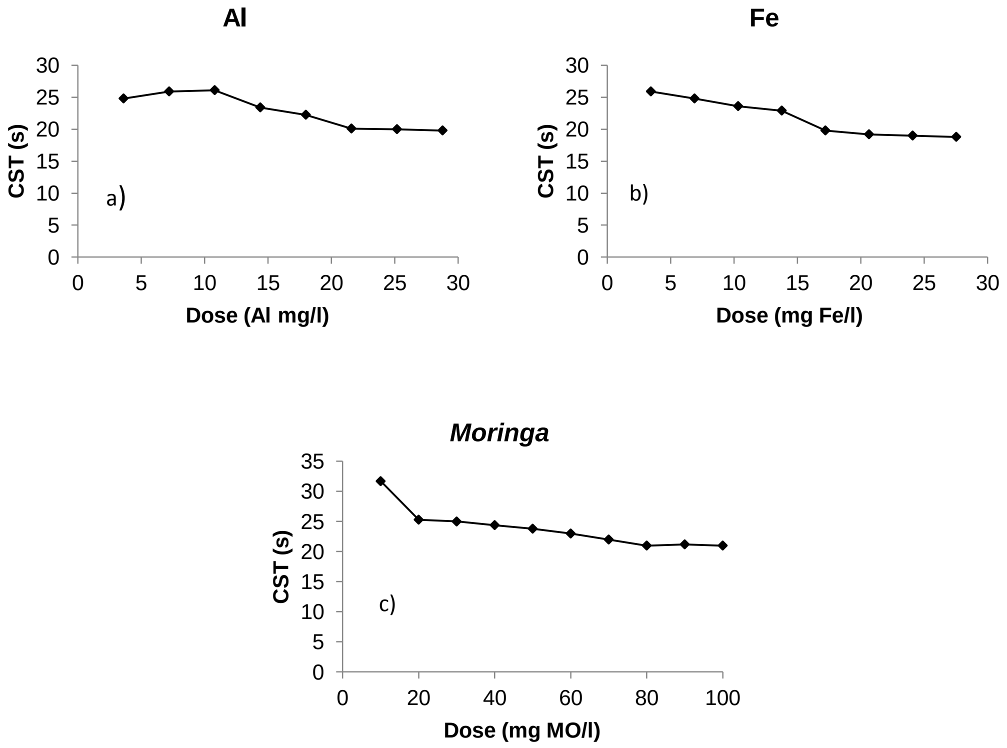


Figure 9. Optimum coagulant doses

Figure 9 shows that in general, as the coagulant dosage increases the CST values decrease. The graphs indicate that the optimum dose for alum is 21 mg Al/l, for ferric is 17 mg Fe/l, and for *Moringa oleifera* is 80 mg *Moringa*/l. The coagulant doses for the synthetic raw water sample and synthetic domestic wastewater were the same.

3.9.3 Determination of Optimum Rapid Mixing Velocity

Rapid mixing velocity was explored in the preliminary research by employing a rapid mixing intensity of 100-2000 rpm or 300-1000 s^{-1} to examine the effect on sludge dewaterability. The lower bound value was selected based on the median value of rapid mixing velocity used in typical wastewater treatment plants, which lies between 40 and 125 rpm (Metcalf & Eddy, 2003); and the upper bound value is related to typical values for coagulation velocity adopted in industry, which commonly lie between 300 and 2000 rpm or 500 and 1000 s^{-1} (UFC, 2004).

In the preliminary investigations, different rapid mixing velocities and times using different shapes of mixer were employed to obtain information about optimum values and/or ranges of values for these variables for the coagulation process. Rapid mixing velocity and rapid mixing time must be performed under optimum conditions.

Rapid mixing velocity varies from 0-2000 rpm and tests using four different shapes of mixer were conducted. The coagulant used was optimum dosage alum. Synthetic raw water was used as the water sample with kaolin as the main ingredient. Rapid mixing time was 1 minute. The results are shown in Figure 10.

Figure 10 indicates that, in general, high rapid mixing velocity does not affect the CST value. The gradual increase in rapid mixing velocities produced a constant effect for the CST value, except for a rapid mixing velocity of less than 100 rpm. For rapid mixing velocities of less than 100 rpm, an increase brings about a decrease in the CST value, with the average removal percentage around 50%. For rapid mixing velocities higher than 100 rpm, an increase has a similar impact on the CST value, with the percentage of removal still about 50%.

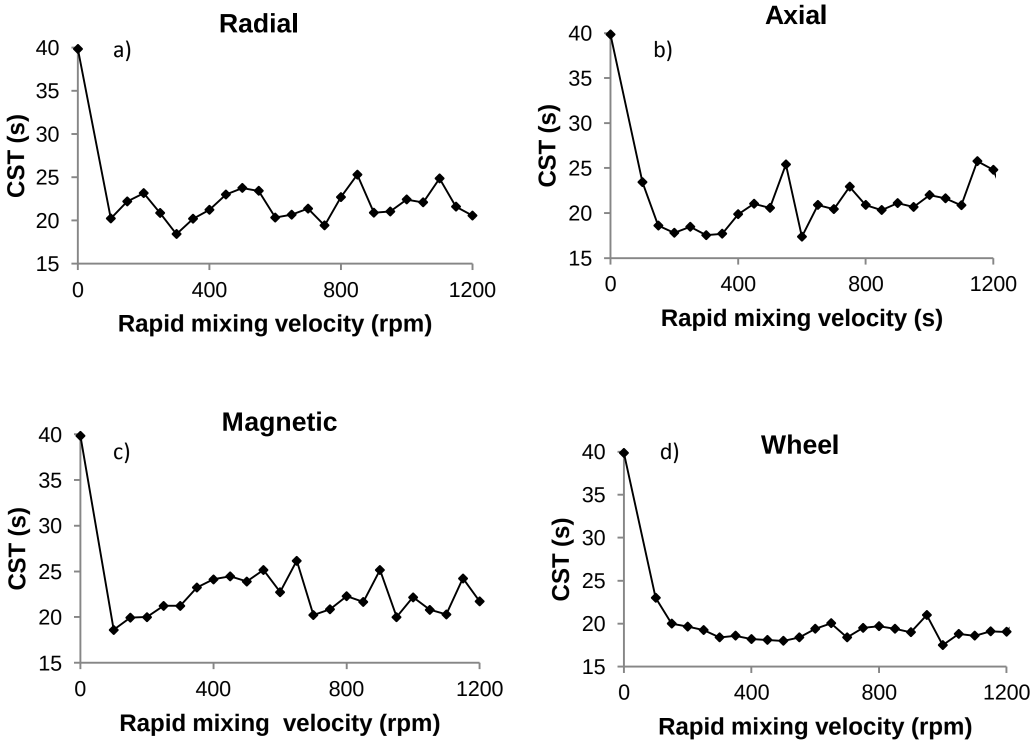


Figure 10. Optimum rapid mixing velocities

In this early investigation, the consistency in the CST value measurement seems to have been slightly influenced by inconsistency in the water-sludge separation process. As a result, it produced an inconsistency in the free water (bulk water that is not bound to sludge, so it can be easily removed by mechanical means and represents a large proportion of the total water) content in the sludge. This factor affects the measurement process of sludge dewaterability. Another influencing factor that produced this constant result may have been an excess of the optimum rapid mixing velocity value. Excess rapid mixing velocities will disturb the contact between the coagulant and the contaminant so that an efficient process can occur (Rossini et al., 1999). Thus, an appropriate mixing velocity is required to produce efficiency in the coagulation process.

Employing this range of velocities in the preliminary research gave an indication that rapid mixing velocity higher than 100 rpm had no significant impact on sludge dewaterability. The investigations were repeated and performed with different shapes of mixer and different rapid mixing velocities, with consistent results which were indicated by the similar sludge dewaterability values. As a consequence, rapid mixing velocities less than 100 rpm were adopted for the main investigation.

In the primary research, the rapid mixing velocity employed was within the range 60-100 rpm. The value of 100 rpm was based on the result from the preliminary research, and the value of 60 rpm on the range of mixing velocity in a typical treatment plant (Tchobanoglous et al., 2003).

3.9.4 Determination of Optimum Rapid Mixing Time

In order to define an appropriate range of mixing times for rapid mixing, a preliminary investigation was undertaken. Initially a range of 0-300 s was considered, informed by research published by Kan et al. (2002a), who observed the impact of rapid mixing time on the coagulation process. This time interval could describe the stage of removing turbidity from the water under the influence of different rapid mixing times. Just as in the rapid mixing velocity investigation, the parameters used were four different shapes of mixer (radial, axial, wheel and magnetic) with a synthetic raw water sample. A mixing velocity of 100 rpm was selected, based on the result from the determination of rapid mixing velocity value. The results are presented in Figure 11.

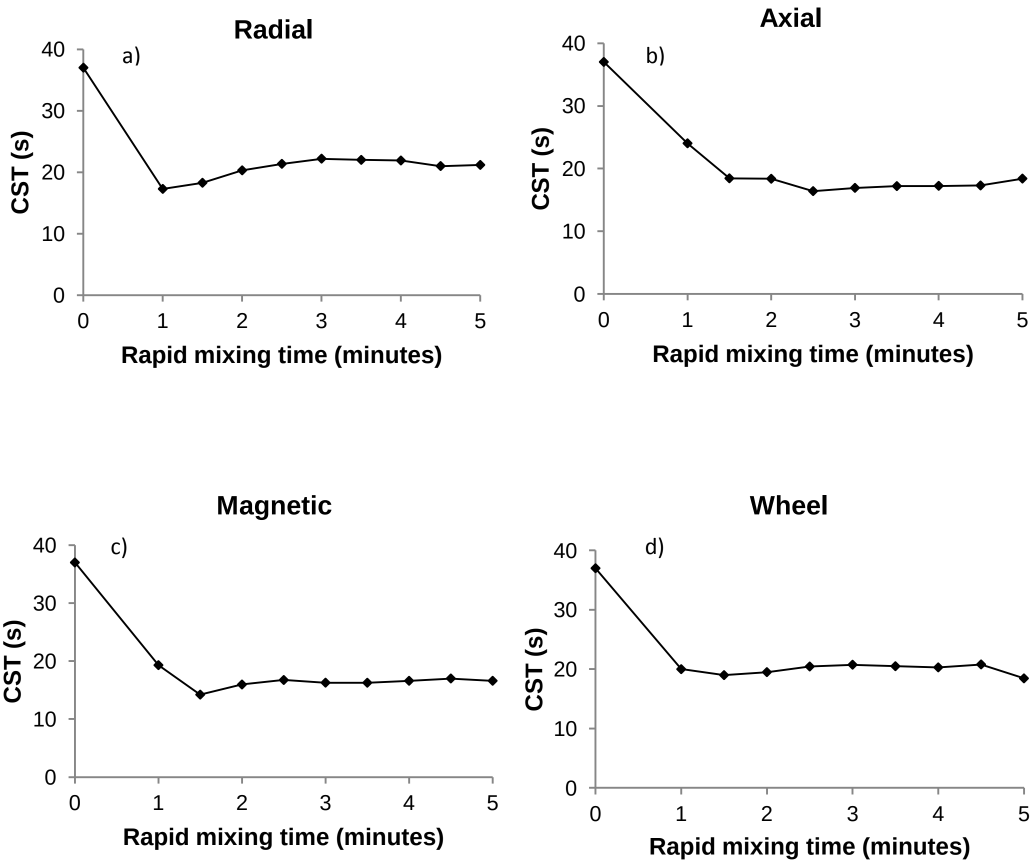


Figure 11. Optimum rapid mixing time determining experimental results

The results show that a rapid mixing time lower than 90 s has a substantial impact on the CST value, compared to times higher than 90 s. For rapid mixing times greater than 90 s, increasing the time brings no change in the CST value. Even though larger floc is formed in the slow mixing process, continued rapid mixing causes the formation of small flocs or microflocs (Rossini et al., 1999). Based on these results, it is essential to investigate rapid mixing times lower than 90 s in the primary investigation. From this result, subsequent investigations considered rapid mixing times within the range 0-90 s.

3.10 Statistical Analysis

In this investigation, Pearson's correlation coefficient was used to describe the strength of the relationship between any two variables. The calculation used IBM SPSS Statistics version 20. Pearson's correlation coefficient was used because it can measure the strength and direction (decreasing or increasing, depending on the sign) of a linear relationship between two variables X and Y (Ahlgren et.al., 2003). The correlation between the two variables can be considered to be good if (r) is close to ±1, and poor if the value is close to zero. The correlation coefficient between two variables is linear if the value (r) is positive and non-linear if it is negative. The linear correlation means that X and Y lie on the same side of their respective means. The non-linear correlation means that X and Y tend to lie on opposite sides of their respective means.

The Pearson's correlation coefficient (r) can be expressed in terms of (Owens & Jones, 1994):

$$\mathrm{r} = \frac{Covariance\ (XY)}{\sqrt{\sigma^2 x \times \sigma^2 y}} \tag{13}$$

The covariance (XY) is :

$$\frac{\sum XY}{n} = \frac{\sum X . \sum Y}{n . n} \tag{14}$$

The variance of X is :

$$\frac{\sum X^2}{n} = \left(\frac{\sum X}{n}\right)^2 \tag{15}$$

The variance of Y is :

$$\frac{\sum Y^2}{n} = \left(\frac{\sum Y}{n}\right)^2 \qquad (16)$$

So, the Pearson’s correlation coefficient can be expressed as :

$$r = \frac{S^2xy}{\sqrt{S^2x \times S^2y}} \qquad (17)$$

3.11 Chapter Summary

This research is based on experimental work, which was conducted in two stages: preliminary testing and primary testing. The preliminary testing was done in order to determine the optimum coagulant dose, the value for rapid mixing velocity and rapid mixing time, and the composition of the water samples. The primary testing is the major testing to prove/disprove the original hypothesis. The large amount of data produced will be presented and discussed in detail in Chapters 4, 5 and 6.

CHAPTER 4

CAPILLARY SUCTION TIME (CST) RESULTS AND DISCUSSION

4.1 Introduction

Rapid mixing has an important role in water coagulation in dispersing the coagulant into the water; the better the dispersal, the better the agglomeration of the contaminant in the water (AWWA, 1999). Rapid mixing needs a mixer to produce and transfer the energy and the turbulence into the water. In order to investigate the influence of a range of process variables on sludge dewaterability (CST value), rigorous experimental work was conducted. The investigation examined:

- mixer shape
- rapid mixing velocity during coagulation
- rapid mixing time during coagulation
- coagulant
- temperature
- water composition.

This chapter presents and discusses the data from the experimental work.

♣ A part content of this chapter has been published as a manuscript in the Journal of Environmental Technology.

Fitria, D., Scholz, M., and Swift, G.M. (2012). *Impact of different shapes and types of mixers on sludge dewaterability*. Journal of Environmental Technology 34 (7), 931 - 936. DOI: 10.1080/09593330.2012.722692.

♣ A part content of this chapter is also under review for the Journal of Environmental Engineering Science.

Fitria, D., Scholz, M. and Swift, G.M. *Impact of temperature, coagulant and mixer type on capillary suction time used as indicators for sludge dewaterability*.

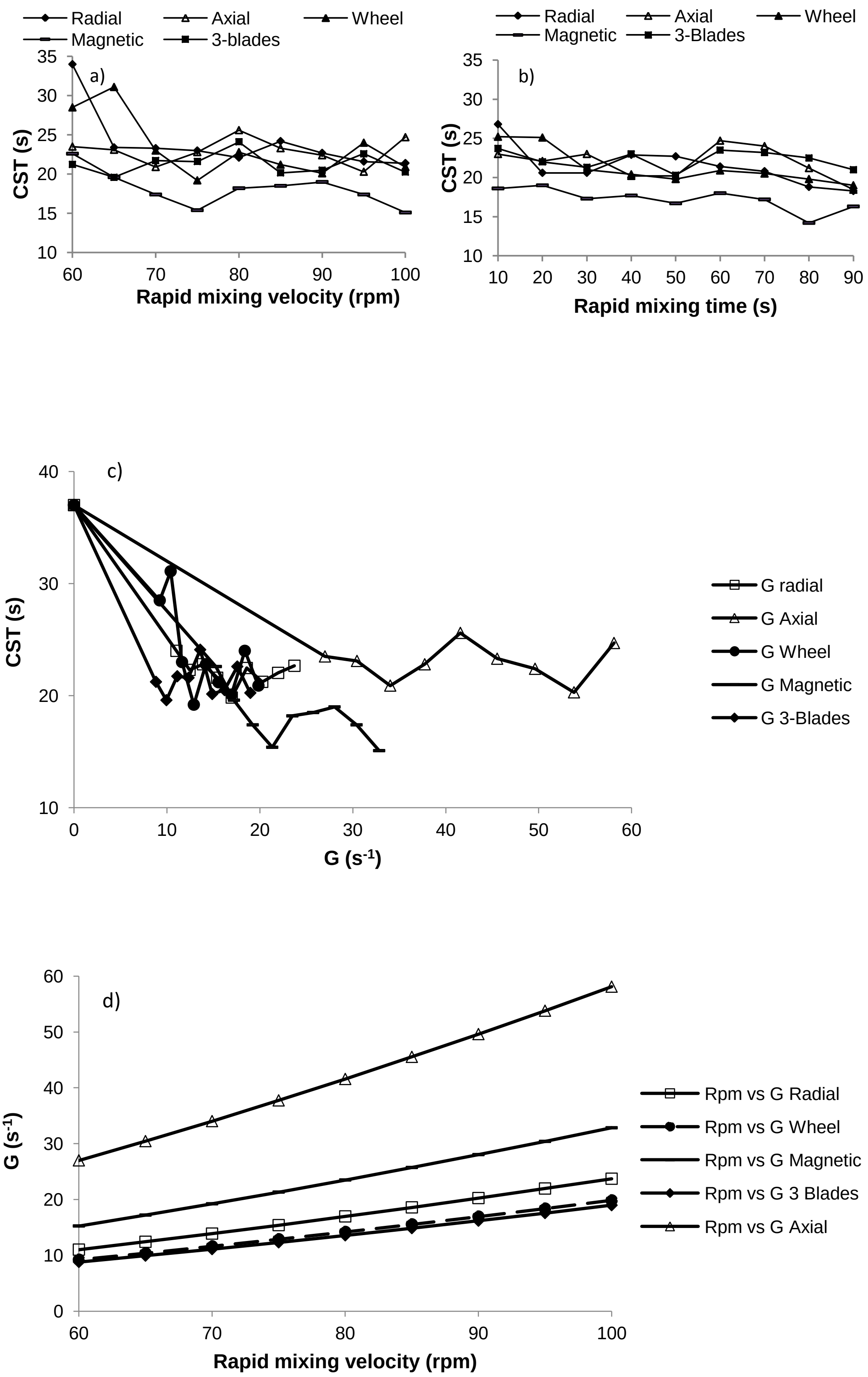
4.2 Synthetic Raw Water

4.2.1 The Influence of Mixer Shape, Rapid Mixing Velocity and Time on CST value

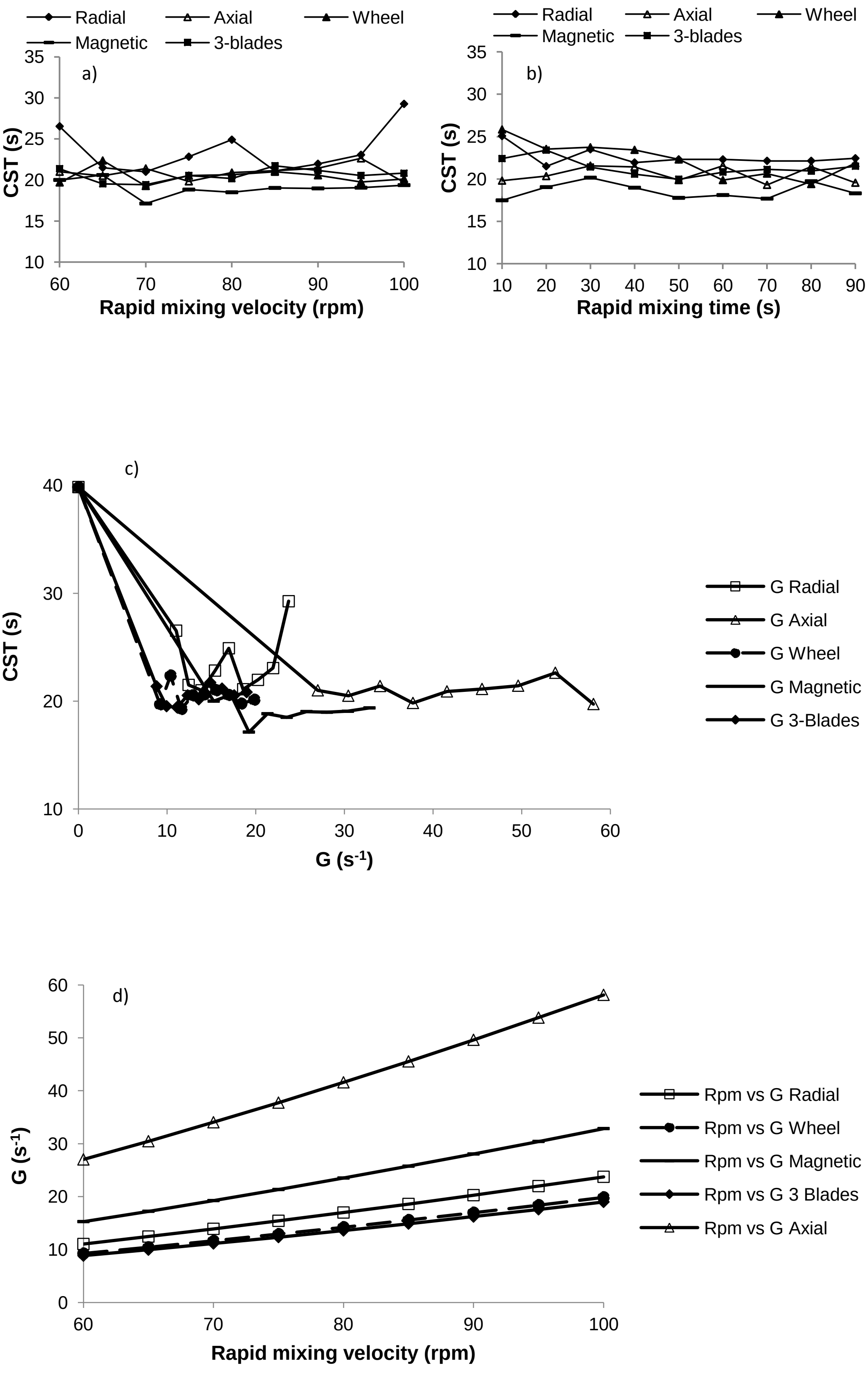
Water and wastewater treatment plants use different shapes and types of mixer in their treatment processes (Tchobanoglous, 2003). In order to investigate the influence of these differences on sludge dewaterability, a series of investigations was undertaken in the laboratory using many different parameters. Five shapes of mixer were used, namely: radial, axial, wheel, 3-blade and magnetic stirrers.

Figure 12 reports the sludge dewaterability results as a function of different shapes of mixer, different rapid mixing velocities, different rapid mixing times, and different coagulants. Figure 12(1) shows the effect of different mixer shapes, used simultaneously with different rapid mixing velocity and different rapid mixing times, on sludge dewaterability, using alum as a coagulant. Figure 12(2) shows the results where ferric is used as the coagulant, Figure 12(3) the results using *Moringa oleifera* as the coagulant.

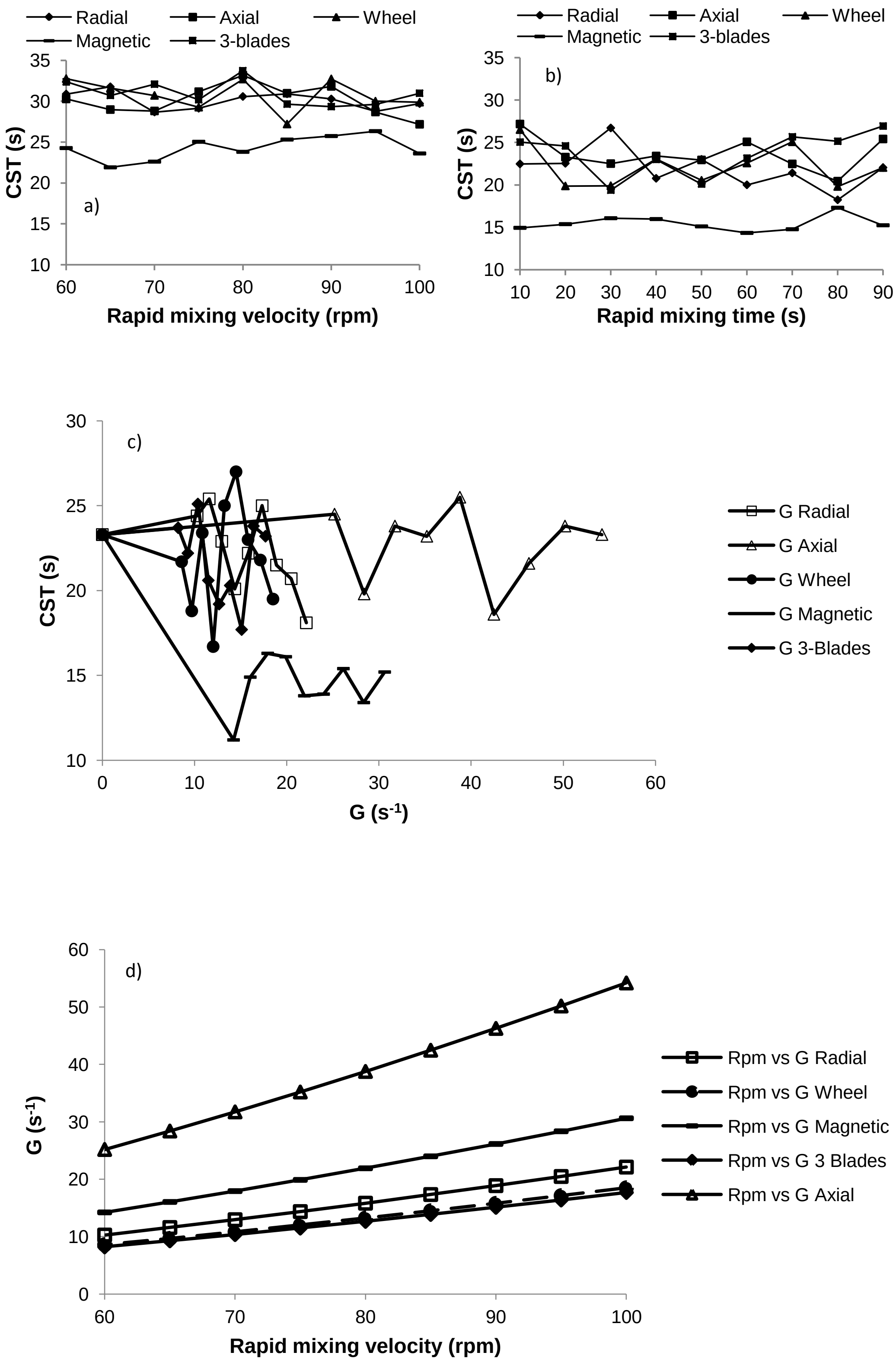
Figure 12a) shows the relationship between rapid mixing velocity (rpm) and CST value (s), Figure 12b) shows the effect of rapid mixing time (s) on the CST value (s), Figure 12c) shows the relationship between G (s^{-1}) and CST value (s) and Figure 12d) shows the relationship between rapid mixing velocity (rpm) and G (s^{-1}). Actually, Figure 12a) has informed about the effect of rapid mixing velocity on sludge dewaterability, but this research used mixers to produce the mixing in to the water so G value information is needed. Figure 12c) and Figure 12d) illustrates more the effects of mixing conditions/turbulence (G) on the CST value, and therefore on sludge dewaterability.



(1). Alum as a coagulant



(2). Ferric as a coagulant



(3). *Moringa oleifera* as a coagulant

Figure 12. The effect of mixer shape on the CST value

4.2.1.1 The Effect of Mixer Shape on CST value

Each of CST value in Figure 12 is an average of 3 replicates CST values. Table 4 informs about descriptive statistic for CST value in responding different mixer shapes.

Table 4. Descriptive statistic of CST value in responding different mixer shapes.

Mixer	Parameter	Al	Fe	*Moringa*
Radial	mean	21.77	23.08	25.99
	min	18.28	21.00	18.23
	max	26.80	29.26	31.76
	std	1.94	2.13	4.56
Axial	mean	22.41	20.75	26.87
	min	18.44	19.30	20.43
	max	25.60	22.63	33.17
	std	1.88	0.92	3.82
Wheel	mean	22.36	21.37	26.45
	min	19.00	19.27	19.80
	max	31.10	25.83	32.76
	std	3.32	1.82	4.91
Magnetic	mean	17.68	18.82	19.87
	min	14.20	17.13	14.33
	max	22.60	20.60	26.33
	std	1.89	0.96	4.69
3-Blades	mean	21.79	20.97	27.31
	min	19.60	19.43	19.37
	max	24.10	23.40	33.73
	std	1.36	0.97	4.26

The results in Figure 12 indicate that a magnetic stirrer produces the lowest CST, although process variables have been changed. The other mixer shapes have similar results regarding CST value. A magnetic stirrer also produces the highest CST value removal of all the mixers (Table C5-Appendix 2).

These results indicate that mixer shapes influence CST value. This result agrees with the findings of Spicer et al.’s (1996) investigation; they also found that the mixer shape affects the coagulation efficiency. Park et al. (2003) stated that the mixer shape controls the mixing conditions in the coagulation process. In order to observe mixing conditions under the influence of mixer shape, G values were calculated. G is a measure of the average velocity in the fluid, higher G values will be observed near the blades and lower at some distance from the blades (Tchobanoglous, 2003). In relation with mixing effectiveness or turbulence, G value describes the average value of mixing or turbulence produced by mixer in the coagulation chamber.

Gradient velocity observation shows that the magnetic stirrer’s G is not the highest among the five shapes of mixer. The axial mixer produces the highest G, followed by magnetic, radial, wheel and 3-blades. Radial, wheel and 3-blades have almost similar G values. The figure also shows that the relation between rapid mixing velocity in rpm is always linear with G values.

The axial impeller transfers the highest gradient velocity to the water but does not produce the lowest CST value. This indicates that G value of axial impeller is too high relating to CST value. The magnetic stirrer produces a more suitable velocity gradient to produce a lower CST value. The remaining three others (radial, wheel and 3-blades) impellers produce insufficient gradient velocity to influence the CST value.

The relation between CST value and G shows that G should be at its optimum value to produce the lowest CST value. It seems that only the magnetic stirrer meets this criterion where its G value produces the lowest CST value. This due to mixing conditions affect the floc formation and floc size (Kan et al., 2002b), and excess mixing will increase floc breakage (Spicer et al., 1996). The size of a floc is an important factor for the assessment of sludge dewaterability (Lee & Liu, 2001; Zhao, 2003; Feng et al., 2009); the bigger the floc size, the lower the overall floc water content and the easier the dewatering process (Larue & Vorobiev, 2003).

Floc size depends on hydrodynamics because it changes when the mixing is modified (Coufort et al., 2005). Higher gradient velocity produces higher shear rates. Increased shear produces smaller floc size (Spicer et al., 1996; Zheng Yu, 2011) and increases the CST value. Further discussion of CST and its correlation to floc size will be presented in Chapter 5.

Beside the G value, the mixer position in the coagulation chamber might also influence the distribution of mixing. The magnetic stirrer works at the bottom of the coagulation chamber or glass. It introduces mixing at the bottom of the beaker glass and circulates the mixing from this point around the whole glass. Due to its shape and position in the coagulation chamber, the mixing is distributed to all part of the chamber appropriately. It seems that the mixing conditions produced by the magnetic stirrer can avoid the creation of dead zones in the outer part of the mixer because the stirrer moves freely and mixing is spread effectively so that all sections of the water are exposed to the turbulence flow.

In contrast, the four other mixers operated from a position higher up the chamber. The mixing is produced at a distance from the bottom of the glass and concentrated around the shaft position. The mixer's position and movement in the chamber produces mixing that, in general, only exists around the mixer's position and is not well distributed to all parts of chamber. Due to this condition, dead zone areas are to be found at the bottom and on the surface of the chamber. Park et al (2003) found that the formation of dead zones reduce the performance of rapid mixing and the efficiency of the coagulation process. This result indicates that the absence of dead zones when using the magnetic stirrer avoids the possibility of non-contacted of contaminant by the coagulant so that produce more efficient floc formation and lower CST value. Due to the lack of evidence to support this mixer position statement, further investigation might be needed to provide a proper explanation.

4.2.1.2 The Effect of Different Rapid Mixing Velocities and Different Rapid Mixing Times on CST values

Before further discussion about the effect of rapid mixing velocity and rapid mixing time on CST value, Table 5 will show the descriptive statistic of CST value. This descriptive is classified in to rapid mixing velocity and rapid mixing time.

Figure 12 shows, in general that the different rapid mixing velocities and times do not influence sludge dewaterability, even though the optimum conditions based on the preliminary research results have been used. Based on Figure 12(1)a, 12(2)a, and12(3)a, employing rapid mixing velocity and rapid mixing time has no significant impact on the CST values. The values are still almost identical in response to the gradual increase of rapid mixing velocities and times; even using *Moringa oleifera* as a coagulant, the use of rapid mixing velocity increases the CST value.

Table 5. Descriptive statistic of CST value in responding rapid mixing velocity

Parameter	Radial	Axial	Wheel	Magnetic	3-blades	Coagulant
mean	22.10	22.96	23.42	18.13	21.31	Al
min	19.83	20.30	19.20	15.10	19.60	
max	24.00	25.60	31.10	22.60	24.10	
std	1.16	1.66	3.97	2.26	1.40	
mean	23.57	20.95	20.44	19.05	20.59	Fe
min	21.00	19.73	19.27	17.13	19.43	
max	29.26	22.63	22.37	20.60	21.73	
std	2.81	0.88	0.91	0.97	0.79	
mean	30.07	30.11	30.76	24.28	30.95	*Moringa*
min	28.67	27.17	27.20	21.90	29.33	
max	31.76	33.17	32.76	26.33	33.73	
std	1.07	1.86	1.89	1.46	1.49	

Table 6. Descriptive statistic for CST value in responding rapid mixing time

Parameter	Radial	Axial	Wheel	Magnetic	3-blades	Coagulant
mean	21.43	21.87	21.30	17.22	22.28	Al
min	18.28	18.44	19.00	14.20	20.30	
max	26.80	24.70	25.20	19.00	23.70	
std	2.53	2.03	2.27	1.42	1.20	
mean	22.59	20.54	22.29	18.58	21.34	Fe
min	21.50	19.30	19.40	17.48	19.97	
max	25.07	21.57	25.83	20.15	23.40	
std	1.07	0.96	2.08	0.95	1.02	
mean	21.90	23.63	22.15	15.45	23.66	*Moringa*
min	18.23	20.43	19.80	14.33	19.37	
max	26.70	27.17	26.50	17.30	26.93	
std	2.33	1.98	2.42	0.88	2.54	

Statistical analysis, specifically the coefficient of correlation, was used to explain the correlation between different rapid mixing velocities and sludge dewaterability. The calculation was in two parts (Table 7 and Table 8). The first used an initial CST value with 0 rpm rapid mixing velocity or 0 minute rapid mixing time, and the second was without the initial value. The purpose of including the initial value was to see the effect of rapid mixing velocity and time employment on the CST value; not including the initial value investigated the effect of increasing rapid mixing velocity and time on the CST value.

Table 7. The impact of rapid mixing velocity on CST value.

Velocity (rpm)	CST Value (s)					Coagulant
	Radial	Axial	Wheel	Magnetic	3-blades	
r (with 0 rpm)	-0.90	-0.84	-0.86	-0.93	-0.86	Alum
r (without 0 rpm)	-0.33	0.00	-0.64	-0.61	0.04	
r (with 0 rpm)	-0.74	-0.87	-0.89	-0.89	-0.87	Ferric
r (without 0 rpm)	0.26	0.14	-0.15	-0.15	0.32	
r (with 0 rpm)	0.05	0.05	0.07	-0.51	0.12	*Moringa*
r (without 0 rpm)	-0.37	-0.18	-0.35	0.53	-0.45	

Table 8. The impact of rapid mixing time on CST value

Time (s)	CST Value (s)					Coagulant
	Radial	Axial	Wheel	Magnetic	3-blades	
r (with 0 rpm)	-0.74	-0.59	-0.76	-0.64	-0.55	Alum
r (without 0 rpm)	-0.73	-0.32	-0.83	-0.75	-0.19	
r (with 0 rpm)	-0.58	-0.53	-0.73	-0.52	-0.58	Ferric
r (without 0 rpm)	-0.47	-0.09	-0.83	-0.02	-0.51	
r (with 0 rpm)	-0.67	-0.56	-0.46	-0.49	-0.04	*Moringa*
r (without 0 rpm)	-0.51	-0.32	-0.16	0.14	0.39	

By including the initial CST value and using alum and ferric, the rapid mixing velocity has a beneficial impact on the CST value. Increasing rapid mixing velocity results in decreasing the CST value. Using *Moringa oleifera*, the correlation between rapid mixing velocity and CST value is poor. Different coefficients of correlation occur if the initial CST value is excluded: they become very low for alum and ferric and slightly higher for *Moringa oleifera*. These data show that the implementation of rapid mixing is very important in decreasing the CST value, but its gradual increase does not have any essential impact when using metal-based coagulants. It seems that as long as the rapid mixing velocity has been applied, the CST value will decrease.

For rapid mixing times, Figure 12(1)b, 12(2)b and 12(3)b show that there is no significant impact on the CST value when different rapid mixing times are applied. The coefficient of correlation values by including 0 rpm into the calculation (Table 8), rapid mixing time has a reasonable association with the CST value. Without an initial value, all the coefficient of correlation values decrease, even though this decrease is not as much as occurred with the rapid mixing velocity coefficient of correlation. Just like the rapid mixing velocity, rapid mixing time is important in decreasing the CST value, but the gradual increase is not important. This means that a low rapid mixing time is sufficient to decrease the CST value.

The trends for rapid mixing velocity and rapid mixing time are slightly different. The former has a fluctuating trend, while the latter is more stable, especially when using alum and ferric. The fluctuating trend in rapid mixing velocity may be due to the difference in the coagulant hydrolysis product which is influenced by the mixing conditions (AWWA, 1999). Every type of hydrolysis product has its own interacting mechanism for removing particles. This result is similar to the investigation results achieved by AWWA (1999) and Byun et al. (2005); both found that different rapid mixing intensities affect the formation of coagulation hydrolysis products and ultimately produce different types of coagulant hydrolysis products. The velocity gradient also determines the number of floc collisions (Mhaisalkar et al., 1991) which is an important influence on the settling performance and sludge dewaterability.

For rapid mixing times, the straight and stable line in Figure 12(1)c, 12(2)c and 12(3)c and the poor correlation show that the enhancement of rapid mixing times does not have any impact on CST value and low rapid mixing time is enough. As explained in Chapter 2, coagulant hydrolysis products are formed shortly after coagulant dosing. Prolonged rapid mixing time can limit floc growth, possibly due to the formation of small flocs during the rapid mixing process. Schuetz and Piesche (2002) have confirmed that sufficient coagulation conditions is needed to enable a floc formation that is easily separated and dehydrated. The excessive mixing time may result in breakage of microflocs and reduce the re-growth potential of the floc (Yu et al., 2011).

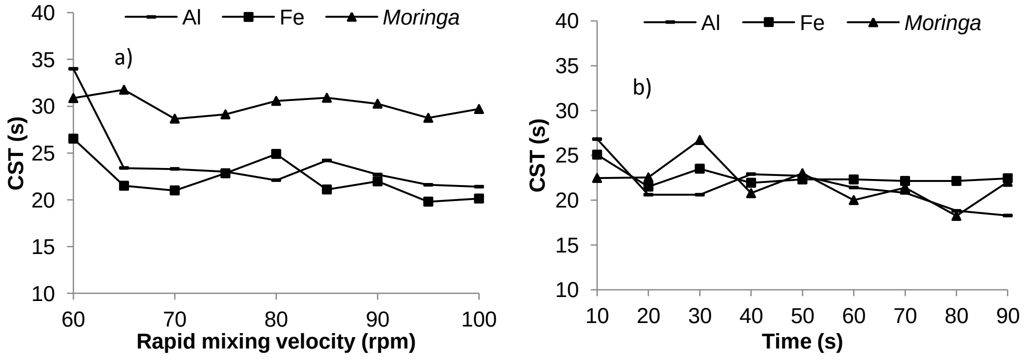
When comparing the effect of different rapid mixing velocity and different rapid mixing times on CST values, the results show that rapid mixing velocity has more impact on the CST values than rapid mixing time. This finding is supported by Mhaisalkar et al. (1991) and Liang et al. (2009).

4.2.2 The Effect of Coagulant on CST value

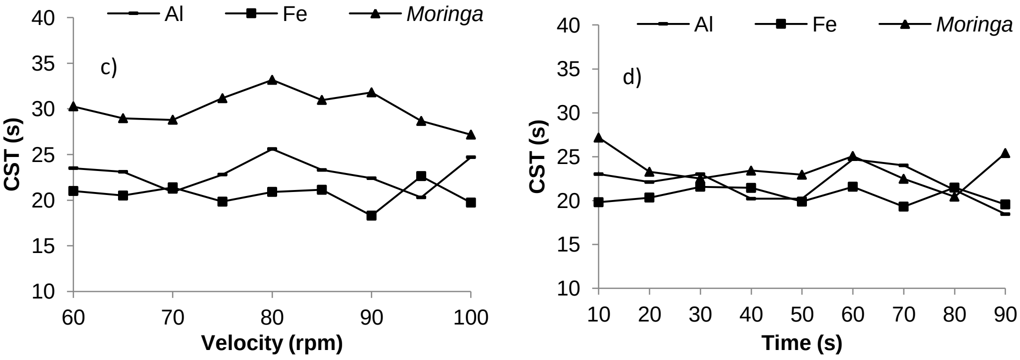
Aluminium sulphate, ferric sulphate and *Moringa oleifera* were used in this research to investigate their effect on the CST value. Table 9 informs about the statistic descriptive of CST value in responding different coagulants. Figure 13 presents the influence of coagulants on the CST value using rapid mixing velocity and rapid mixing time.

Table 9. Statistic descriptive of CST value in responding different coagulants

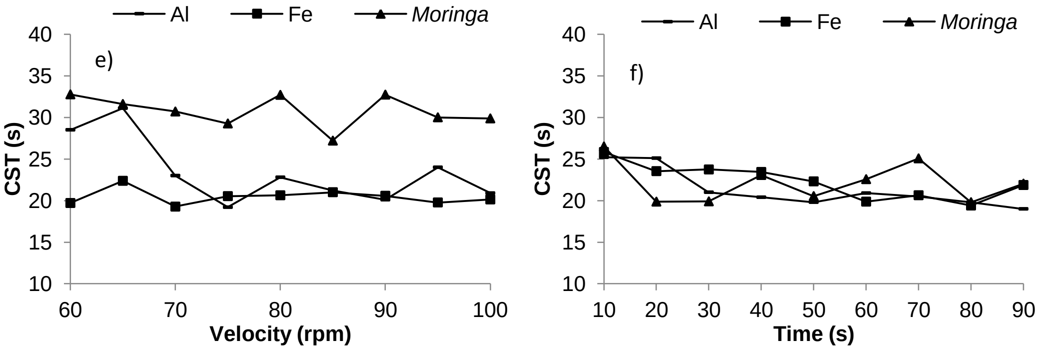
Coagulant	Parameter	Radial	Axial	Wheel	Magnetic	3-blades
Al	mean	21.77	22.41	22.36	17.68	21.79
	min	18.28	18.44	19.00	14.20	19.60
	max	26.80	25.60	31.10	22.60	24.10
	std	1.94	1.88	3.32	1.89	1.36
Fe	mean	21.77	22.41	22.36	17.68	21.79
	min	18.28	18.44	19.00	14.20	19.60
	max	26.80	25.60	31.10	22.60	24.10
	std	1.94	1.88	3.32	1.89	1.36
Moringa	mean	25.99	26.87	26.45	19.87	27.31
	min	18.23	20.43	19.80	14.33	19.37
	max	31.76	33.17	32.76	26.33	33.73
	std	4.56	3.82	4.91	4.69	4.26



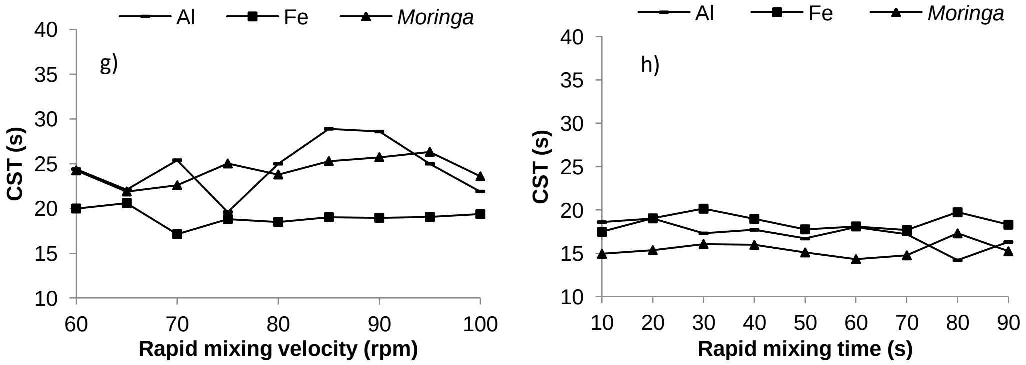
(1). Radial Mixer



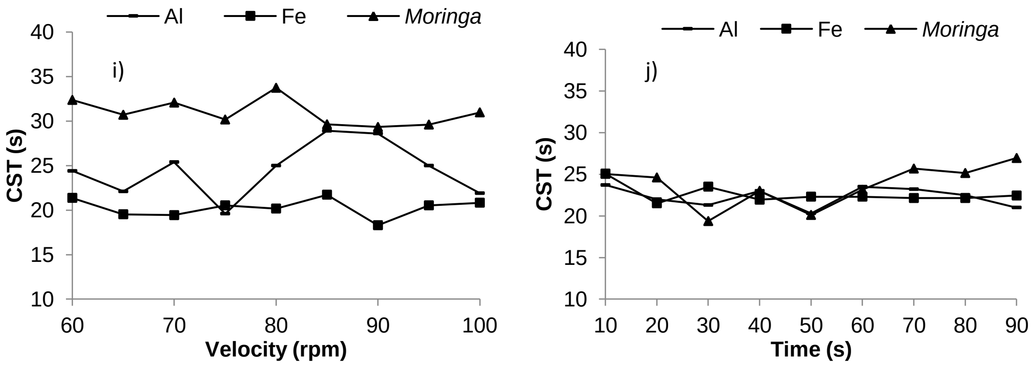
(2). Axial Mixer



(3). Wheel Mixer



(4). Magnetic Stirrer



(5). 3-blades mixer

Figure 13. Comparison of coagulants performances

Figure 13 shows that coagulants are more sensitive to rapid mixing velocity than to rapid mixing time. Using rapid mixing velocity, alum and ferric have an almost similar impact on the CST value, and a lower CST value than *Moringa oleifera*. On the rapid mixing time variable, no conclusion can be drawn. Different coagulant trends on rapid mixing velocity and rapid mixing time also indicate that rapid mixing velocity plays a more important role in accommodating coagulant mechanism in water than does rapid mixing time.

Using mixer shapes and rapid mixing velocity provides evidence that different coagulants produce different CST values, which means that the coagulant characteristics affect sludge dewaterability. The difference in performance of different coagulants is influenced by their base material. Alum and ferric are metal-based coagulants, which produce coagulant hydrolysis products (AWWA, 1999). On the other hand, *Moringa oleifera* does not yield coagulant hydrolysis products. The agglomeration happens as a result of adsorption and charge neutralization processes of the contaminant by *Moringa oleifera*’s active protein (Ndabingengesere et al., 1995; Bhatia et al., 2007).

Ndabingengesere et al. (1995) said that every coagulant produces different sludge volume, so it influences the concentration of solid in the water. *Moringa oleifera* produces a smaller volume of sludge compared to a metal-based coagulant because it only stimulates small contaminants to gather together without generating a precipitated coagulant. Metal-based coagulants like alum and ferric are associated with larger volumes of sludge (Ndabingengesere & Narasiah, 1998).

The explanation about coagulant and rapid mixing time seems correlated with the explanation of the effect of rapid mixing time on CST value. This can be found in the previous sub chapter.

4.2.3 The Effect of Temperature on CST value

Temperature is a crucial factor in the sludge dewatering process because it affects sludge viscosity (Sawalha & Scholz, 2012). Christensen et al. (1993) found that viscosity has a linear correlation with sludge dewaterability. In theory, viscosity is reduced at higher temperatures, and water will be released from the sludge more easily. This means sludge dewaterability is reduced as the temperature rises. In the coagulation process, the temperature determines the distribution of the coagulant (Duan & Gregory, 2003). The reaction rate increases with increasing temperature and vice versa.

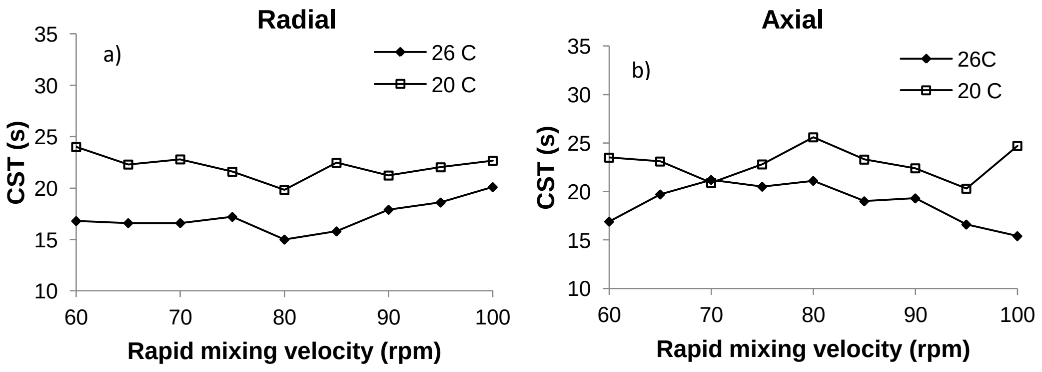
In this research, the effect of mixer shape was studied simultaneously with temperature, coagulant and rapid mixing velocity. Rapid mixing time was not investigated because it has already been demonstrated in this study that its impact on sludge dewaterability is less significant.

4.2.3.1 Using Alum as a Coagulant

Alum was used as a coagulant to investigate the effect of mixer shape on the CST value. In this research, a temperature of 20ºC was compared with a temperature of 26ºC. Five shapes of mixer were used as a paddle (Table 10), and a comparison of the different shapes at 26ºC has been produced (Figure 14).

Table 10. Statistic descriptive of CST value in responding temperature (alum)

Temperature	Parameter	Radial	Axial	Wheel	Magnetic	3-blades
20ºC	mean	22.10	22.96	23.42	18.13	21.31
	min	19.83	20.30	19.20	15.10	19.60
	max	24.00	25.60	31.10	22.60	24.10
	std	1.16	1.66	3.97	2.26	1.40
26ºC	mean	141.98	23.90	15.99	11.88	12.24
	min	0.39	0.55	1.32	0.75	0.47
	max	921.11	89.00	31.10	22.60	24.10
	std	343.71	30.47	11.44	8.73	10.63



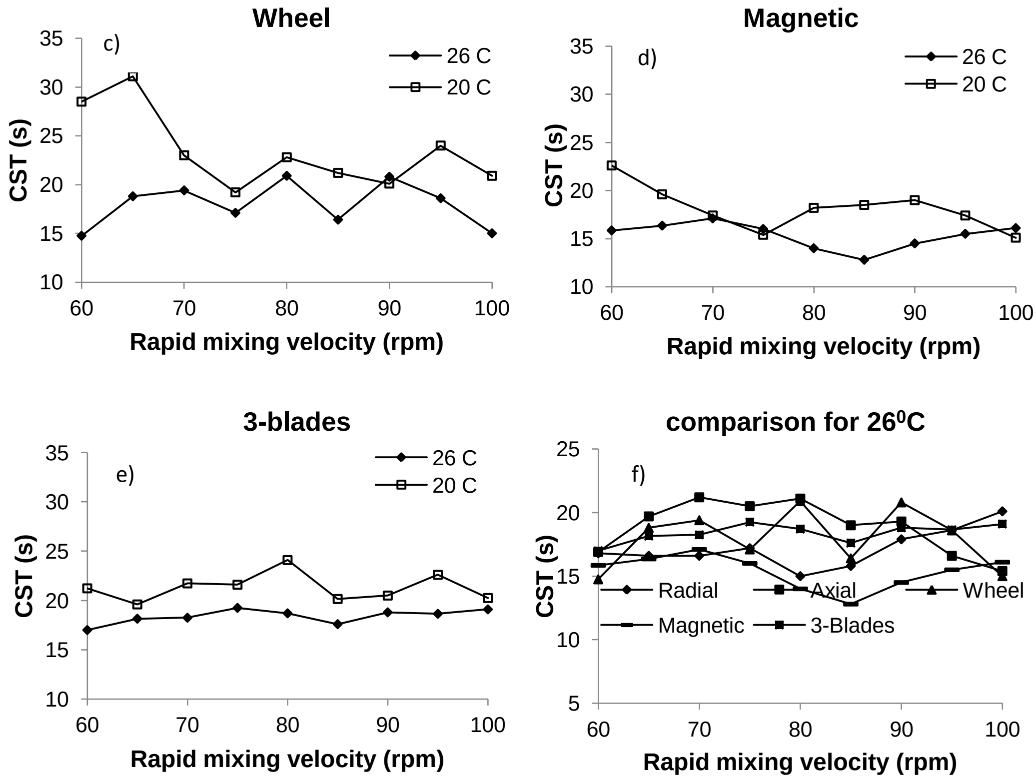


Figure 14. The influence of temperature on CST value (alum)

Of the five mixers, the magnetic stirrer still yields the lowest CST value. This same result is similar at 20℃, again confirming that the magnetic stirrer is superior to the other four shapes of mixer. Using different temperatures shows that 26℃ produces a lower CST value than 20℃ for each of the mixer shapes. This phenomenon is supported by the results of Duan and Gregory (2003), that temperature affects the distribution of coagulant types in the water. A higher temperature makes the coagulant distribution easier than at a lower temperature, and ultimately affects the floc conditions. As the condition of the flocs is an important factor in sludge dewaterability (Lee & Liu, 2001), the impact of temperature is also important on the sludge dewatering process.

In relation to the viscosity, it confirms the theory that the higher the temperature, the lower the viscosity. At 20°C, water has a higher viscosity than at 26°C, so it cannot be released from the sludge as easily as at the higher temperature (Sawalha & Scholz, 2012). As a result, the CST values at 20°C are higher than those at 26°C. As alum was used as the coagulant, it can be concluded that alum's performance is affected by temperature.

4.2.3.2 Ferric as a Coagulant

The second coagulant to be used was ferric. Table 11 and Figure 15 show the influence of temperature on sludge dewaterability using this coagulant.

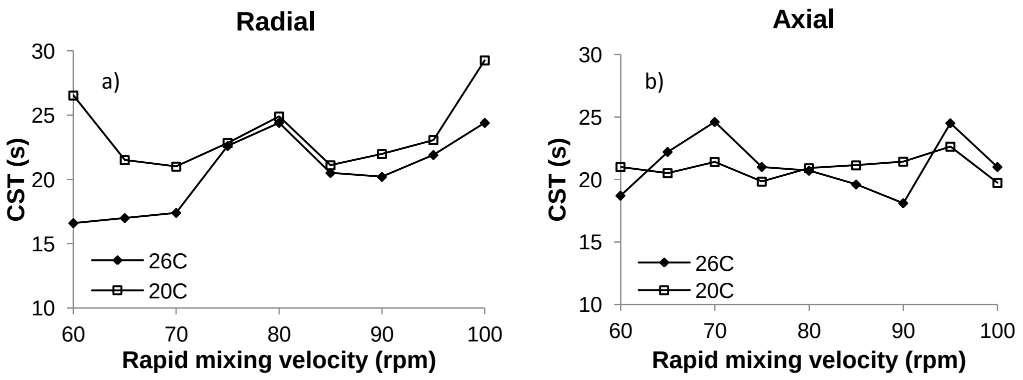
Table 11. Statistic descriptive of CST value in responding temperature (ferric)

Temperature	Parameter	Radial	Axial	Wheel	Magnetic	3-blades
20ºC	mean	23.57	20.95	20.44	19.05	20.59
	min	21.00	19.73	19.27	17.13	19.43
	max	29.26	22.63	22.37	20.60	21.73
	std	2.81	0.88	0.91	0.97	0.79
26ºC	mean	20.56	21.16	19.70	17.99	21.91
	min	16.60	18.10	16.90	14.60	18.90
	max	24.40	24.60	22.30	20.80	28.50
	std	3.04	2.30	1.79	1.89	2.85

Comparison of the five shapes of mixer using ferric as a coagulant at a temperature of 26°C indicates that, in general, the magnetic stirrer produces the lowest CST values. This result is comparable to previous tests using different parameters; that the magnetic stirrer produces better mixing conditions so that the coagulant and water can be properly mixed and thus produce a better agglomeration compared with the four other shapes of mixer.

The results show that temperature does not have a significant impact on sludge dewaterability while using ferric as a coagulant. Although the comparison was done repeatedly using different shapes of mixer, findings still indicate that the performance of ferric is not affected by temperature. In contrast, other investigations have shown that ferric as a coagulant was influenced by temperature (Van der Woude & De Bruyn, 1983; Flynn, 1984; Kang & Cleasby,1995).

The insignificant effect of temperature on ferric performance can be explained by the previous observation. It found that an increase in temperature results in reduced amounts of soluble oxygen, and the formation of iron salts is inhibited by protons (Vilcaez et al., 2009). Moris and Knocke (1984) also found the same for the range of temperatures 1-23℃; the rate of iron (III) growth was not affected significantly. Moreover, Hanson and Cleasby (1990) found that at temperatures of 5-20℃ and constant pOH, almost identical ferric sulphate coagulation kinetics occurred.



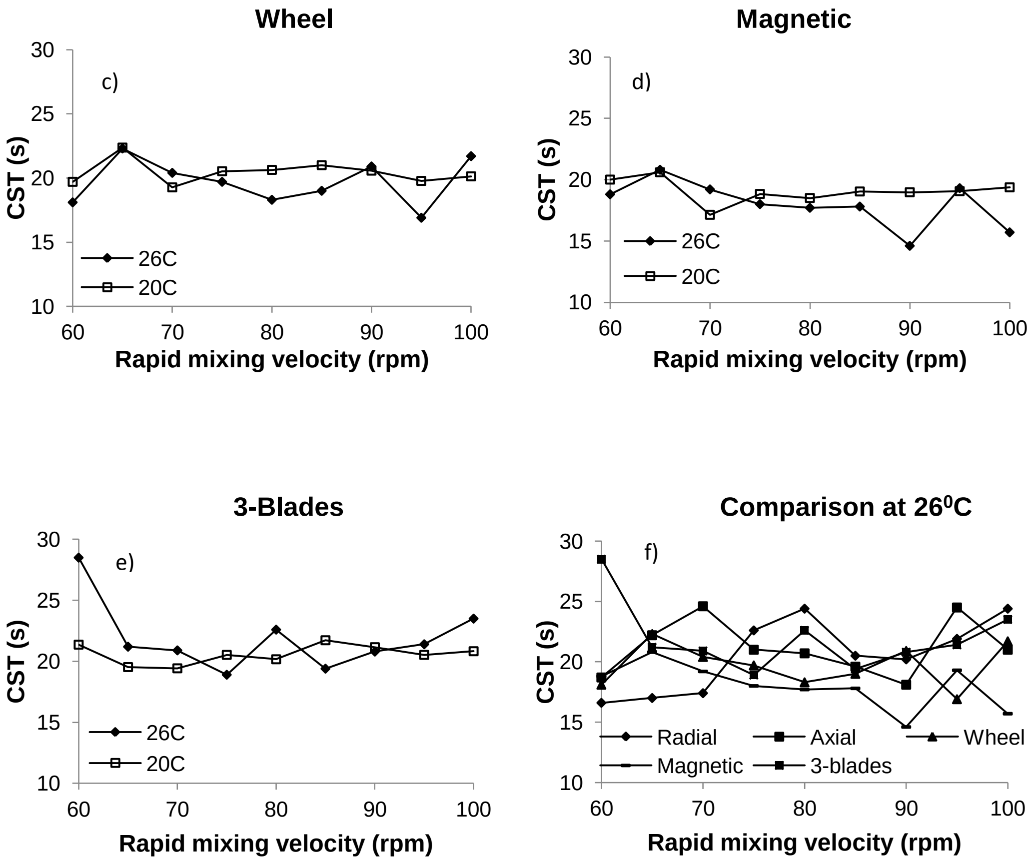


Figure 15. The influence of temperature on CST value (ferric)

4.2.3.3 *Moringa oleifera* as a Coagulant

As an alternative coagulant, *Moringa oleifera* is yet to be fully explored. This section shows the results from an investigation into the effect of mixer shape and temperature on sludge dewaterability. Table 12 and Figure 16 indicate the impact of temperature on the CST value using *Moringa oleifera* as a coagulant.

Table 12. Statistic descriptive of CST value in responding temperature (Moringa)

Temperature	Parameter	Radial	Axial	Wheel	Magnetic	3-blades
20ºC	mean	30.07	30.11	30.76	24.28	30.95
	min	28.67	27.17	27.20	21.90	29.33
	max	31.76	33.17	32.76	26.33	33.73
	std	1.07	1.86	1.89	1.46	1.49
26ºC	mean	22.26	22.68	21.88	14.47	21.76
	min	18.10	18.60	16.70	11.20	17.70
	max	25.40	25.50	27.00	16.30	25.10
	std	2.43	2.25	3.19	1.59	2.45

Using radial, axial, wheel, magnetic and 3-blade types of mixer, the CST values yielded at temperatures between 20℃ and 26℃ were compared. The graphs present the results. The CST value decreases as temperature increases. This is due to the effects of viscosity. For sludge which does not contain cations, especially of potassium and calcium, the viscosity of the sludge increases as the temperature decreases (Sawalha, 2010).

In general, at 20℃, as the rapid mixing velocity increases the CST value increases. However, at 26℃, an increase in rapid mixing intensity causes a reduction in the CST value. This indicates that *Moringa oleifera*'s performance is better at 26℃ than 20℃, which is probably because the higher temperature makes the *Moringa oleifera* protein more active, thus increasing the sludge dewaterability. Further investigation is still needed to support this finding.

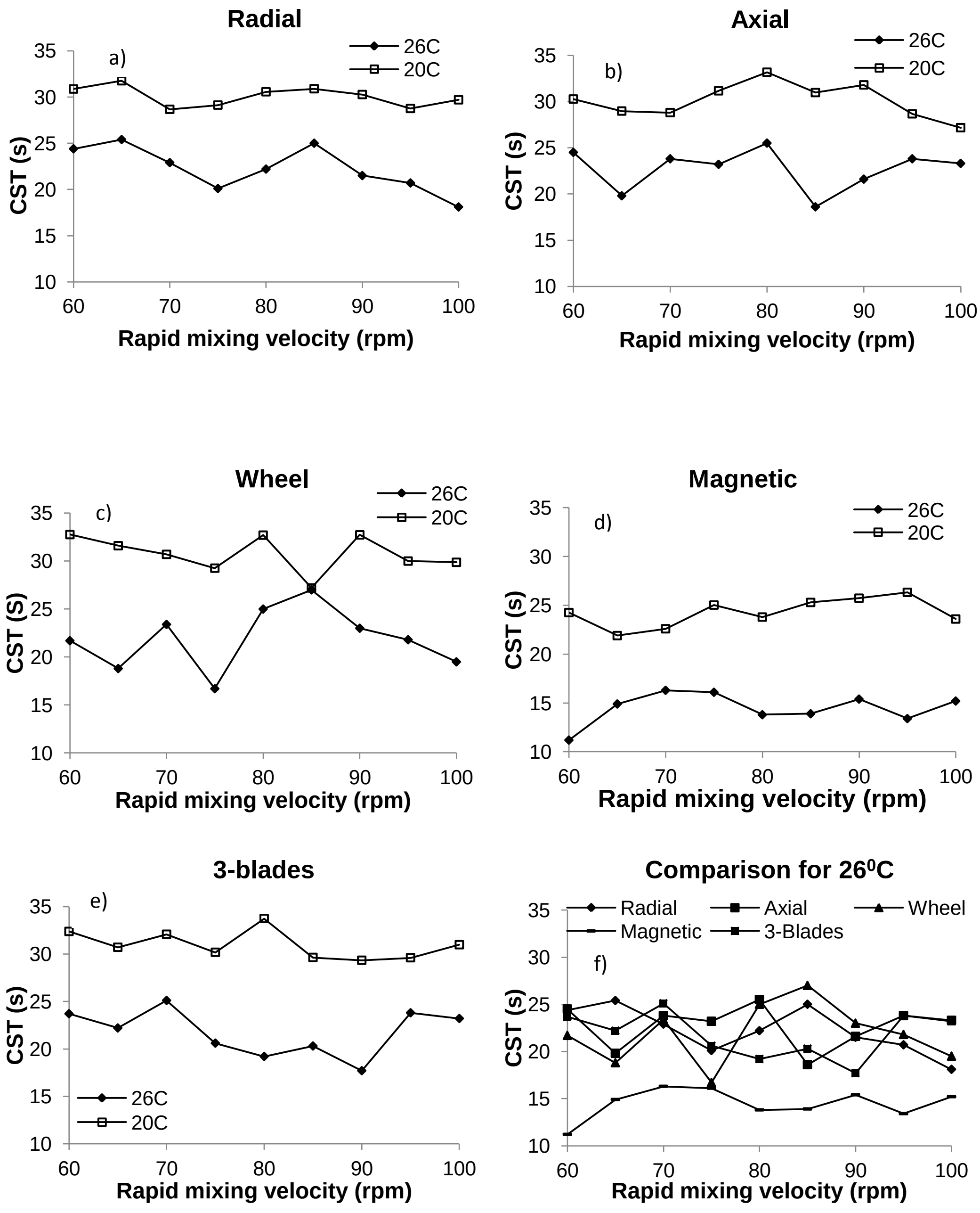
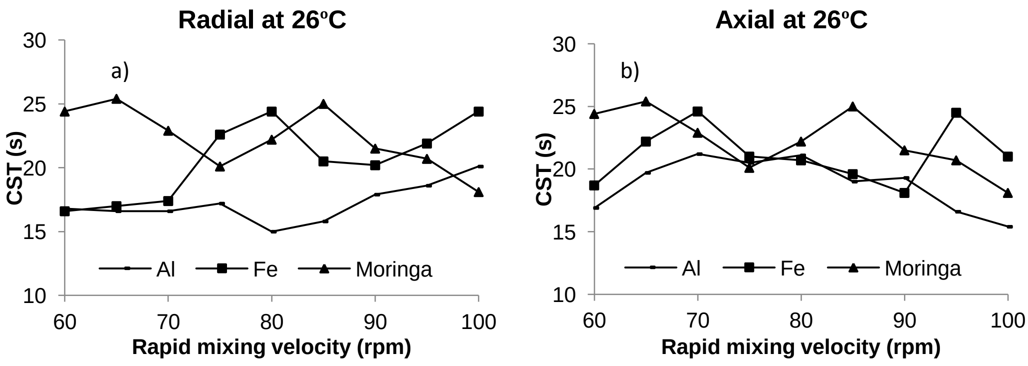


Figure 16. The influence of temperature on CST value (*Moringa oleifera*)

4.2.3.4 The Influence of Different Coagulants at 26°C

The aim of this analysis was to compare the performance of different coagulants with increasing temperature. Figure 17 represents the CST values in respect of different mixers, different velocities and different coagulants at 26°C. It can be seen that different coagulants have no significant influence on CST values; in general, all of the coagulants have a similar impact at 26℃. However, if the data is examined in more detail, alum is seen to give the lowest CST value.

Most of the lowest CST values were produced by alum. Overall, the highest CST values were obtained using *Moringa oleifera* as a coagulant. The coagulant type determines the amount and properties of sludge. A temperature of 26℃ produces different results from a temperature of 20℃. At 20℃, alum and ferric were shown to be the best coagulant with the lowest CST values. This shows that alum and ferric are more effective than *Moringa oleifera* at 20℃ but not at 26℃. At 26ºC, all three coagulants have a similar impact on the CST value. This may be because *Moringa oleifera*'s protein is more active at 26ºC than at 20ºC, so that all the coagulants have a similar impact on sludge dewaterability at the higher temperature.



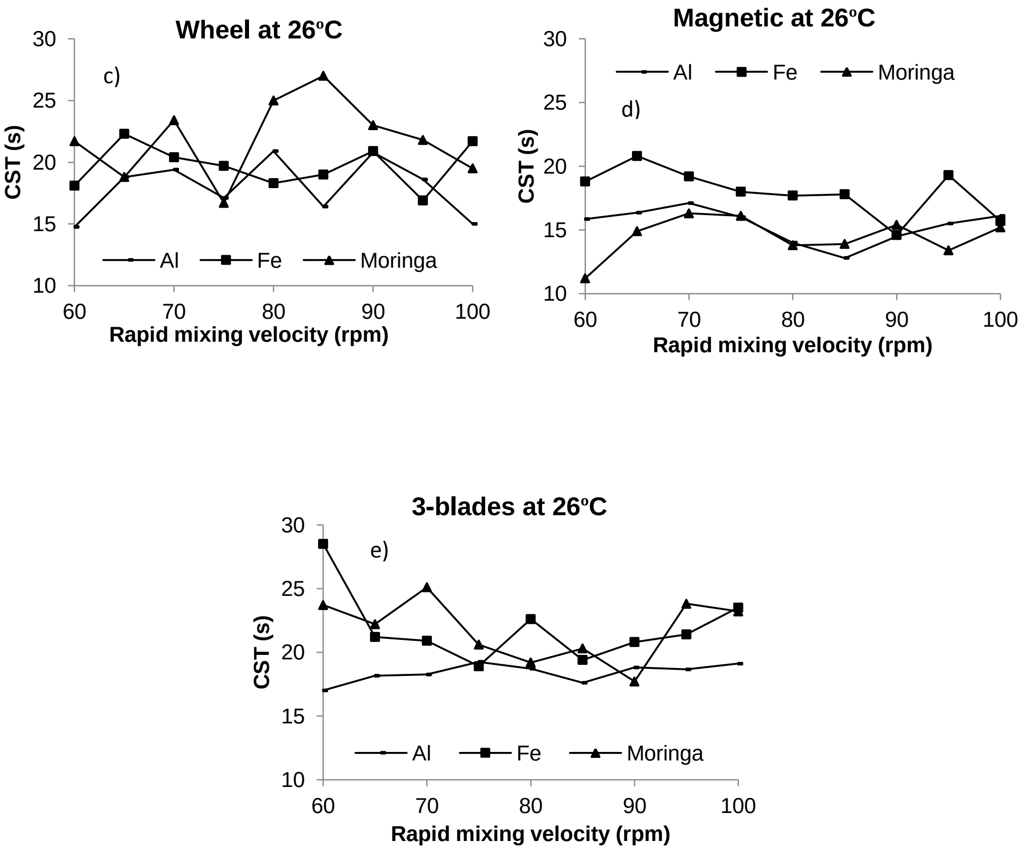


Figure 17. Comparison of different coagulants' performance at 26°C

4.3 Synthetic Domestic Wastewater Sample

4.3.1 Observation Results

The aim of this investigation was to examine the effect of water composition on CST values. It was undertaken simultaneously with the study of the effect of mixer shape, rapid mixing velocity and coagulant on CST value and turbidity. In order to obtain a comparative measurement, a turbidimeter was used for the first time when using synthetic domestic wastewater. Using synthetic raw water, rapid mixing time had less effect on the CST value, so that in this investigation only rapid mixing velocity is used. Table 13, Table 14 and Figure 18 show the results.

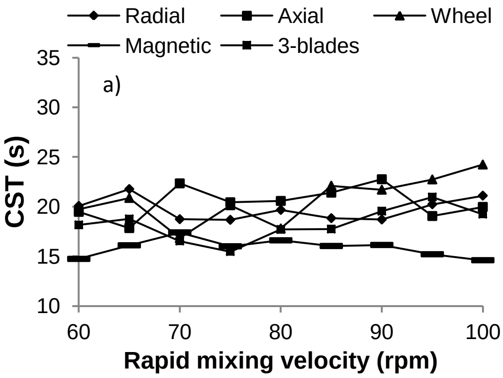
Table 13 and Table 14 inform about the statistic descriptive of CST and turbidity values in responding mixer shapes. Figure 18 (1) shows the result of CST and turbidity using alum as a coagulant, Figure 18 (2) using ferric as a coagulant and Figure 18 (3) using *Moringa* as a coagulant.

Table 13. Statistic descriptive of CST value in responding mixer shapes

Mixer	Parameter	Al	Fe	Moringa
Radial	mean	19.75	20.50	24.21
	min	18.67	18.90	21.70
	max	21.77	22.40	26.80
	std	1.14	1.26	1.70
Axial	mean	20.42	20.76	24.64
	min	17.83	15.20	23.70
	max	22.75	26.70	26.87
	std	1.57	3.51	1.08
Wheel	mean	20.68	22.24	24.31
	min	16.83	19.50	22.77
	max	24.23	26.50	25.53
	std	2.35	2.22	1.08
Magnetic	mean	15.87	17.61	23.14
	min	14.60	16.20	21.30
	max	17.40	19.50	25.23
	std	0.89	0.97	1.23
3-Blades	mean	18.23	22.73	22.15
	min	15.47	20.60	19.80
	max	20.97	25.00	24.20
	std	1.64	1.42	1.38

Table 14. Statistic descriptive of turbidity in responding mixer shapes

Mixer	Parameter	Al	Fe	*Moringa*
Radial	mean	592.85	609.56	367.70
	min	538.67	542.00	328.33
	max	742.67	703.00	412.00
	std	78.79	48.27	25.30
Axial	mean	530.44	596.11	395.37
	min	501.00	467.00	368.67
	max	641.50	686.00	439.33
	std	45.41	86.06	25.29
Wheel	mean	517.96	543.67	417.04
	min	479.33	479.00	375.00
	max	598.00	605.00	446.33
	std	36.75	38.51	24.72
Magnetic	mean	438.33	452.22	379.15
	min	424.33	417.00	332.00
	max	460.00	488.00	411.33
	std	11.80	24.33	26.48
3-Blades	mean	539.74	688.00	424.89
	min	519.67	451.00	392.33
	max	570.00	886.00	481.00
	std	18.66	139.02	34.14


Radial
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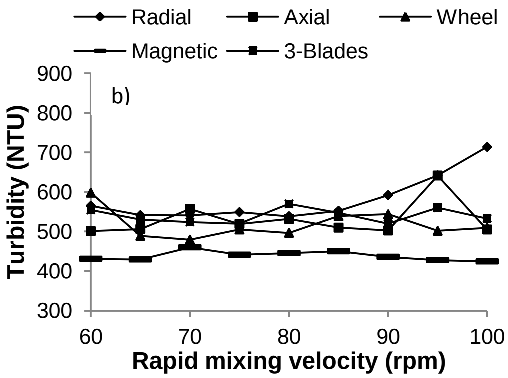
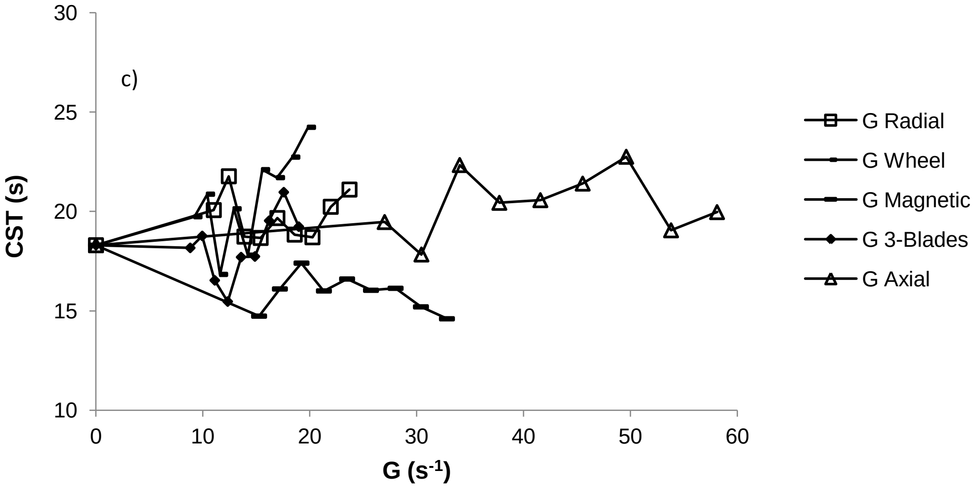
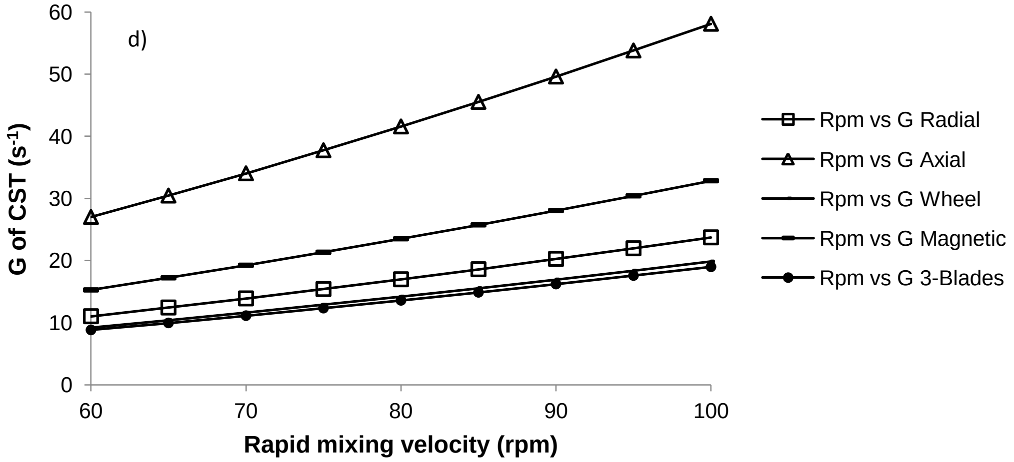
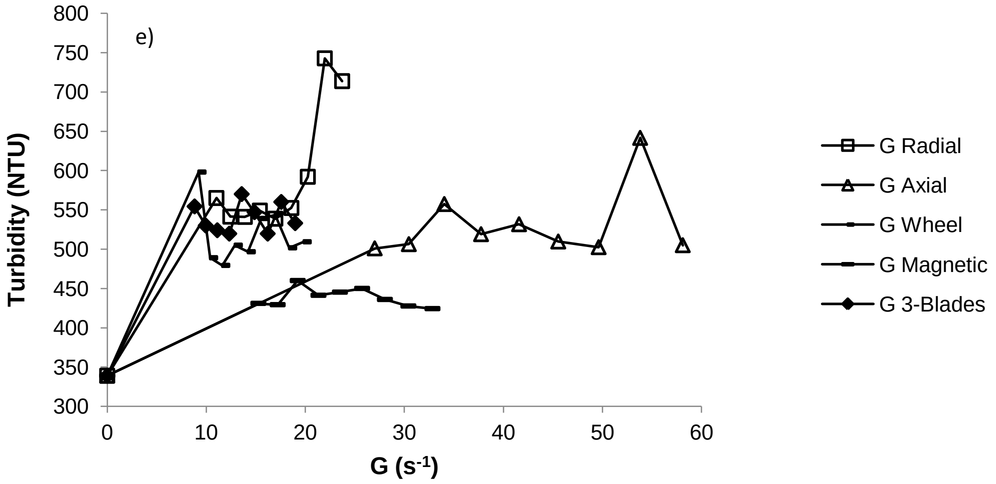
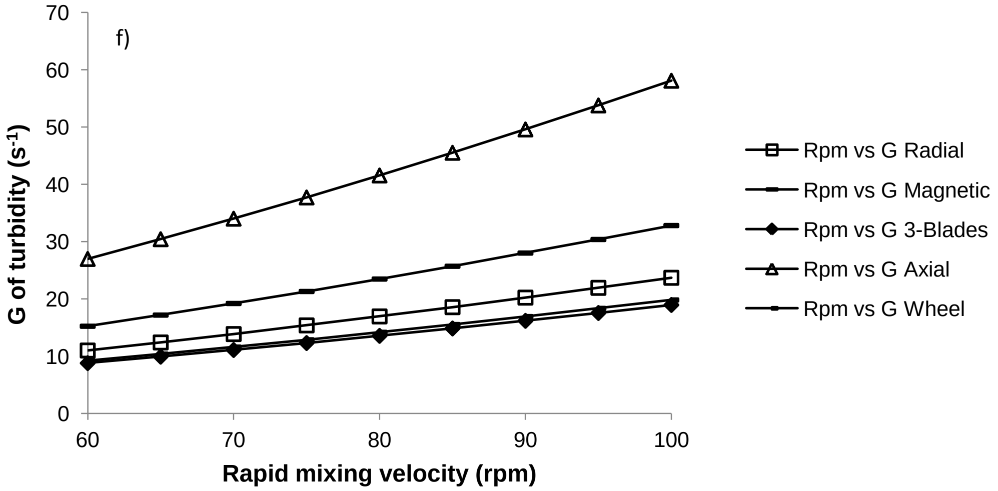
70
80
90
100
Rapid mixing velocity (rpm)


Radial
Axial
Wheel
Magnetic
3-Blades
b)
Turbidity (NTU)
900
800
700
600
500
400
300
60
70
80
90
100
Rapid mixing velocity (rpm)

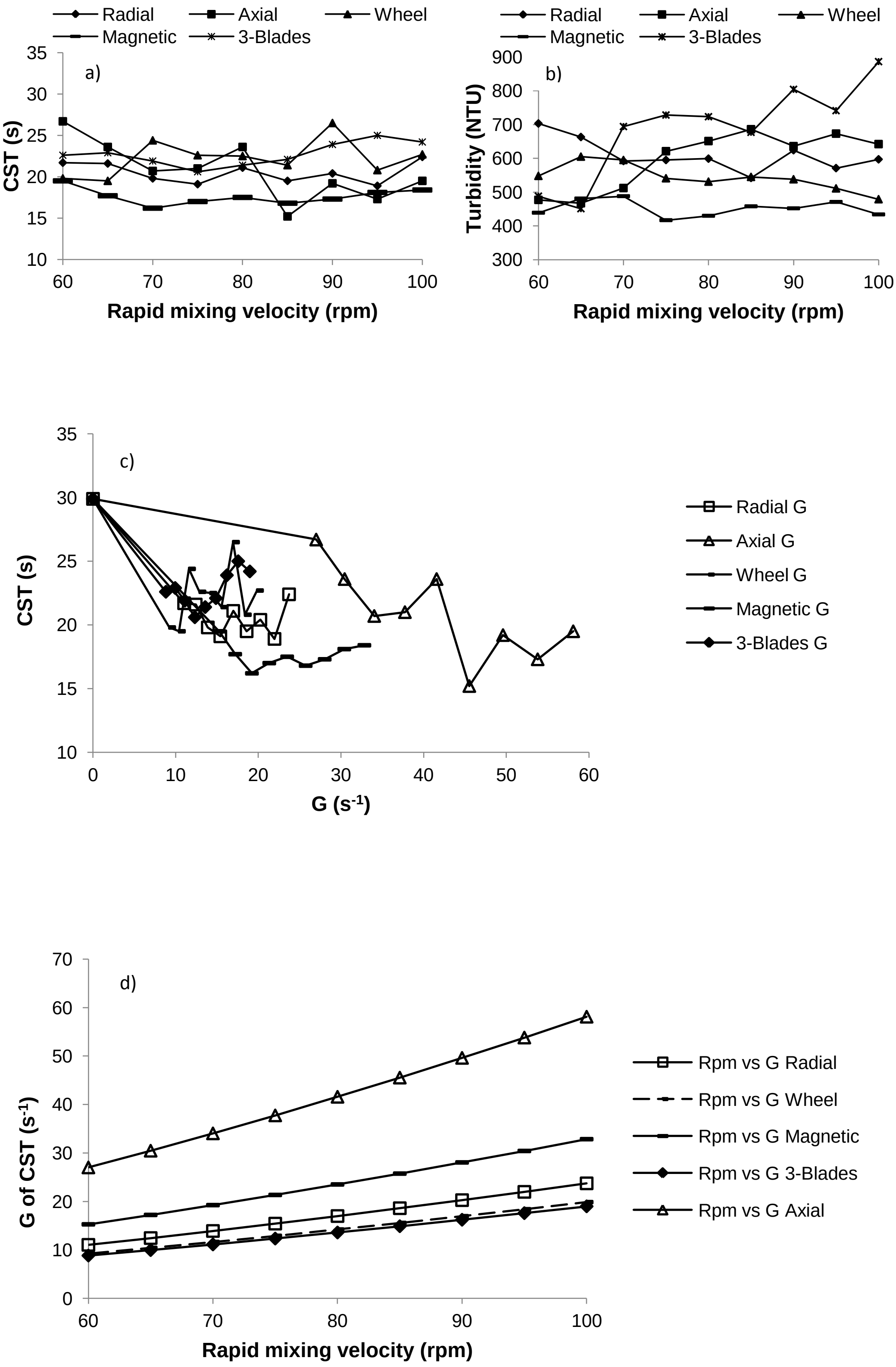

c)
CST (s)
30
25
20
15
10
0
10
20
30
40
50
60
G (s-1)
G Radial
G Wheel
G Magnetic
G 3-Blades
G Axial


d)
G of CST (s-1)
60
50
40
30
20
10
0
60
70
80
90
100
Rapid mixing velocity (rpm)
Rpm vs G Radial
Rpm vs G Axial
Rpm vs G Wheel
Rpm vs G Magnetic
Rpm vs G 3-Blades





(1) Alum as a coagulant


Radial
Axial
Wheel
Magnetic
3-Blades
a)
CST (s)
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Rapid mixing velocity (rpm)
Radial
Axial
Wheel
Magnetic
3-Blades
b)
Turbidity (NTU)
900
800
700
600
500
400
300
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70
80
90
100
Rapid mixing velocity (rpm)
c)
CST (s)
35
30
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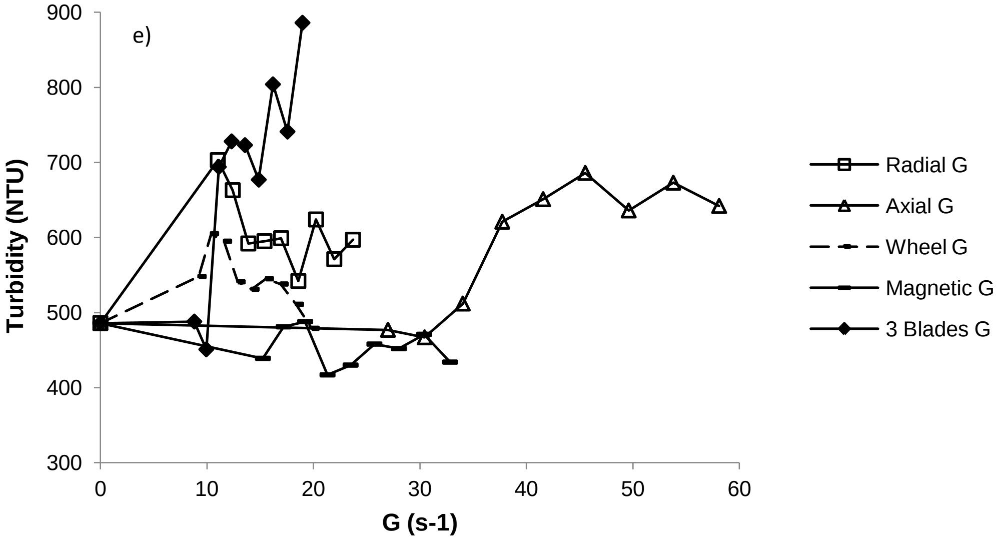
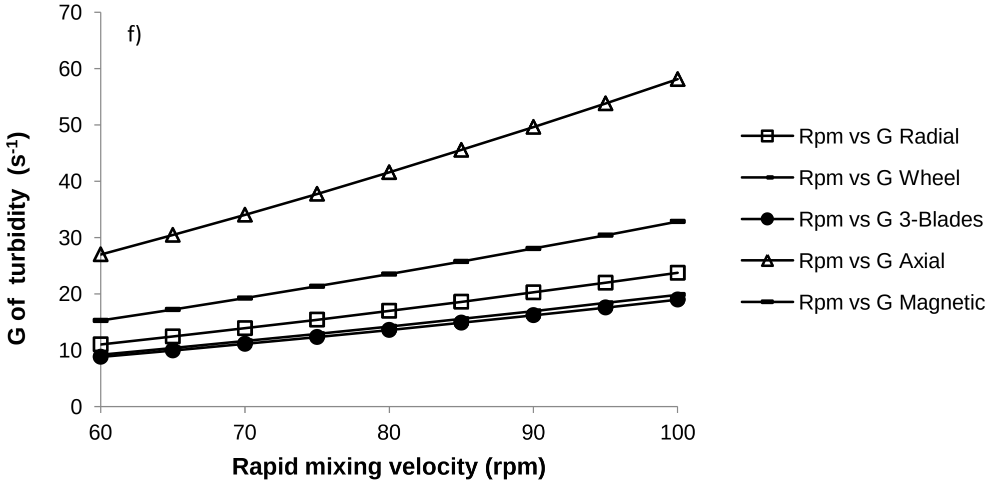
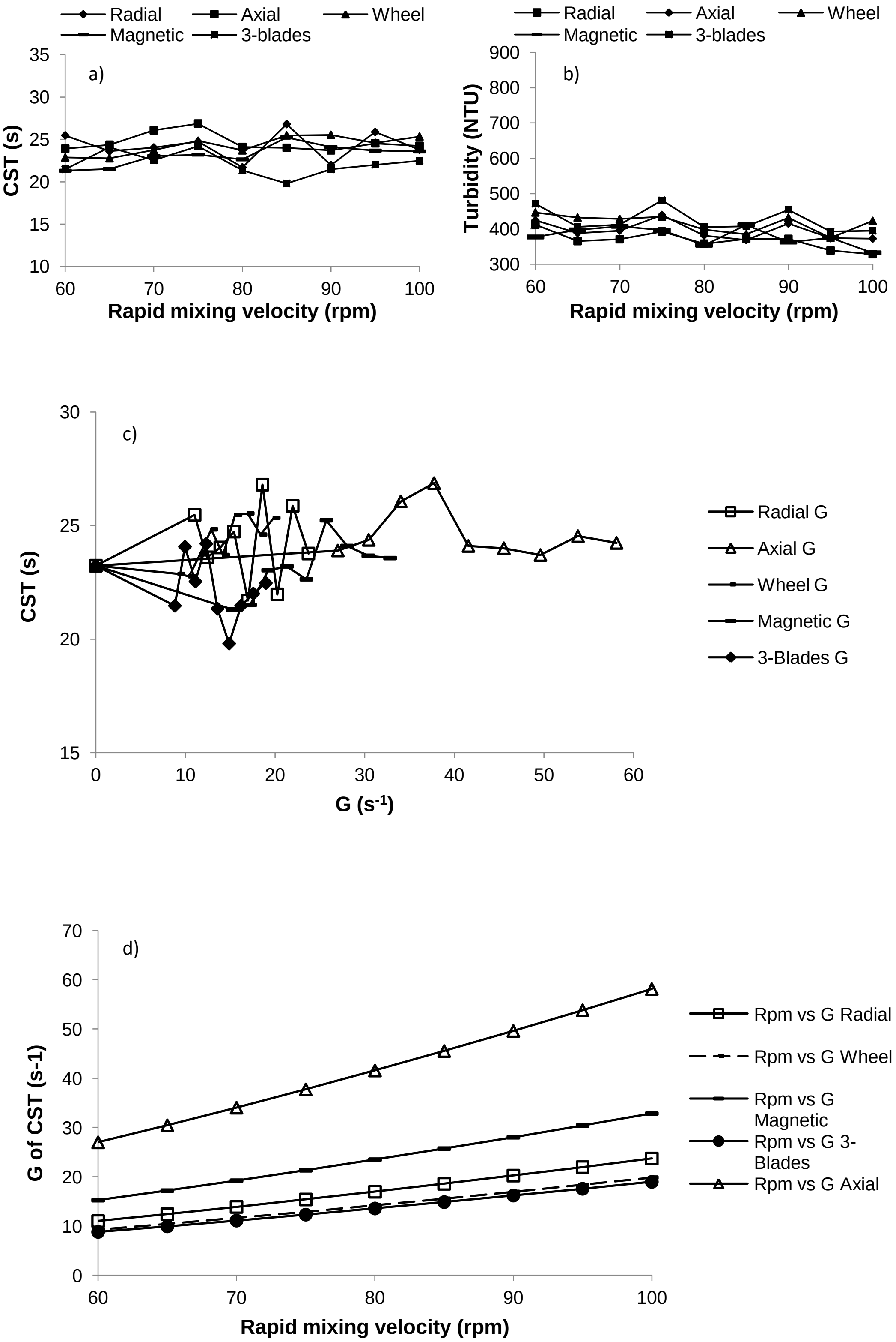
50
60
G (s^{-1})
Radial G
Axial G
Wheel G
Magnetic G
3-Blades G
d)
G of CST (s^{-1})
70
60
50
40
30
20
10
0
60
70
80
90
100
Rapid mixing velocity (rpm)
Rpm vs G Radial
Rpm vs G Wheel
Rpm vs G Magnetic
Rpm vs G 3-Blades
Rpm vs G Axial





(2) Ferric as a coagulant


a)
Radial
Axial
Wheel
Magnetic
3-blades
CST (s)
35
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60
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80
90
100
Rapid mixing velocity (rpm)
b)
Radial
Axial
Wheel
Magnetic
3-blades
Turbidity (NTU)
900
800
700
600
500
400
300
60
70
80
90
100
Rapid mixing velocity (rpm)
c)
CST (s)
30
25
20
15
0
10
20
30
40
50
60
G (s-1)
Radial G
Axial G
Wheel G
Magnetic G
3-Blades G
d)
G of CST (s-1)
70
60
50
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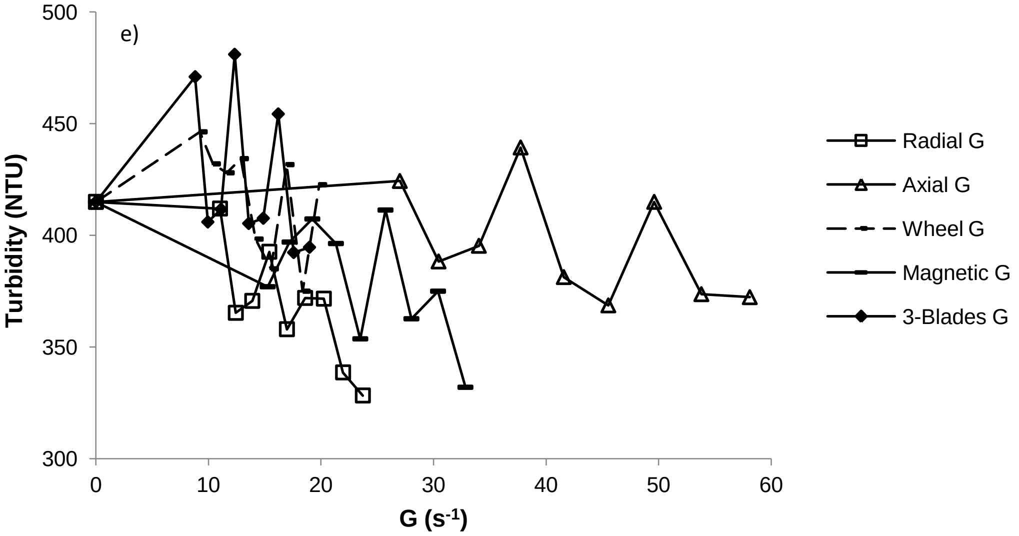
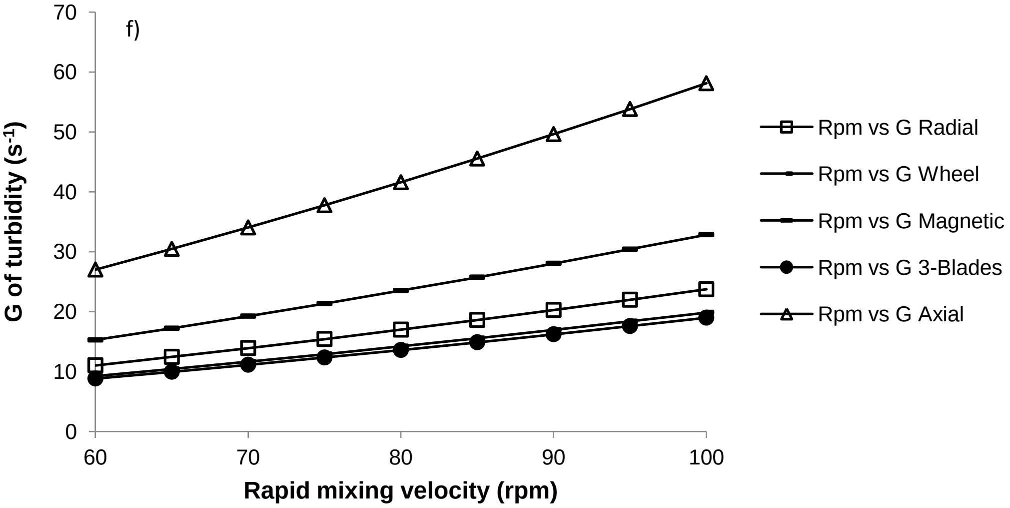
30
20
10
0
60
70
80
90
100
Rapid mixing velocity (rpm)
Rpm vs G Radial
Rpm vs G Wheel
Rpm vs G Magnetic
Rpm vs G 3-Blades
Rpm vs G Axial





(3) *Moringa oleifera* as a coagulant

Figure 18. Results of using domestic wastewater as a water sample

Figure 18a) shows the relationship between rapid mixing velocity (rpm) and CST value (s), Figure 18b) shows the effect of rapid mixing velocity (rpm) and turbidity value (NTU), Figure 18c) shows the relationship between G (s^{-1}) and CST value (NTU) and Figure 18d) shows the relationship between rapid mixing velocity (rpm) and G of CST (s^{-1}). Furthermore, Figure 18e) informs the relationship between G (s^{-1}) and turbidity value (NTU), and Figure 18f) informs the relationship between rapid mixing velocity (rpm) and G of turbidity (s^{-1}).

Investigating the effect of mixer shapes on CST value gave similar results using different coagulants, except for *Moringa oleifera*. The magnetic stirrer produced the lowest CST value compared to other shapes of mixer. The lowest turbidity was also produced by the magnetic stirrer. Hence, although the water sample is different, in general, the magnetic stirrer still produces the lowest CST values. Therefore, it can be concluded that water composition does not influence the effectiveness of the magnetic stirrer as a paddle when using metal-based coagulants.

Despite the same trend of the CST value and turbidity results, the turbidity value after coagulation was still very high, more than 400 NTU, although the optimum coagulant dose was used. Determination of coagulant dose was done using CST apparatus, but this maybe inappropriate for turbidity, as the CST apparatus and turbiditimeter measure different things. So, probably this is the reason why the turbidity is still very high after coagulation process and it indicates that the optimum coagulant dosage by using CST apparatus is not suitable for turbidity removal.

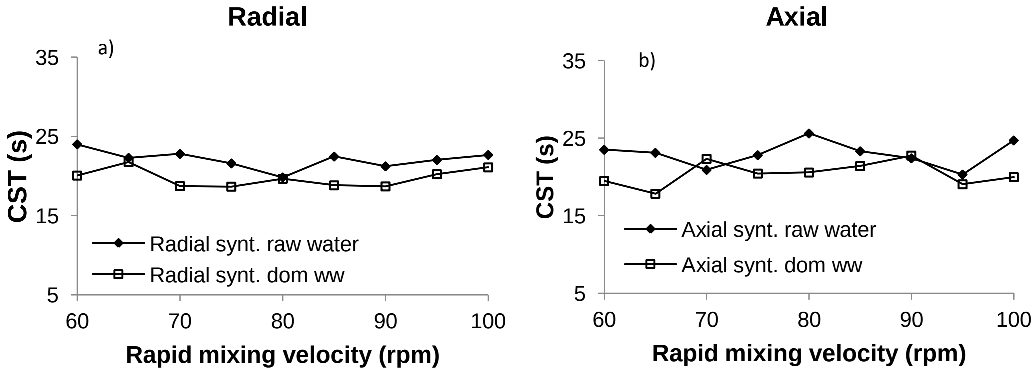
Using synthetic domestic wastewater, rapid mixing was not significant in decreasing the CST value. Although the mixer shapes and coagulants were changed the rapid mixing velocity still had little impact on the decrease of the CST value. The turbidity results also confirm that gradual increasing rapid mixing velocity is not important in removing turbidity. Synthetic domestic wastewater has a different composition from synthetic raw water, but it was revealed that this difference did not result in any significant variation in the sludge CST value. Synthetic raw water and synthetic domestic wastewater contain 1% kaolin along with other ingredients, and has a turbidity value of more than 300 NTU. This result further indicates that highly turbid water does not need an excessive rapid mixing velocity (Mhaisalkar et al., 1991).

4.4 The Effect of Water Sample Composition on CST value

4.4.1 Alum as a Coagulant

Rigorous experiments were carried out by utilizing synthetic raw water and synthetic domestic wastewater. These water types have different compositions. Figure 19 shows the result of direct comparison of water composition when using alum as the coagulant. Domestic raw water produces slightly higher CST results than synthetic domestic wastewater for all mixer shapes.

Table 15 shows the decrease in CST values. It can be seen that there is a significant difference in CST values between synthetic raw water and synthetic domestic wastewater, the former having a higher removal percentage.



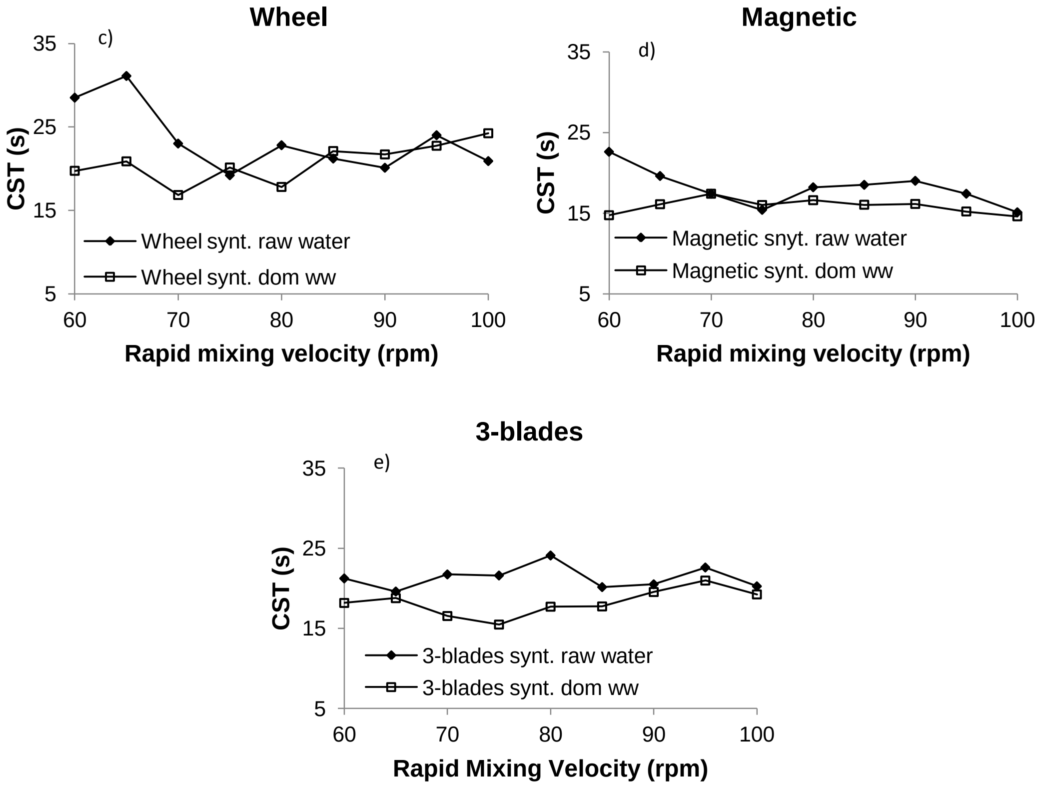


Figure 19. Comparison of different water composition (alum)

Table 15. CST and rapid mixing velocity coefficient of correlation

Mixer shape	Decrease in CST value (%)	
	synt. raw water	synt. dom ww
Radial	40.26	-7.93
Axial	37.95	-11.59
Wheel	36.69	-13.00
Magnetic	50.99	13.30
3-blade	42.41	0.36

Despite the higher CST value of synthetic raw water, synthetic raw water has a higher decrease in CST value (the result of comparison between average CST values after coagulation to initial CST value before coagulation) than synthetic domestic wastewater. This is probably a result difference element in the water sample. Synthetic raw water only contains kaolin, which is inorganic, but synthetic domestic wastewater contains not only inorganic but also organic and biological material. This result indicates that the coagulation process removes inorganic content better than the organic and biological content. This is due to the presence of the hydrophilic content in synthetic domestic wastewater. Coagulation removes hydrophobic matter better than hydrophilic matter (Zhan et al., 2010b). The hydrophobic fraction has a higher molecular weight and lower repulsion of the flocculant (Kim et al., 2006).

The CST values for synthetic raw water are slightly higher than synthetic domestic wastewater after coagulation, although the decreasing CST value is much higher. This is due to the presence of microorganisms which is presented by yeast in the wastewater. Yeasts are eukaryotic microorganism (Kurtman and Fell, 2006). The presence of any microorganism is associated with a relatively large surface area (Jin et al., 2003). This means that synthetic domestic wastewater produces a lower CST value even though the coagulation process does not happen effectively. This indicates that alum is less effective to decrease CST value in synthetic domestic wastewater than synthetic raw water.

4.4.2 Ferric as a coagulant

Figure 20 shows the influence of different water compositions on the CST value. Ferric is used as a coagulant, along with different mixer shapes and rapid mixing velocity.

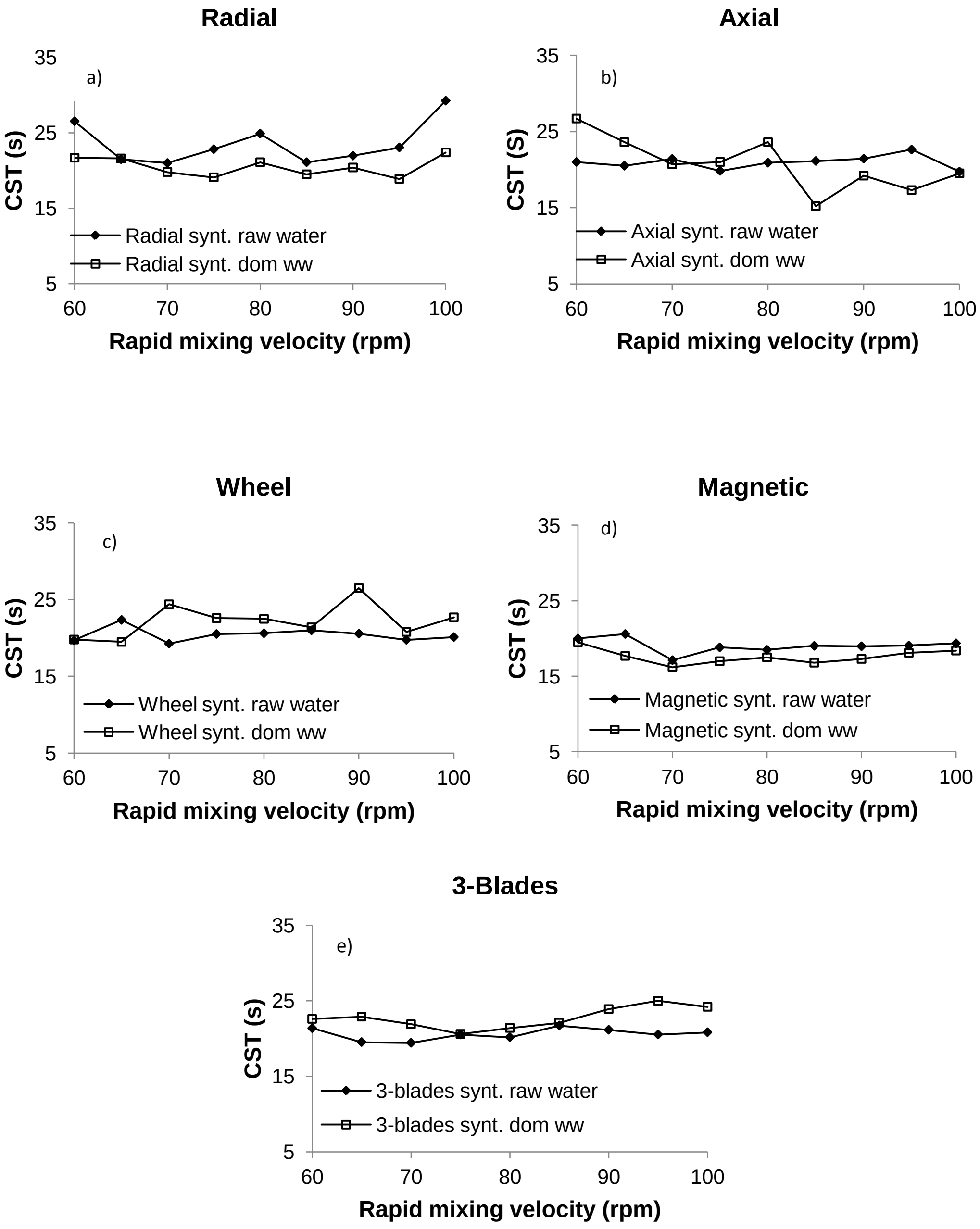


Figure 20. Comparison of different water composition (ferric)

Table 16. CST and rapid mixing velocity coefficient of correlation (ferric)

Mixer shape	The decreasing of CST value (%)	
	synt. raw water	synt. dom ww
Radial	40.84	31.43
Axial	42.42	30.58
Wheel	48.70	25.60
Magnetic	52.18	41.09
3-blade	48.33	23.96

Using ferric with both water samples produces different trends to those produced when using alum. With ferric, in general, there is no difference in the trend of CST results between synthetic raw water and synthetic domestic wastewater, although there is a slight difference in the decrease of CST value (Table 16). Again, the slight difference the CST value is due to the presence of hydrophilic content in synthetic domestic water, which is unfavourable to the coagulation process (Zhan, 2010). This indicates that ferric is effective in coagulating the contaminants in synthetic raw water and synthetic domestic wastewater.

4.4.3 *Moringa Oleifera* as a Coagulant

Moringa oleifera was used as a coagulant in investigating the effect of water composition on the CST. This observation also involved mixer shape and rapid mixing velocity. The results can be found in Figure 21.

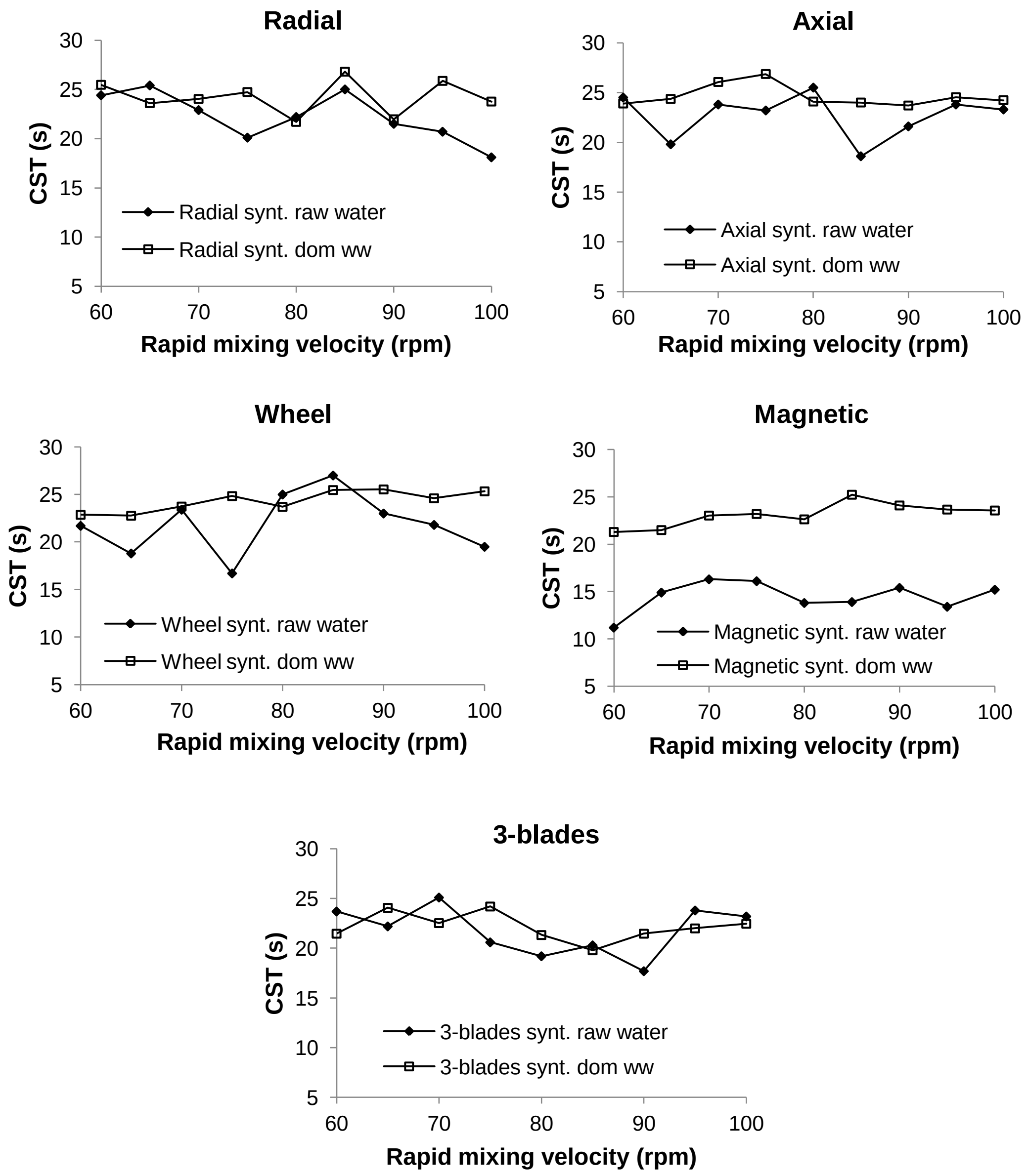


Figure 21. Comparison of different water compositions (*Moringa oleifera*)

Table 17. CST and rapid mixing velocity coefficient of correlation (*Moringa*)

Mixer shape	The decreasing of CST value (%)	
	synt. raw water	synt. dom ww
Radial	-2.62	-4.24
Axial	-2.76	-6.07
Wheel	-4.97	-4.66
Magnetic	17.12	0.40
3-blade	-5.63	4.65

Figure 21 and Table 17 show that when using *Moringa oleifera* as a coagulant, in general, there is no significant influence of water composition on the CST. All the mixer shapes, except for the magnetic stirrer, show that the effect of water composition on CST value is almost similar. It means, in general, there is no effect of different water samples while using *Moringa oleifera* as a coagulant on CST value.

4.4 Summary

Using the Capillary Suction Time (CST) apparatus as a measurement tool for sludge dewaterability, a number of parameters were investigated: shape of mixer, rapid mixing velocity and rapid mixing time, coagulant, temperature and water composition. Only the magnetic stirrer appears to have influenced sludge dewaterability, with the four other mixers similar to each other. The magnetic stirrer consistently produced the lowest CST value although rapid mixing velocity and rapid mixing time, coagulant, temperature and water compositions were modified. This is due to the optimum mixing intensity applied to water by the magnetic stirrer. Rapid mixing velocity had a more important effect on CST values than rapid mixing time although increased rapid mixing velocity and rapid mixing time are not important to the CST value.

Alum and ferric have the same impact on the CST value, with consistently lower CST values than *Moringa oleifera*. This indicates that metal-based coagulants play a more important role than non-metal based coagulants in determination the CST values. Temperature has an important role to play when using alum or *Moringa oleifera* as a coagulant, although with ferric, the CST values appeared insensitive to temperature. Water composition did not have a significant effect on CST values when using alum, ferric or *Moringa oleifera*. Synthetic raw water and synthetic domestic wastewater produced similar CST values when using ferric and *Moringa oleifera*, but lower on decrease of CST value when using alum.

In order to compare and verify the CST value, turbidity and floc size have been examined; details are presented in Chapter 5.

CHAPTER 5

PARTICLE SIZE ANALYSIS

RESULTS AND DISCUSSION

5.1 Introduction

Coagulation increases the tendency of particles to attach to each other in order to form a larger contaminant. Particle (floc) size is therefore an important factor in the coagulation process (Zhan, 2011) where it influences settlement following coagulation. The larger the floc, the more readily it can be removed from water (Besra et al., 2000). As a consequence, sludge conditions, including particle size, have an important role in sludge dewaterability (Razi & Molla, 2007).

In order to verify the CST results, floc sizes produced by the coagulation process has been investigated, using a particle size analyzer. As with the CST analysis, five shapes of mixer were used while varying the rapid mixing velocity and rapid mixing time, choice of coagulant, temperature and water composition.

♣ A part content of this chapter has been published as a manuscript on the Journal of Chemical Engineering and Techology.

Fitria, D., Scholz, M., Swift, G.M. and Hutchinson, S.M. (2013). *Impact of sludge floc size and water composition on sludge dewaterability*. Chemical Engineering and Technology Journal. DOI: 10.1002/ceat.201300378

5.2 Synthetic Raw Water

5.2.1 The Effect of Mixer Shape on Particle Size

Experiments using the CST were undertaken using synthetic raw water and synthetic domestic wastewater. In order to obtain a deeper understanding of the subject, the research continues using a particle size analyzer to investigate floc size.

Initially, synthetic raw water was utilised with only ferric as a representative coagulant, because in the earlier research metal based coagulants produced the lowest CST value. Figure 12 showed that four shapes of mixer, (radial, axial, wheel and 3-blade) had a consistent influence on the CST result; in this investigation, only three mixer shapes (radial, axial and magnetic stirrer) were investigated. Radial and axial mixers are representative of the four shapes of mixer in that they act at a certain height from the bottom of the chamber; a magnetic stirrer was also used as this was the most effective mixer in producing the lowest CST value. The investigation results are shown in Table 18 and Figure 22.

Table 18. Descriptive statistic of floc size in responding mixer shape

Mixer	Parameter	CST
Radial	mean	6.11
	min	5.35
	max	7.06
	std	0.63
Axial	mean	6.79
	min	5.17
	max	7.53
	std	0.82
Magnetic	mean	19.05
	min	17.13
	max	20.60
	std	0.97

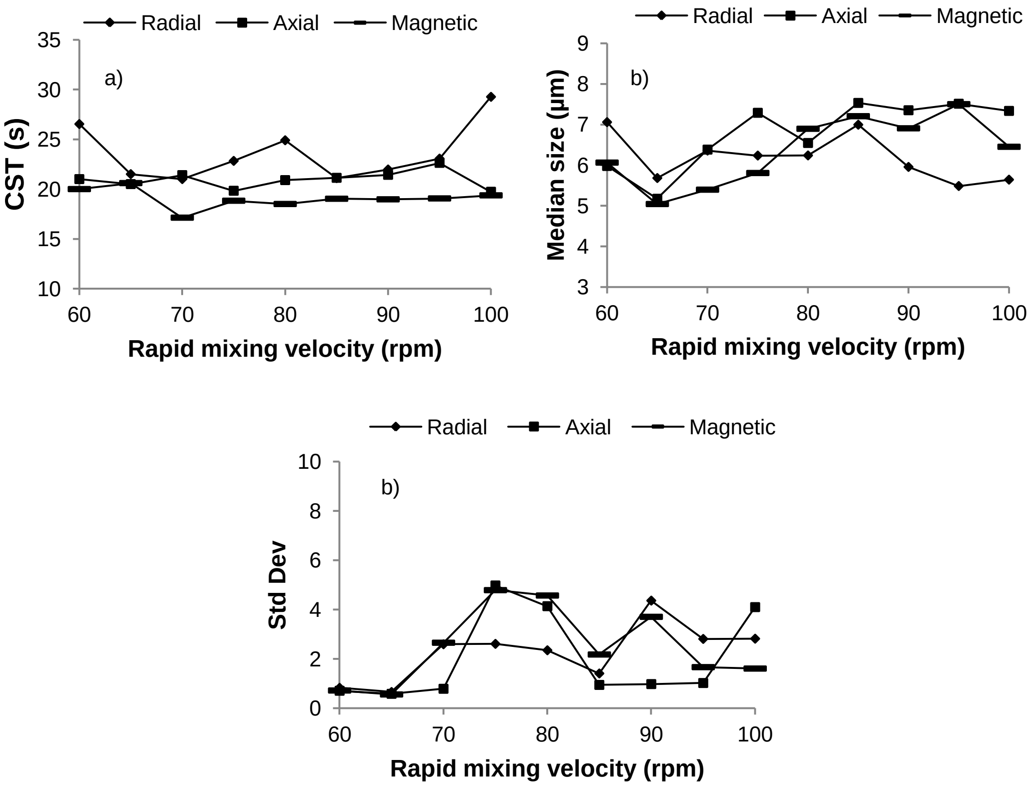


Figure 22. Comparison of sludge dewaterability, median floc size and size standard deviation (synthetic raw water)

In this investigation, the median particle size was used to evaluate the floc size after coagulation, flocculation and sedimentation processes. This is because the median presents the upper half data of floc size, and in due course it can be used as representative floc size data. Figure 22a indicates the CST value, Figure 22b the floc size and Figure 22c the floc standard deviation .

In relation to mixer shape, the magnetic stirrer produced the lowest CST values, but this result was not supported by the floc size. The data indicated that the magnetic stirrer did not produce the largest flocs of the three mixer shapes in this experiment. It appears that when using synthetic raw water, there is no correlation between the floc size and sludge dewaterability. This is due to the density of floc. Another experiment was conducted to give evidence. The result indicates that floc density of synthetic raw water is higher than synthetic domestic wastewater floc (Figure 23). And, sludge produced using the magnetic stirrer has a higher density floc than sludge from other mixer shapes (Figure 24); therefore the magnetic stirrer still produced the lowest CST value even though it did not have the largest flocs.

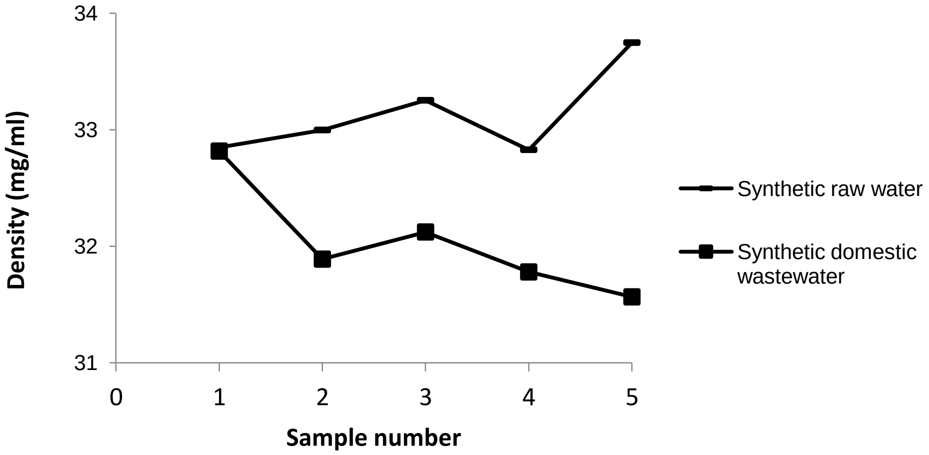


Figure 23. Density of different water sample

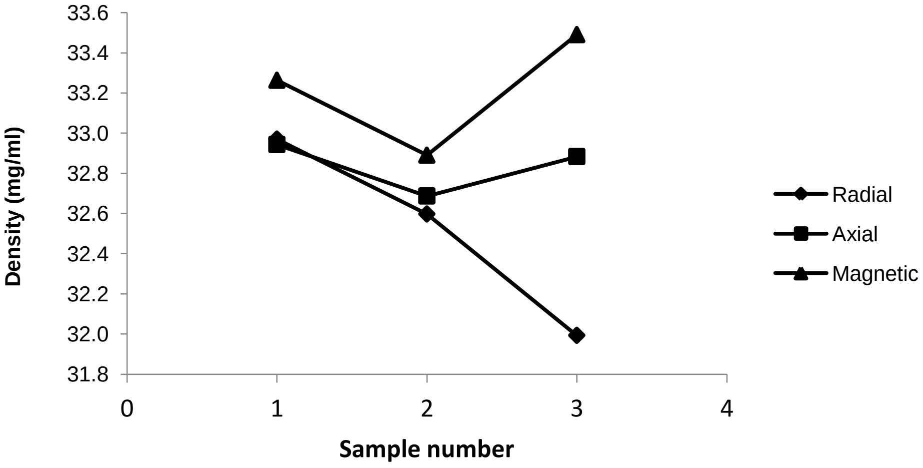


Figure 24. Water density related to mixer shapes

This mechanism could be explained by the work of Turchiulli and Fargues (2004); they stated that one of the factors that determine sludge dewaterability is the floc structure and its physical characteristics (size and density). A high-density solution has a high concentration of solids, and these have smaller basic units and less bound water. These sludges are, therefore, dewatered further and faster than those obtained from solutions with low concentrations of solid.

Figure 22 shows that increasing the rapid mixing velocity has an impact on floc size. Floc size data suggest that lower rapid mixing velocity produces smaller flocs. Increasing rapid mixing velocity increases the floc sizes, but once the optimum rapid mixing velocity has been reached, the floc size decreases in response to the increase in velocity. Rapid mixing velocity seems to have an important role in the formation of flocs and on its size, and this result confirms the investigation result in Sub chapter 4.2.3.2.

Furthermore, using synthetic raw water as the water sample in the coagulation process produced short-range standard deviation, as it appears that using only kaolin creates a uniform floc size in the coagulation process. This is probably due to the cohesive property of kaolin clay particles and their edge-to-face electrostatic alignment (Sawalha, 2010). As utilizing kaolin in the water sample brings about similar floc sizes, further research needs to be conducted using different water compositions.

5.3 Synthetic Domestic Wastewater

It appears that a single ingredient makes the agglomeration process slower. This was shown using kaolin as the only ingredient in synthetic raw water, producing a uniform size of floc and short-range particle size distribution in response to different mixers. In order to compare the use of kaolin, the investigation then used a synthetic domestic wastewater sample. This additional investigation was to obtain a more definitive explanation for the influence of the coagulation parameters on sludge dewaterability and also the effect of the composition of the water.

5.3.1 The Influence of Mixer Shape

Five shapes of mixer were used, with only ferric as the coagulant. Table 19 and Figure 25 represent the influence of mixer shape on CST values and turbidity. In general, there is a similarity between these factors in their response to the different shapes of mixer, as shown in Figure 25. From the CST, turbidity and particle size analyzer readings, the magnetic stirrer, in general, produced the lowest CST and turbidity values but larger floc size and higher standard deviation.

Table 19. Statistic descriptive of floc size and turbidity in responding mixer shape

Mixer	Parameter	CST	Turbidity
Radial	mean	8.44	609.56
	min	5.74	542.00
	max	10.80	703.00
	std	1.49	48.27
Axial	mean	9.98	596.11
	min	7.70	467.00
	max	12.55	686.00
	std	1.94	86.06
Wheel	mean	9.98	596.11
	min	7.70	467.00
	max	12.55	686.00
	std	1.94	86.06
Magnetic	mean	11.72	452.22
	min	10.00	417.00
	max	13.25	488.00
	std	1.15	24.33
3-Blades	mean	8.32	688.00
	min	5.90	451.00
	max	11.90	886.00
	std	1.70	139.02

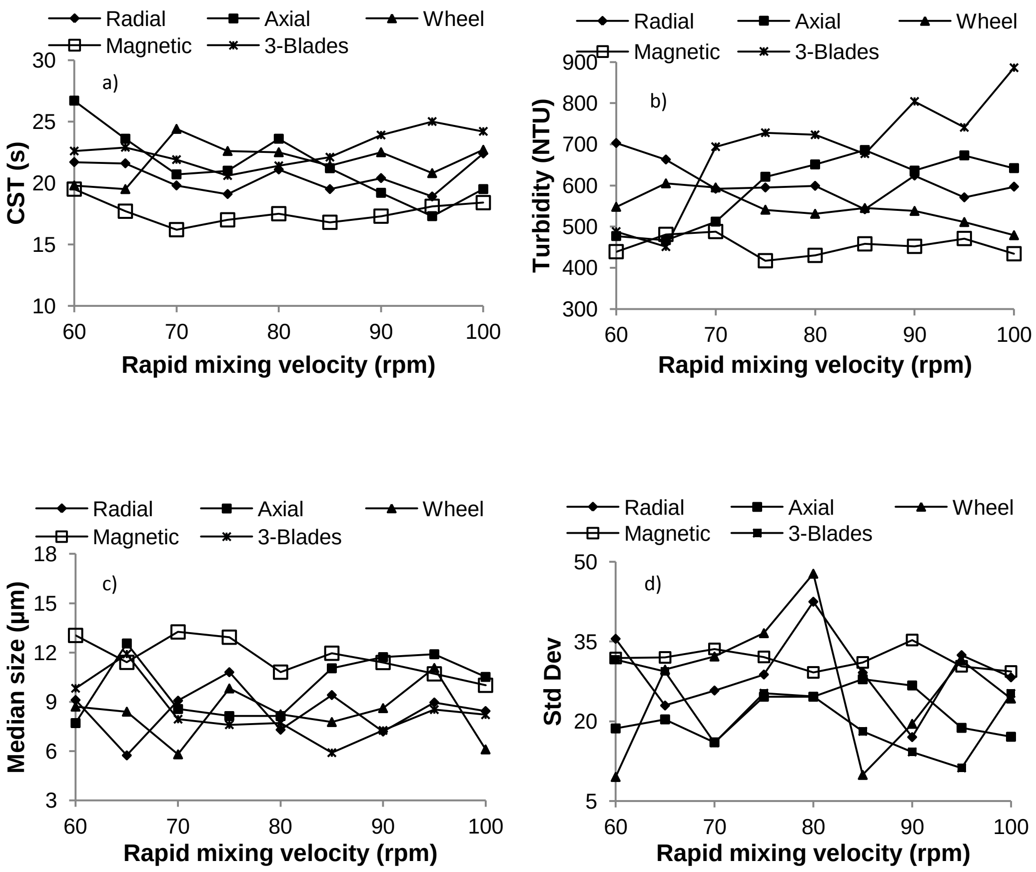


Figure 25. Comparison of CST, turbidity, median floc size and standard deviation while using different shapes of mixer

Floc size investigation showed that the magnetic stirrer was the best mixer shape to produce larger floc size. As mentioned in Chapter 4, the magnetic stirrer produced more appropriate hydrodynamic conditions for floc formation in the water than did the other mixers as indicated by CST and the turbidity meter. The correlation is the lower of CST value, the lower of turbidity, the larger of floc size and the higher of standard deviation.

The lower CST value means that it is easier for the sludge to release water; and, normally, the larger the floc size, the easier it is for water to be released (Turchiulli & Fargues, 1994; Larue & Vorobiev, 2003). Small flocs with narrow capillaries do not easily release water (Besra et al., 2000). In respect of water turbidity, the larger floc size makes it easier for particles to settle (Guo et al., 2009), thereby reducing the turbidity.

5.3.2 The Influence of Rapid Mixing Velocity and Rapid Mixing Time

The influence of rapid mixing velocity and rapid mixing time were observed using the CST and turbidimeter. The CST value was unaffected by the rapid mixing velocity and the rapid mixing time, and turbidity was also unaffected by the mixing velocity. As the coagulation process produces a larger particle size that is more easily removed, particle size investigation could be useful in this research. Particle size analyzer results should be able to verify the CST and turbidity results.

In this part of the investigation, a magnetic stirrer was used to create mixing in the water sample. The use of only the magnetic stirrer was because the results previously presented indicated that this is the most effective shape of mixer for sludge dewaterability. Therefore, the magnetic stirrer was selected as representative of all of the mixers in the investigation of the influence of coagulant on floc size. Table 20 and Table 21 inform about descriptive statistic of CST and turbidity values in responding rapid mixing velocity and rapid mixing time.

Table 20. Descriptive statistic of CST and turbidity values in responding rapid mixing velocity

Variable	Parameter	Al	Fe	*Moringa*
CST	mean	12.05	11.72	7.20
	min	7.30	10.00	4.29
	max	18.12	13.25	8.20
	std	3.20	1.15	1.18
Turbidity	mean	436.78	452.22	850.89
	min	403.00	417.00	583.00
	max	465.00	488.00	1042.00
	std	17.01	24.33	186.24

Table 21. Descriptive statistic of CST and turbidity values in responding rapid mixing time

Variable	Parameter	Al	Fe	*Moringa*
CST	mean	10.08	11.72	8.63
	min	7.08	10.00	7.34
	max	16.95	13.25	9.38
	std	2.92	1.15	0.62
Turbidity	mean	504.00	452.22	656.67
	min	415.00	417.00	471.00
	max	677.00	488.00	966.00
	std	86.18	24.33	155.57

5.3.2.1 Alum as a Coagulant

In order to obtain better information about the influence of rapid mixing velocity and rapid mixing time, different coagulants were used as a comparison. Figure 26, Table 22 and Table 23 show the results of the influence of rapid mixing velocity and time on CST values, floc size and turbidity when using alum as a coagulant.

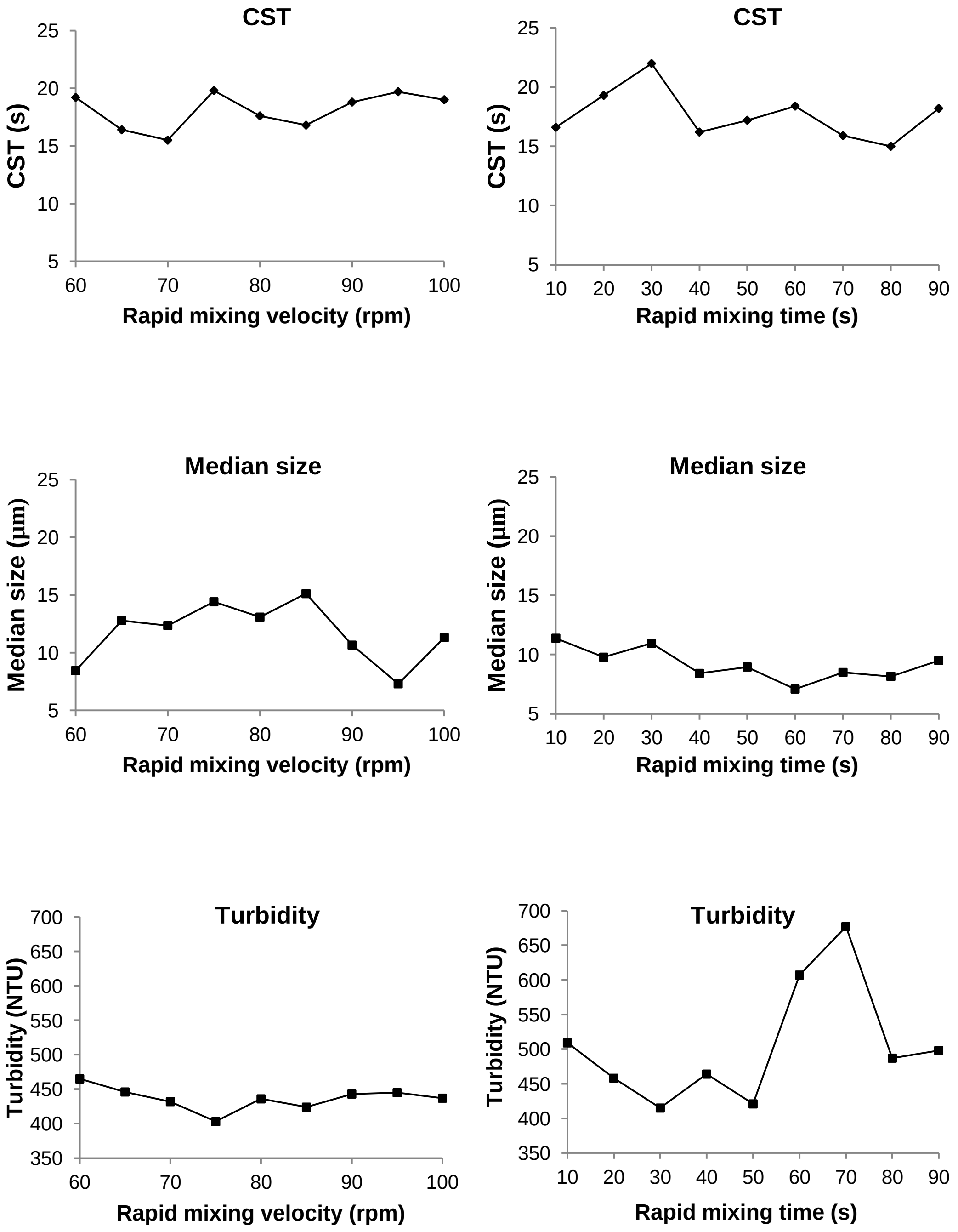


Figure 26. Influence of rapid mixing velocity and time on CST, floc size and turbidity (alum)

Table 22. The coefficient of correlation of CST value, median floc size and turbidity (alum)

Parameter	r
Velocity & CST	-0.29
Velocity & floc size	-0.07
Velocity & turbidity	-0.19

Table 23. The coefficient of correlation of rapid mixing time, CST value, median floc size and turbidity (alum)

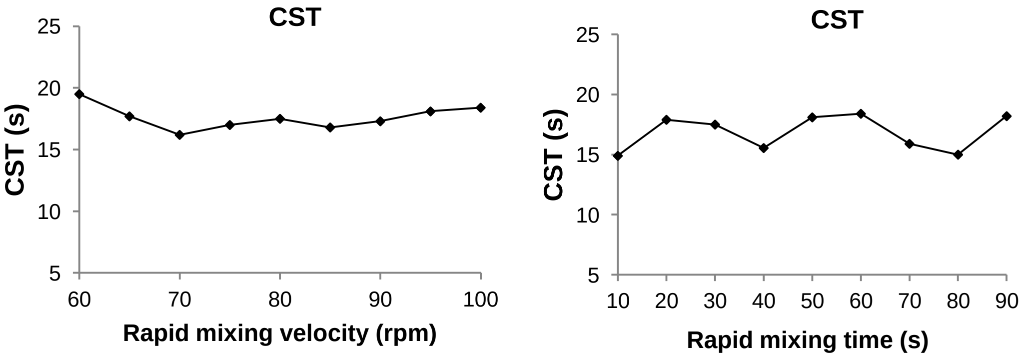
Parameter	r
Time & CST	-0.35
Time & floc size	-0.29
Time & turbidity	0.37

From Figure 26 it can be seen that the CST, floc median size and turbidity have almost identical trends. At lower rapid mixing velocity and time, the CST values and turbidity measurement become higher and floc size become smaller. When increasing the rapid mixing velocity and time, the CST and turbidity also decrease, as more effective contact between the coagulant and the particles is achieved; as a consequence, the floc size increases. As the rapid mixing velocity and time increases further, the CST and turbidity values continue to increase until the optimum rapid mixing velocity and time have been reached. When the optimum rapid mixing velocity and time have been exceeded, the floc size is reduced because the breakage process dominates over floc formation.

Tables 22 and 23 indicate that the CST value, floc size and turbidity are correlated with each other when considering rapid mixing velocity and time. Rapid mixing velocity and time without an initial value (0 rpm) have similar impacts on CST, floc size and turbidity. Floc size and turbidity results have confirmed CST value in term of gradual increasing rapid mixing velocity and rapid mixing time using alum as a coagulant.

5.3.2.2 Ferric as a Coagulant

The experiment with rapid mixing velocity and time was repeated, but with ferric as the coagulant. Figure 27, Table 24 and Table 25 present the results of this investigation.



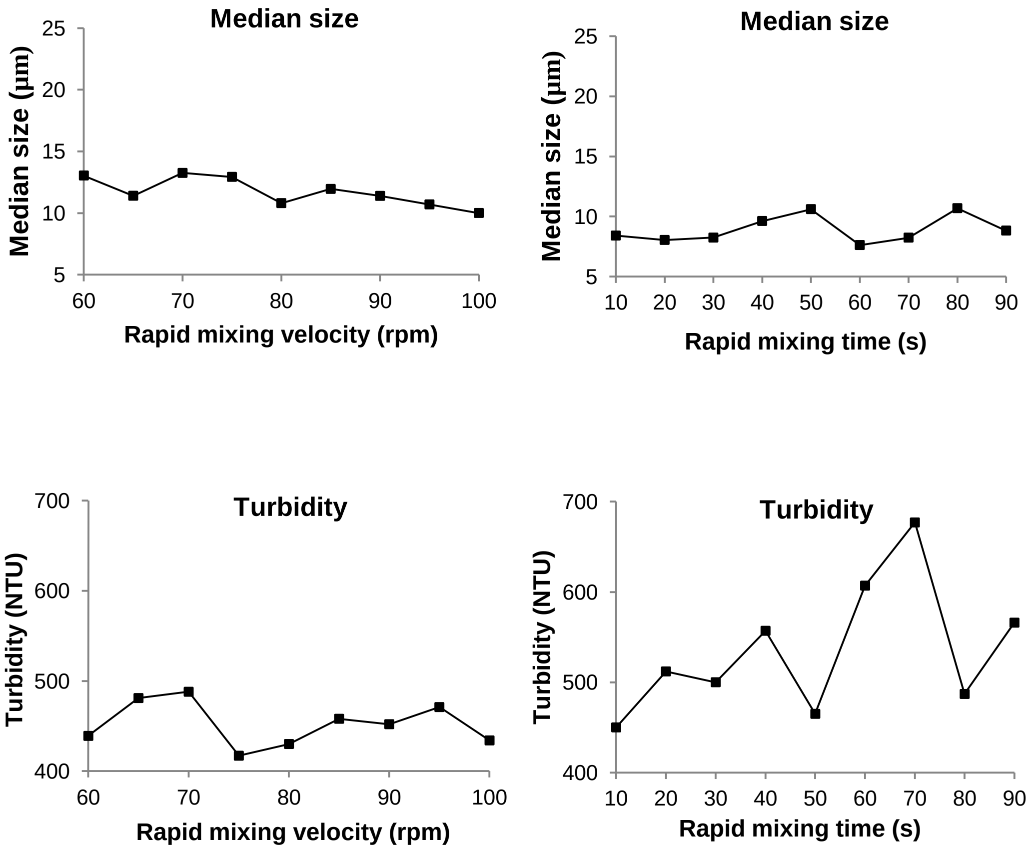


Figure 27. Influence of rapid mixing velocity and time on CST, floc size and turbidity (ferric)

Table 24. The coefficient of correlation for rapid mixing velocity, CST value, floc size and turbidity (ferric)

Parameter	r
Velocity & CST	-0.06
Velocity & median size	-0.75
Velocity & turbidity	-0.15

Table 25. The coefficient of correlation for rapid mixing time, CST value, median floc size and turbidity (ferric)

Parameter	r
Time & CST	0.13
Time & median size	0.30
Time & turbidity	0.49

All the coefficient correlation values in Tables 24 and 25 show that, in general, rapid mixing velocity and rapid mixing have little impact on CST values, even though when examined in more detail, rapid mixing velocity is seen to have a good correlation with median floc size. Increasing turbidity reduces the median floc size, but this effect is insufficient to affect CST and turbidity.

Rapid mixing time slightly correlates with turbidity. Except for the correlation between rapid mixing velocity and median floc size, all the results verify the CST value that rapid mixing velocity and time does not have an important influence on CST value. Changing the coagulant to ferric resulted in the CST value, median floc size and turbidity producing the same relationship with rapid mixing velocity and rapid mixing time. This confirms that the CST is not sensitive to increasing rapid mixing velocity and rapid mixing time.

5.3.2.3 *Moringa oleifera* as a Coagulant

The effects of *Moringa oleifera* on the relationship between CST value, floc size and turbidity are shown in Figure 28, Table 26 and Table 27.

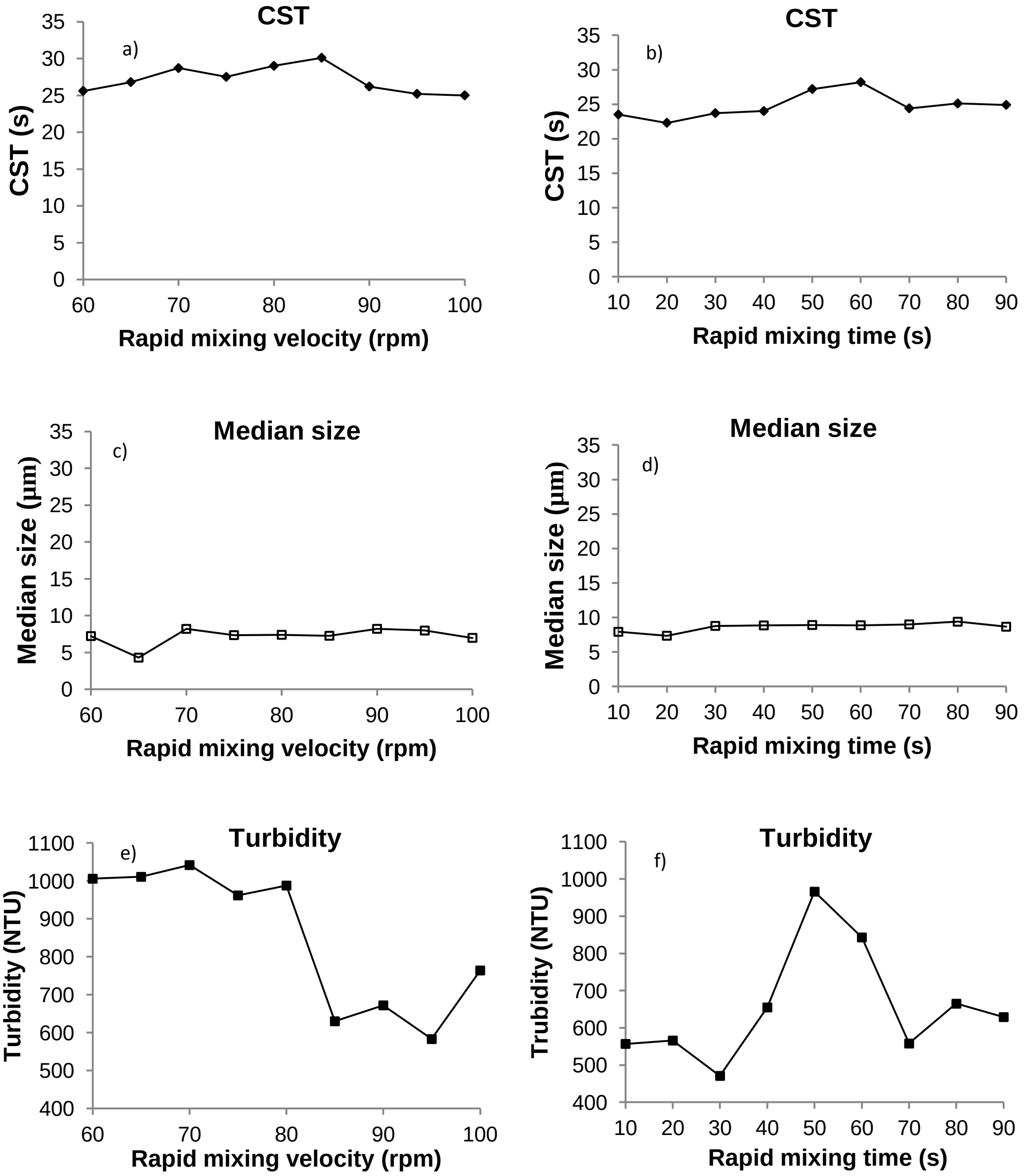


Figure 28. Influence of rapid mixing velocity and time on CST, floc size and turbidity (*Moringa oleifera*)

Table 26. The coefficient of correlation of rapid mixing velocity, CST value, median floc size and turbidity (*Moringa oleifera*)

Parameter	r
Velocity & CST	0.73
Velocity & median size	0.38
Velocity & turbidity	-0.55

Table 27. The coefficient of correlation of rapid mixing time, CST value, median floc size and turbidity (*Moringa oleifera*)

Parameter	r
Time & CST	0.48
Time & median size	0.70
Time & turbidity	0.28

Figure 28 indicates that the influence of rapid mixing velocity and rapid mixing time on the CST value and median floc size look similar. Turbidity is the exception.

From Table 26, the coefficient of correlation data for rapid mixing velocity shows that floc size and turbidity values do not verify the CST value. Only rapid mixing velocity has a significant impact on turbidity, though the correlation is not very good. Increasing rapid mixing velocity increases the CST value, but there is no effect on floc size and the turbidity reduces. Although the floc size and turbidity do not correlate well with the CST results, this still indicates that rapid mixing velocity is not important to the CST value, floc size or turbidity result.

These figure and tables show that turbidity verifies the CST value in its relationship with rapid mixing time but not with floc size. The relationship between the CST value and turbidity with rapid mixing time is poor. However, floc size has a good relationship with rapid mixing time. This data indicates that increasing floc size does not have a beneficial effect on the CST value. It seems that even though the floc size becomes larger, there is still no beneficial effect on the CST value and turbidity. In summary, with *Moringa oleifera* increasing rapid mixing velocity and time are not important to the CST value.

5.3.3 The Effect of Coagulants on CST, turbidity and floc size

The comparison of the effect of different coagulants on sludge dewaterability was based on CST and turbidity values. In order to obtain a comparison from particle size analysis results, a further comparison must be made, and this is presented in Figure 29. In this investigation, a magnetic stirrer was again used as the mixer.

Figures 29a) and 29b) illustrate the performance of different coagulants in terms of CST and turbidity. Figure 29c) shows the floc size data. All of the graphs show similar trends, that ferric and alum are almost identical in term of CST, turbidity and floc size. They produce lower CST and turbidity results, and larger floc sizes than when using *Moringa oleifera* as a coagulant.

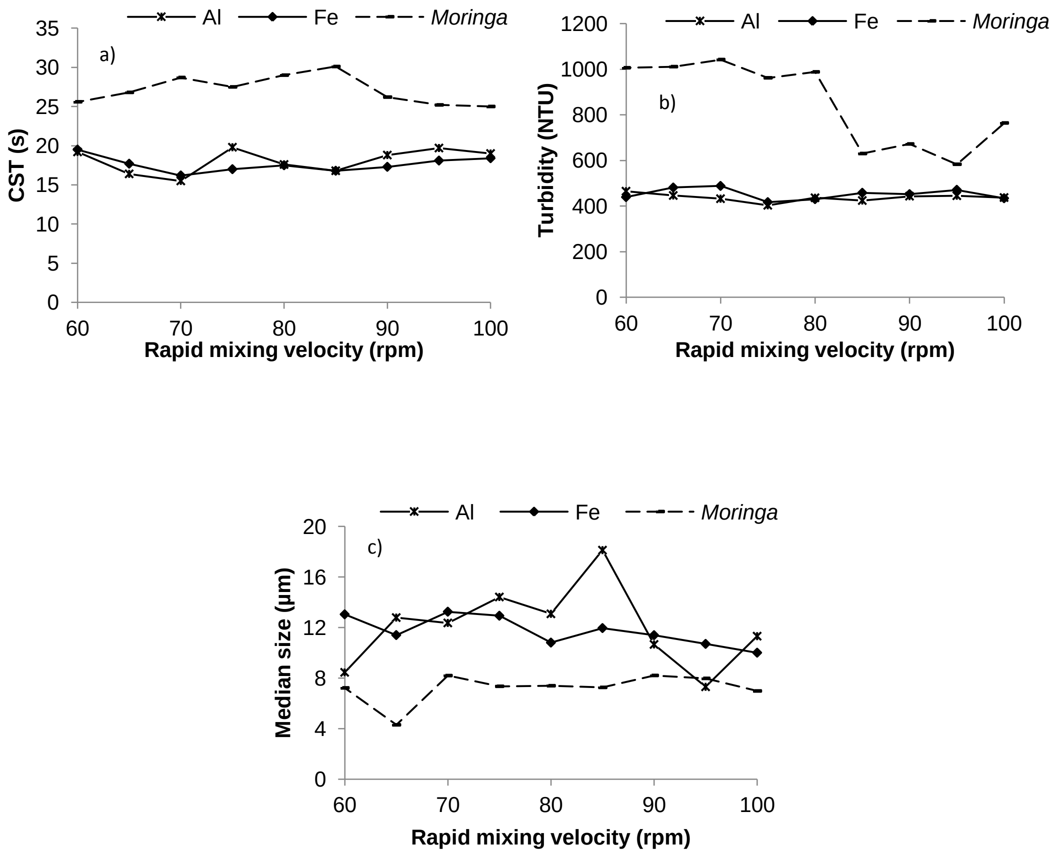


Figure 29. Comparison of different coagulants on CST, turbidity and floc size

The turbidity and floc size results confirm those results described in Chapter 4. In the previous results, alum and ferric have almost the same effect on CST values. Moreover, they have a more positive impact than *Moringa oleifera*. It appears that the presence of coagulant hydrolysis products plays an important role in determining the CST value, floc size and turbidity. This investigation has shown that alum and ferric, which contain precipitated coagulant species, have lower CST values, larger floc sizes and lower turbidity results. *Moringa oleifera* floc does not contain precipitated coagulant, and the results show higher CST values, smaller floc sizes and higher turbidity. In summary, the coagulant comparison shows that the higher CST value results in a higher turbidity value, and lower floc sizes. These results also indicate that sludge dewaterability, turbidity and particle size are inter-related.

5.3.3 The Effect of Temperature

5.3.3.1 Ferric as a Coagulant

The CST results showed that alum and *Moringa oleifera* sludge dewaterability are influenced by changes in temperature; as the temperature increases, sludge dewaterability is reduced. This was not evident in the ferric CST results. Using ferric as a coagulant and altering the temperature revealed that ferric was not affected by changes in temperature. Following the investigation described in Chapter 4, tests were carried out with temperatures of 16℃, 20℃ and 26℃, using a particle size analyzer to observe the particle size and temperature (Figure 30).

Figure 30 indicates that at a range of temperatures, ferric has a different effect on the CST, turbidity and floc size. Since the effect for each parameter is different, so no conclusion can be drawn from these results. The impact trends of temperature on these factors are irregular. It seems that the inconsistency of ferric in responding different temperatures has indicated about no effect of temperature on CST value using coagulant ferric. The particle size analyzer and turbidity results confirmed that the sludge dewaterability when using ferric is virtually unaffected by differences in temperature. As explained in Chapter 4, this is because temperature did not significantly influence the rate of metal ion precipitation, and for temperatures between 1 and 23℃, temperature did not affect the rate of iron precipitation (Moris & Knocke, 1984). Furthermore, ferric hydrolysis product at 20°C and 5°C were almost identical if pOH remained constant (Hanson et al., 1990).

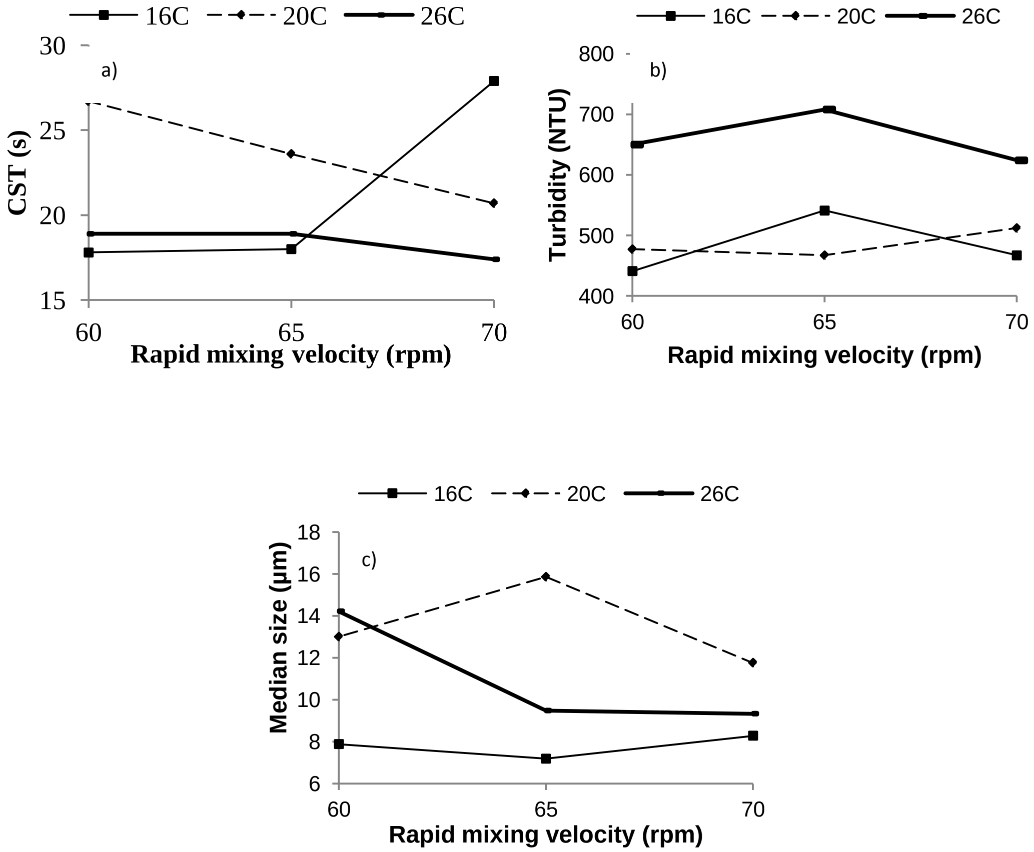


Figure 30. The effect of using ferric at different temperatures

5.4 Comparison of Different Water Compositions

The particle size analysis allows the statistical distribution of floc sizes to be examined. Particle size distribution graphs illustrate the floc size distribution due to the coagulation process.

The investigation was carried out using synthetic raw water and synthetic domestic wastewater. This comparison was made in order to obtain additional explanation of the process in each sample, and its influence on floc size and, ultimately, on sludge dewaterability.

5.4.1 Synthetic Raw Water

Synthetic raw water has an inorganic content. Particle size data from this study allows for an assessment of the distribution of floc sizes. Each data point was based on three readings from the particle size analyzer. Particle size statistical distribution graphs illustrate the floc size distribution influenced by the coagulation process (Figure 31). Floc diameter distribution is in X axis, a percentage of similar floc size (q) is in first Y axis and the accumulative percentage of similar floc size (undersize) is in the second Y axis.

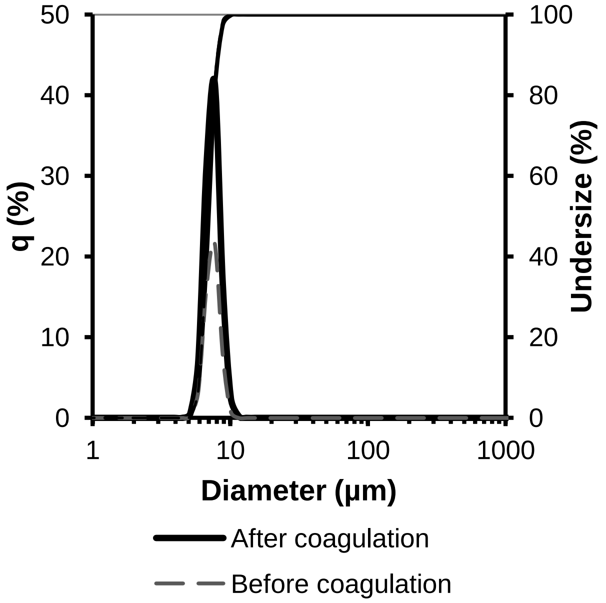


Figure 31. General synthetic raw water floc size distributions

Kaolin was the only ingredient in the synthetic raw water recipe. Figure 31 shows the similarity in floc size before and after the coagulation process. This means that the coagulation process is not effective in increasing synthetic raw water floc size. Corresponding general particle size analysis indicated a small range of uniform floc distribution (concentrated around 7 µm) with kurtosis and skewness values of 3.51 and 0.47, respectively. The kurtosis value indicates that the particle size distribution of this sample is extremely leptokurtic (i.e. narrow with a sharp peak). Moreover, there is very little skewness in the distribution. This data verifies the data presented in Chapter 5.2, that coagulation has no impact at all on kaolin floc size.

5.4.2 Synthetic Domestic Wastewater

In this investigation the recipe for synthetic domestic wastewater has ten different ingredients. The purpose of using this water sample was to obtain further information about the influence of different water compositions on floc size.

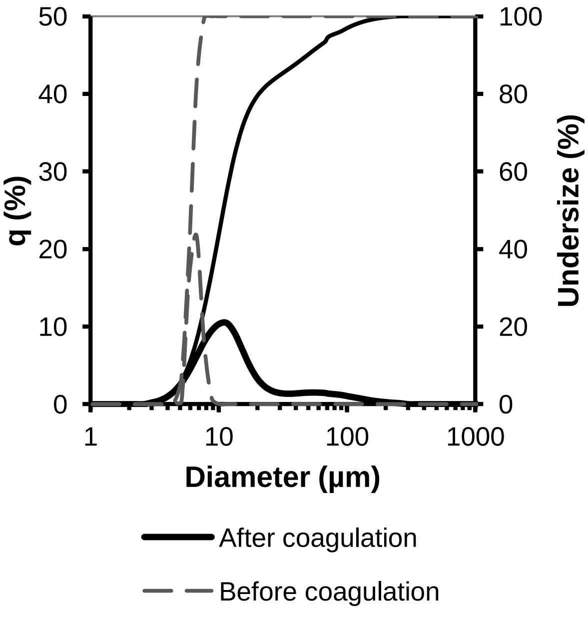


Figure 32. General synthetic domestic wastewater floc size distribution

Figure 32 indicates the corresponding general particle size distribution for synthetic domestic wastewater; it has different floc size after coagulation compare to floc size before coagulation process. This particle distribution has no clear peak, unlike the distribution of raw water (Figure 31). Synthetic domestic wastewater has a wider range of particle sizes and a larger mean floc size than synthetic raw water. The distribution can be described as platykurtic (i.e. a wide and flat profile) with an asymmetric particle size distribution and a tendency towards coarse characteristics. The synthetic domestic wastewater may also have a different impact on the floc formation process. A synthetic domestic wastewater floc is characterized more by its size, while a synthetic raw water floc is influenced considerably by its density, as indicated by the poor correlation between the CST value and floc size.

Synthetic domestic wastewater, with its ten different ingredients, produces a wider range of particle sizes and larger flocs. In contrast, synthetic raw water, which has only a single ingredient, produces a narrow particle size range and relatively small flocs. This might be explained by the more likely presence of naturally developing microorganisms within synthetic domestic wastewater, compared to the synthetic raw water. The presence of any microorganism is associated with a relatively large surface area (Jin et al., 2003), ultimately affecting the floc size distribution.

Coagulation increases the floc size of synthetic domestic wastewater. This indicates that water composition influences floc size.

5.5 Summary

Observation of floc sizes using the particle size analyzer was carried out. The results make it clear that for synthetic raw water, which has a single ingredient, small flocs are produced and there is no correlation between sludge dewaterability and floc size. Synthetic domestic wastewater produced larger flocs, so the study of floc size was continued by using this sample.

Using synthetic domestic wastewater, floc size had a better correlation with CST, rapid mixing velocity and turbidity when using alum and ferric as a coagulant. The floc sizes analysis show that the magnetic stirrer is the most effective mixer shape, confirming the CST and turbidity values. Alum and ferric, in contrast to *Moringa oleifera*, produces a sludge with larger floc sizes, thus lowering the sludge dewaterability. Using the floc size data, it was shown that the performance of ferric as a coagulant was insensitive to temperature, which is consistent with the CST test result. The study of water samples' statistical distribution indicates the importance of floc size on sludge dewaterability. It appears that the wider the range of floc size and the larger the size of floc, the lower the sludge dewaterability. The floc size and turbidity results correlate well with the CST data.

The next chapter will present the data from the SRF results and the comparison with CST values.

CHAPTER 6

SPECIFIC RESISTANCE TO FILTRATION (SRF) RESULTS AND DISCUSSION

6.1 Introduction

Along with the CST, Specific Resistance to Filtration (SRF) is one of the most common methods of measuring sludge dewaterability. As the SRF result was intertwined with the CST result in many investigations (Buyukkamaci, 2004; Scholz 2005, 2006; Sawalha, 2010), it was important to carry out an investigation to verify the CST results.

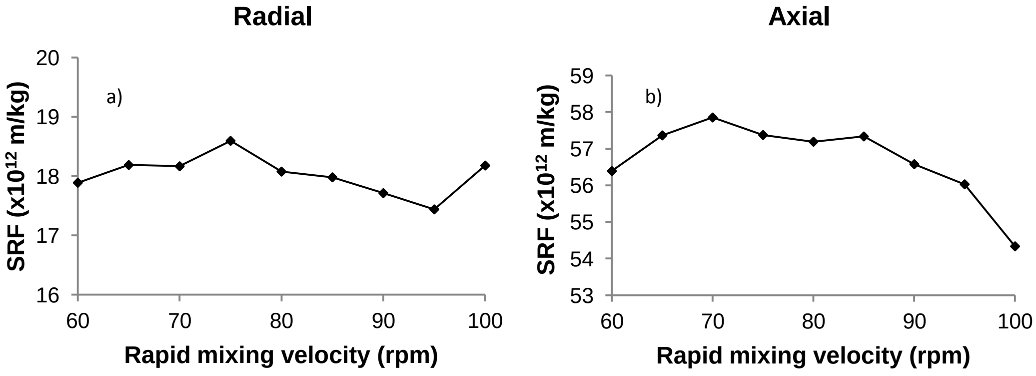
6.2 Synthetic Raw Water

Previous results using the CST apparatus, the turbidimeter and the particle size analyzer indicated a general related trend. In order to explore further the influence of different parameters on sludge dewaterability, the SRF test was carried out as an alternative measurement of sludge dewaterability. Synthetic raw water was used with different mixer shapes, different rapid mixing velocities and ferric as a coagulant (Table 28 and Figure 33). Ferric was used as it produces the lowest CST value.

♣ The content of this chapter is being under review as a manuscript to the Journal of Separation and Purification Technology.
Fitria, D., Scholz, M. and Swift, G.M. *Sludge dewaterability testing: relationship between capillary suction time and specific resistance to filtration*. Under review for Journal of Separation and Purification Technology.

Table 28. Descriptive statistic of SRF value in responding different mixer shapes

Mixer	Parameter	SRF value
Radial	mean	18.03
	min	17.44
	max	18.60
	std	0.33
Axial	mean	56.72
	min	54.33
	max	57.85
	std	1.06
Wheel	mean	18.66
	min	18.20
	max	19.65
	std	0.41
Magnetic	mean	52.57
	min	50.79
	max	53.98
	std	0.88
3-blades	mean	30.05
	min	29.21
	max	30.79
	std	0.51



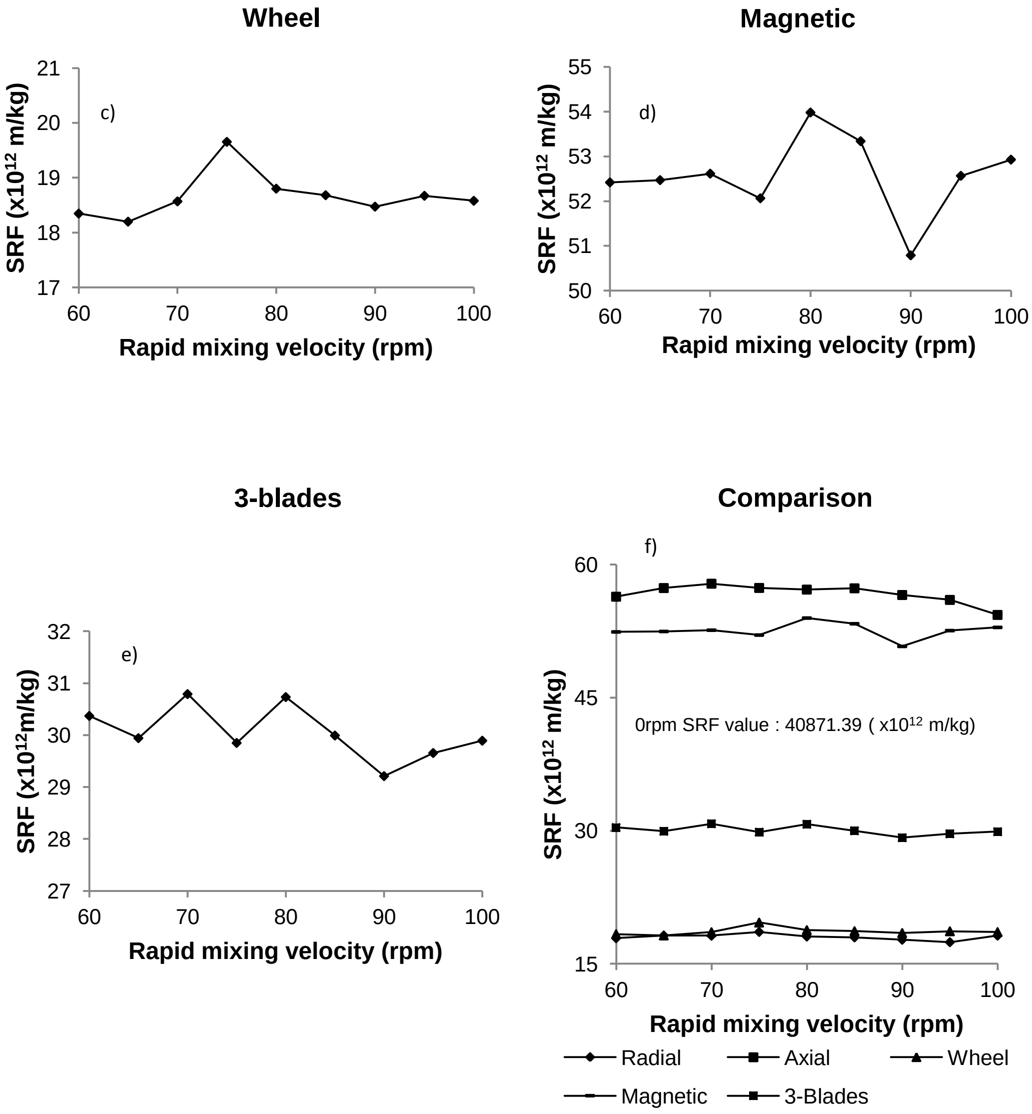


Figure 33. The effect of mixer and rapid mixing velocity on SRF using synthetic raw water

Figure 33 presents the results of this stage of the investigation. Each mixer responds to different rapid mixing velocity in a different way. The SRF result shows that each mixer shape produces a different SRF value, except for radial and wheel, which have the same effect on SRF. Radial and wheel mixers are also the best shape to produce the lowest SRF.

In response to rapid mixing velocity, in general at the beginning of the experiment lower intensity resulted in lower SRF values. With an increase in rapid mixing velocity the SRF value also increased up to a certain point, after which it began to decrease. Based on the graph f) in Figure 33, rapid mixing velocity and SRF trends are almost similar to CST, turbidity and floc size. This trend is due to the difference in floc condition produced by different rapid mixing velocities. As explained in Chapter 5, Muyibi and Evison (1995) and AWWA (1999) observed that the different rapid mixing velocities produce different coagulation pathways, each pathway producing a different coagulant hydrolysis product. Therefore, this affects the floc formation through the interaction between the coagulant and the contaminant. Furthermore, the CST and SRF results can be compared in order to explore the relationship between the two tools (Figure 34).

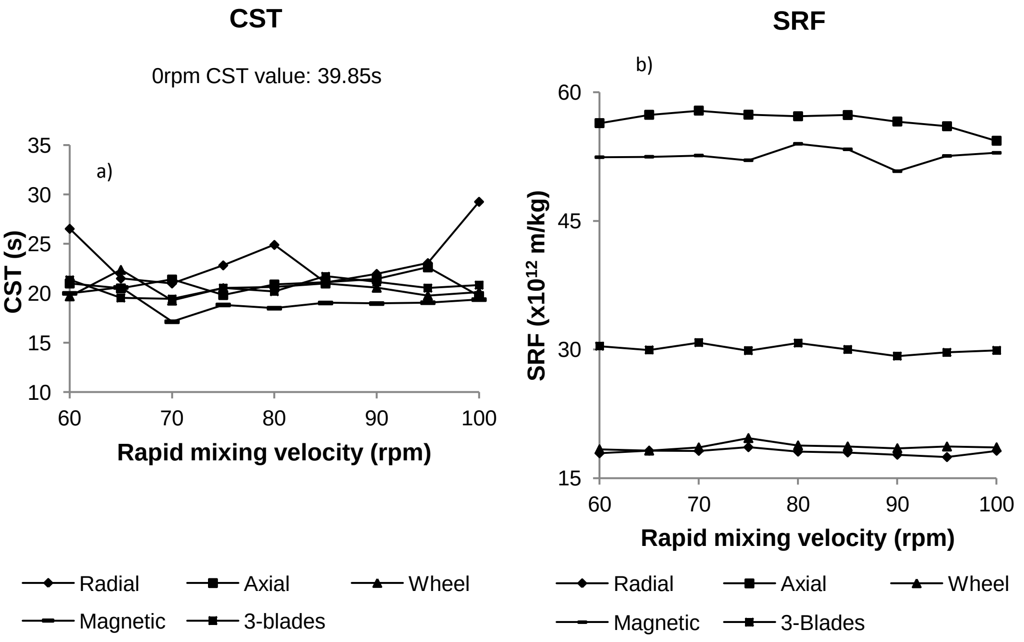


Figure 34. Comparison of CST and SRF results

Figure 34 shows that for different rapid mixing velocities, the CST and SRF trends are quite similar. Both CST and SRF results show almost the same response for sludge dewaterability, even though a variation in rapid mixing velocity was employed.

With the CST test as a measurement apparatus, the magnetic stirrer produced the lowest sludge dewaterability; in contrast, the four other types of mixer producd almost similar trends (Figure 34a). With the SRF test as a measurement apparatus (Figure 34b), the wheel and radial mixer shapes produced the lowest SRF results, and the axial mixer produced the highest SRF value. Based on this result, wheel and radial are the most effective mixers compared to axial, 3-blade and the magnetic stirrer.

SRF values show that there is a significant impact of the mixer shape on sludge dewaterability. Figure 34b reveals that different shapes of mixer do have a significant impact on sludge dewaterability. Comparing CST and SRF results by using a synthetic raw water sample, the difference is quite significant.

6.3 Synthetic Domestic Wastewater

Following the previous investigation, synthetic domestic wastewater was used as the water sample. Using these two different compositions of water, the CST apparatus, turbidimeter and particle size analyzer yielded similar results. In order to verify the effect of water composition, further research was conducted using the coagulants ferric and alum.

6.3.1 Impact of Rapid Mixing Velocity

Different parameters such as mixer shape, rapid mixing velocity and rapid mixing time, coagulant and temperature were also used in this study. Table 29 and Figure 35 present the effect of different mixer shapes and different rapid mixing velocity on the SRF test results.

Table 29. Descriptive statistic of SRF value in responding different mixer shapes (rapid mixing velocity)

Mixer	Parameter	SRF value
Radial	mean	51.25
	min	49.57
	max	53.09
	std	1.33
Axial	mean	77.87
	min	75.10
	max	83.09
	std	2.89
Wheel	mean	142.29
	min	135.04
	max	155.81
	std	6.28
Magnetic	mean	248.15
	min	238.13
	max	257.02
	std	7.56
3-blades	mean	65.33
	min	62.83
	max	71.13
	std	2.76

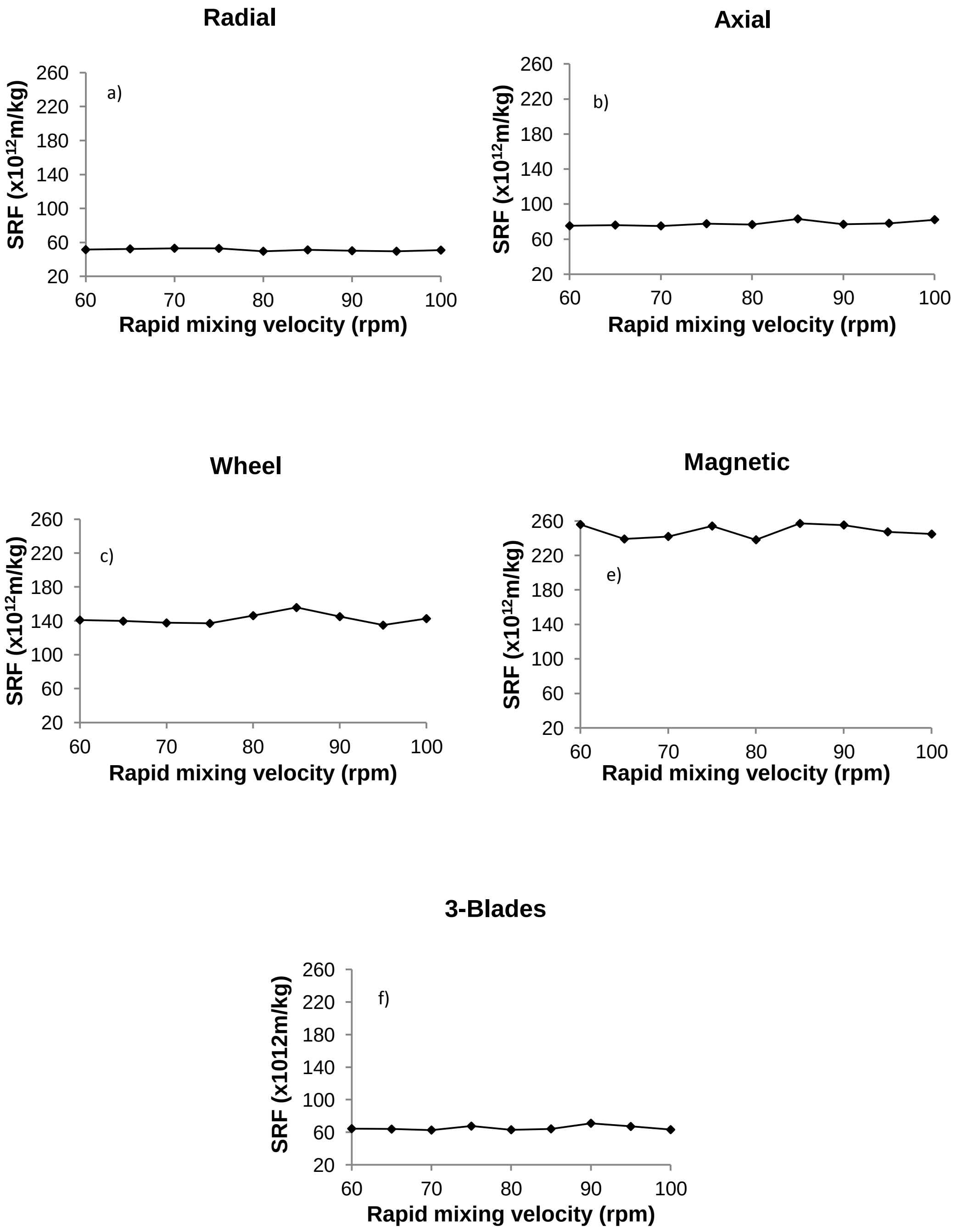


Figure 35. Effect of different mixers and different rapid mixing velocity on SRF value

Table 30. Coefficient of correlation of rapid mixing velocity and SRF value using a synthetic domestic wastewater sample

Mixer Shape	Parameter	r
Radial	Velocity & SRF	-0.62
Axial	Velocity & SRF	0.68
Wheel	Velocity & SRF	0.19
Magnetic	Velocity & SRF	0.06
3-blade	Velocity & SRF	0.29

Figure 35 shows the effect of different rapid mixing velocity on the SRF varies. The graphs show a fluctuating trend and the coefficient of correlation in Table 30 reveals a variable relationship between rapid mixing velocity and SRF value. Only in using the radial shape did rapid mixing velocity have a beneficial relationship with SRF. In general, this is similar to the CST results, where the effect of rapid mixing velocity was not significant on sludge dewaterability. To compare this SRF value and the CST value, tests using different mixer shapes were carried out, presented in Figure 36 and Table 31.

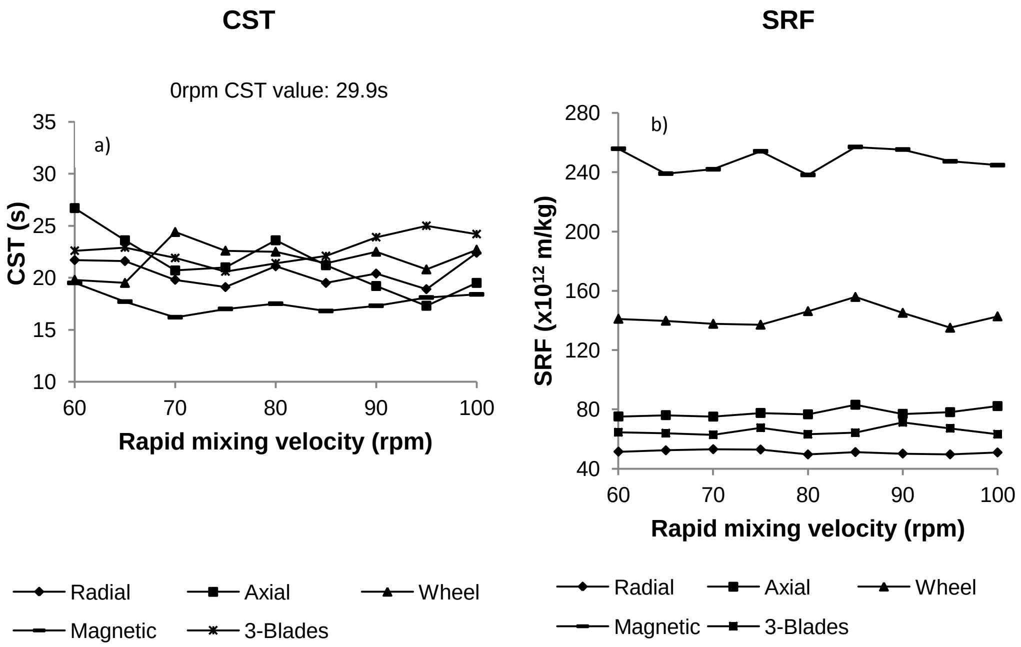


Figure 36. Effect of mixer and rapid mixing velocity on CST and SRF

Table 31. CST and SRF rapid mixing velocity coefficient of correlation values using a synthetic domestic wastewater sample

Mixer Shape	Parameter	r
Radial	CST & SRF	-0.07
Axial	CST & SRF	0.72
Wheel	CST & SRF	0.09
Magnetic	CST & SRF	0.12
3-blades	CST & SRF	0.27

The correlation of rapid mixing velocity and CST and SRF values was good only when using the axial impeller; it was poor for other four mixers. The above comparison also suggests that different mixers have different impacts on SRF results. The radial mixer produced the lowest SRF values, followed by 3-blade, axial and wheel, with magnetic stirrer as the highest. These results differ from those using synthetic raw water. The difference in ingredients seems to bring about a change in the coagulation mechanism, and thus in the SRF value. In the case of comparing CST and SRF results, there are distinctive trends between the CST and SRF values. As explained before, with the CST value, only the magnetic stirrer produced distinctive sludge dewaterability, while the other four shapes all showed the same trend as each other. On the other hand, for the SRF value, every mixer produced different sludge dewaterabilities.

6.3.2 The Impact of Rapid Mixing Time

SRF observation continued by investigating the effect of different rapid mixing times on the SRF test. In the previous results with CST, turbidity and floc size followed a similar trend, with no significant impact of different rapid mixing times on these factors. Table 32 and Figure 37 present the effect of different mixer shapes and different rapid mixing times on SRF values.

Table 32. Descriptive statistic of SRF value in responding different mixer shapes (rapid mixing time)

Mixer	Parameter	SRF value
Radial	mean	390.90
	min	372.81
	max	422.63
	std	18.93
Axial	mean	13.09
	min	12.60
	max	13.93
	std	0.42
Wheel	mean	178.15
	min	157.99
	max	206.13
	std	15.79
Magnetic	mean	22.44
	min	20.66
	max	26.05
	std	1.53
3-blades	mean	104.72
	min	99.65
	max	113.97
	std	4.60

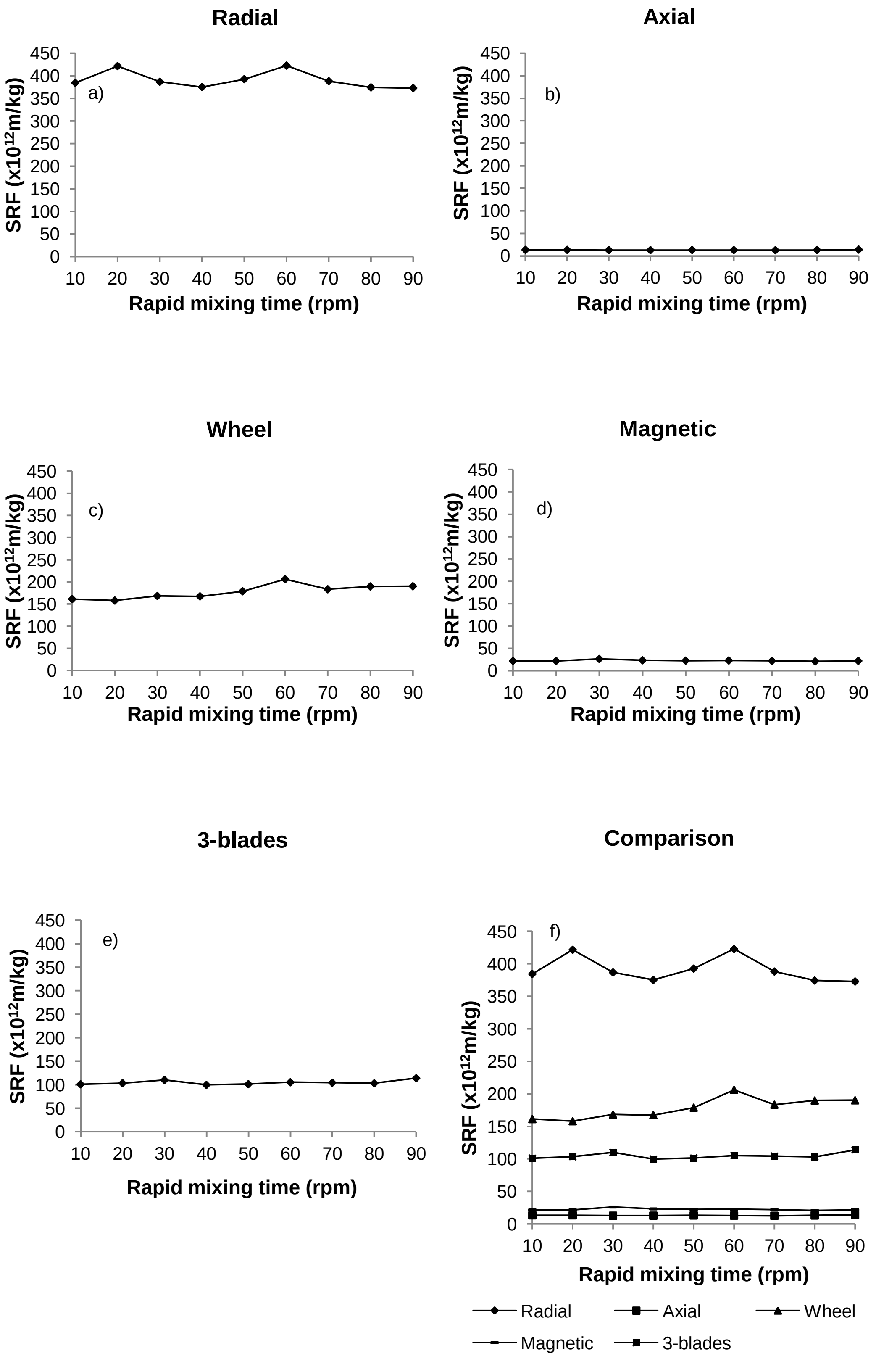


Figure 37. The effect of mixer shape and rapid mixing time on SRF value

Table 33. Coefficient of correlation for rapid mixing time and SRF using synthetic domestic wastewater

Mixer Shape	Parameter	r
Radial	Time & SRF	-0.33
Axial	Time & SRF	-0.14
Wheel	Time & SRF	0.81
Magnetic	Time & SRF	-0.33
3-blade	Time & SRF	0.44

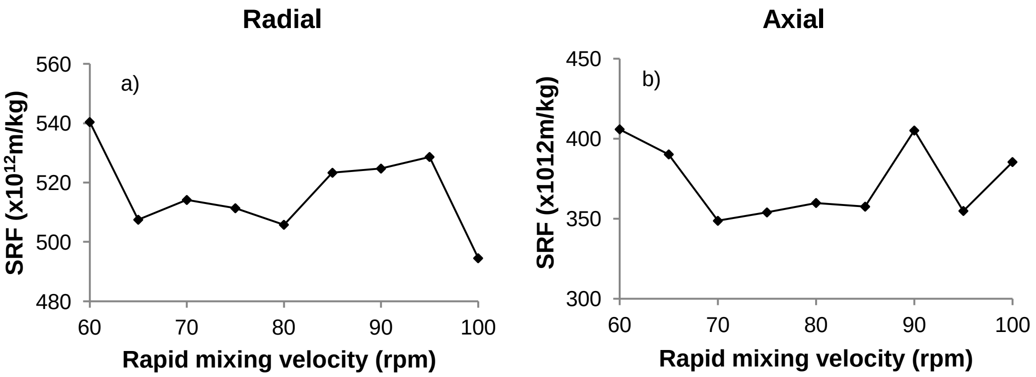
Figure 37 shows that different mixers yield different SRF results. The radial mixer produced the lowest SRF, and the wheel mixer the highest. Different rapid mixing times, except for the wheel impeller, had no significant impact on the SRF value. This observation is aligned with those from the CST experiments, turbidity and floc size investigations, that rapid mixing time does not have a significant impact on sludge dewaterability.

6.3.3 Alum as a Coagulant

Alum was used as a coagulant with different shapes of mixer, different rapid mixing velocities and the synthetic raw water sample. The purpose of this part of the study was to investigate the effect of choice of coagulant on sludge dewaterability as measured by the SRF. As part of this investigation, other process variables were also considered, including mixer shape, mixing velocity and water sample composition. Table 34 and Figure 38 show the results of these investigations.

Table 34. Descriptive statistic of SRF value in responding different mixer shapes

Mixer	Parameter	SRF value
Radial	mean	518.24
	min	496.18
	max	540.39
	std	13.55
Axial	mean	373.44
	min	348.65
	max	405.81
	std	23.06
Wheel	mean	197.68
	min	181.77
	max	225.13
	std	12.31
Magnetic	mean	25.39
	min	24.26
	max	27.33
	std	0.96
3-blades	mean	236.29
	min	0.32
	max	540.39
	std	188.96



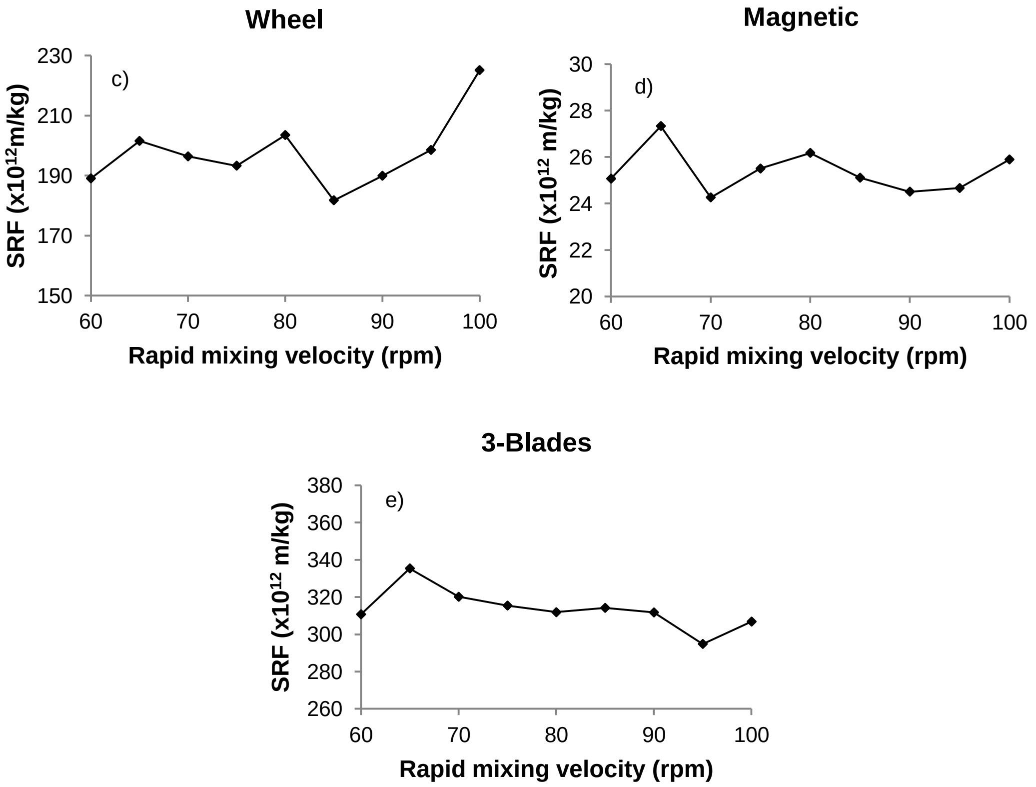


Figure 38. Relationship between coagulant, mixer shape and rapid mixing velocity on SRF value

Table 35. Coefficient of correlation between rapid mixing velocity and SRF

Mixer Shape	Parameter	r
Radial	Velocity & SRF	-0.27
Axial	Velocity & SRF	-0.14
Wheel	Velocity & SRF	0.41
Magnetic	Velocity & SRF	-0.21
3-blades	Velocity & SRF	-0.65

Different rapid mixing velocities while using different mixer shapes exhibited fluctuating trends, similar to those produced from the CST, turbidity and floc size investigations presented earlier. There was a similar response to changes in the rapid mixing velocity for four of the mixers, the radial, axial, wheel, and magnetic. The coefficient of correlation between rapid mixing velocity and SRF (Table 35) are similar to previous results, that rapid mixing velocity does not have a beneficial impact on the SRF value.

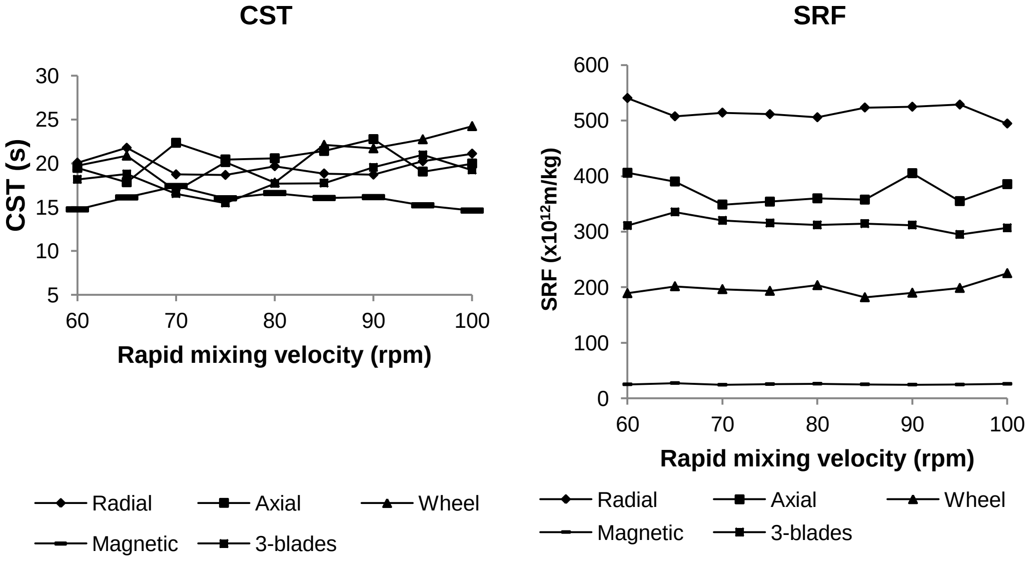


Figure 39. Comparison of CST and SRF results

Table 36. Coefficient of correlation for rapid mixing velocity and SRF

Mixer Shape	Parameter	r
Radial	CST & SRF	-0.33
Axial	CST & SRF	-0.16
Wheel	CST & SRF	0.29
Magnetic	CST & SRF	-0.11
3-blades	CST & SRF	-0.45

The coefficient of correlation between CST and SRF results shows a poor association, with the exception of the 3-blades results. This supports the contention that CST and SRF are not related for certain water treatment process variables.

6.4 Comparison of Different Coagulants on CST and SRF value

Ferric, alum and *Moringa oleifera* were compared in this stage of the investigation, using the magnetic stirrer to examine the influence of different coagulants on sludge dewaterability in terms of the SRF. The results are presented in Figure 40.

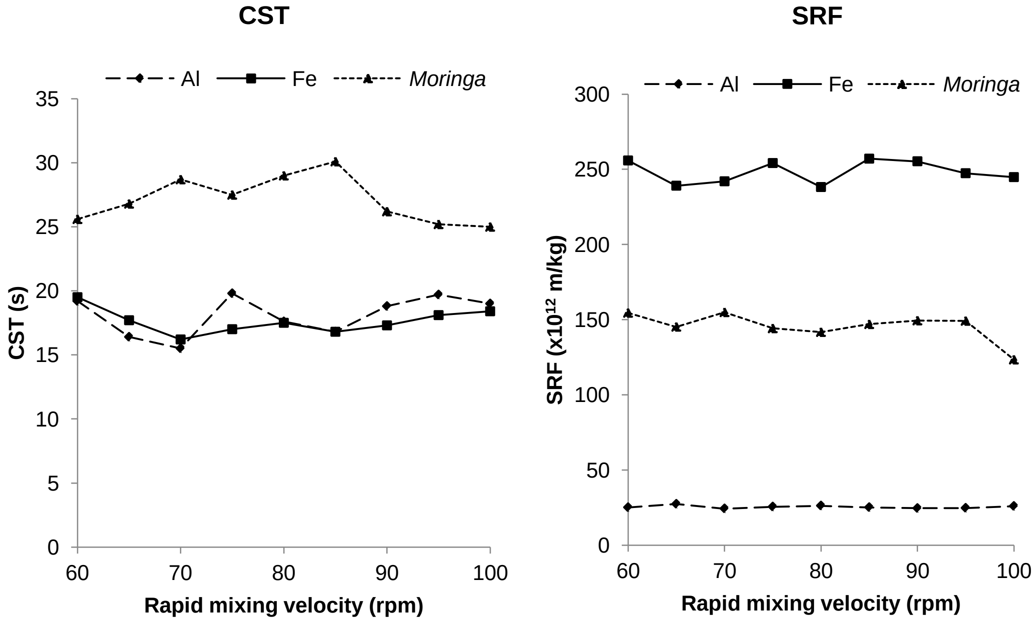


Figure 40. Influence of coagulant on SRF value

Figure 40 indicates that different coagulants have different influence on the SRF test. Alum produced the lowest SRF values, followed by *Moringa oleifera* and then ferric. This result contradicts the CST results in which ferric produced the lowest CST values followed by alum and *Moringa*. Again, this suggests that the CST and SRF tests do not appear to correlate well when different coagulants are used.

6.5 Influence of Temperature

6.5.1 The Effect of Temperature on the SRF value

It was shown previously that changing the water sample composition, rapid mixing velocity and rapid mixing time produces different trends in terms of the performance of different mixers at a constant temperature of 20ºC. Each of these parameters had a different effect on the test results. Results of exploring further the effect of different shapes of mixer at a different constant temperature (26ºC) using SRF are presented in Figure 41.

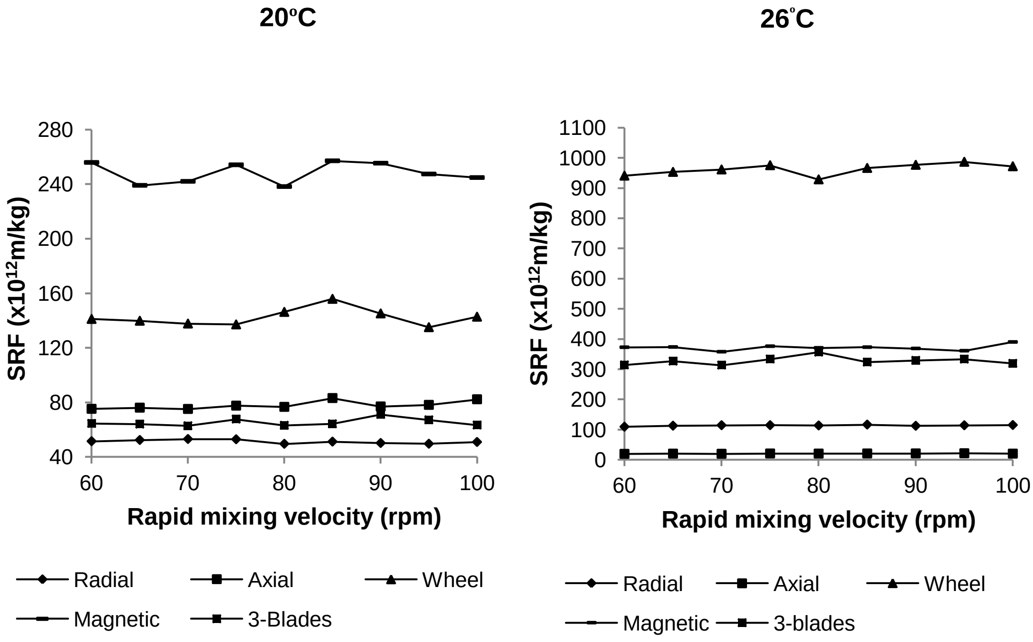


Figure 41. The effect of temperature on mixer performance using the SRF

The increase in temperature produced a different trend in the results, compared with previous test results. In the previous result, the radial mixer produced the lowest SRF value and the magnetic mixer the highest. As with previous experimental results, SRF appears to be insensitive to rapid mixing velocity.

6.5.2 Comparison of temperature effects on CST and SRF value

From the experimental work presented earlier, it appears that the effectiveness of the coagulant ferric as part of the water treatment process is unaffected by the operating temperature. This conclusion is based on the experiments using CST. When using SRF, however, a different conclusion was reached. This is illustrated in Figure 42, in which the SRF results are presented for the coagulant ferric at three different operating temperatures. It is clear that when using SRF as a measure of sludge dewaterability, temperature does affect the performance of the coagulant ferric in the treatment process.

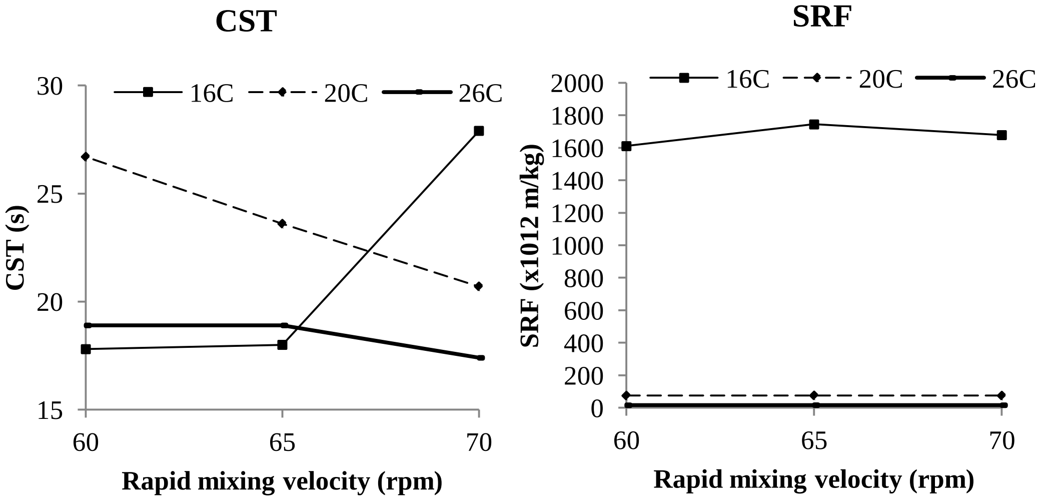
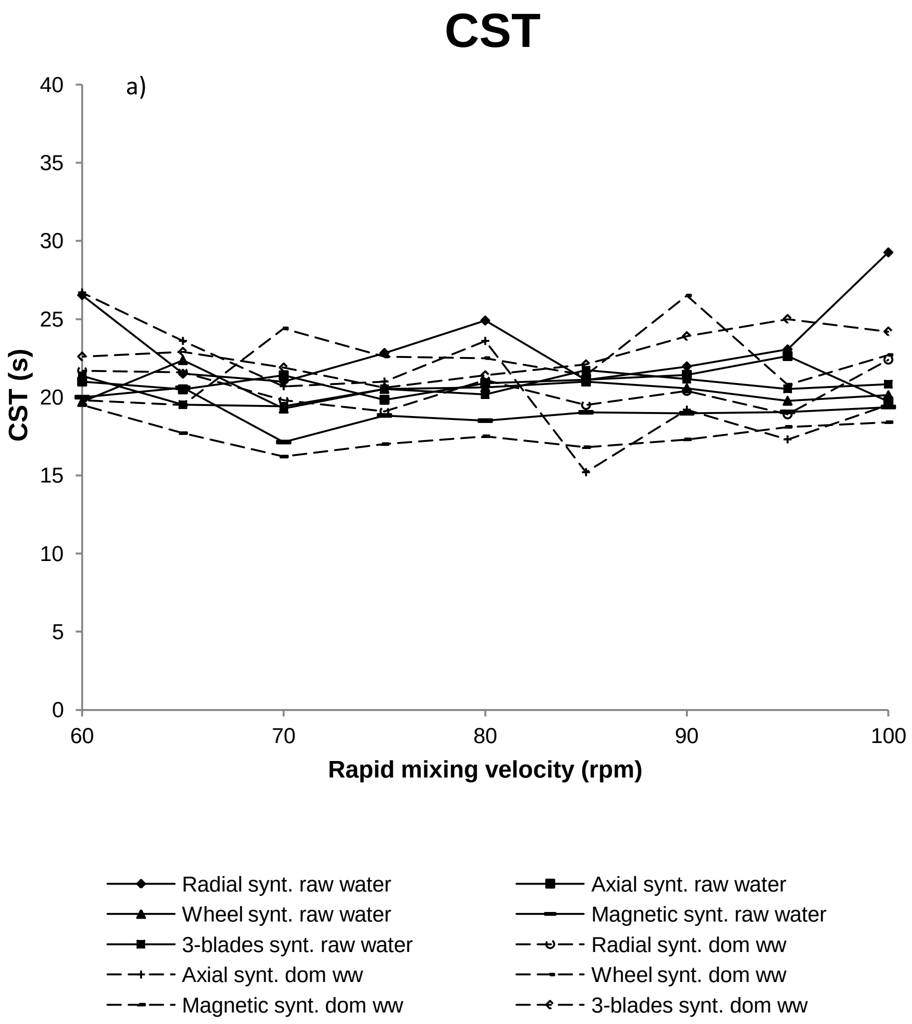


Figure 42. Influence of temperature on SRF value using ferric

Linear correlation between temperature and the SRF value is probably due to the effect of the negative pressure in SRF testing. Unlike CST, which uses positive (atmospheric) pressure, SRF uses constant negative (vacuum) pressure. From this result, it seems that the effect of temperature is more apparent when using negative pressure. The higher temperature reduces the sludge viscosity and makes it easier for the sludge to release water under the influence of negative pressure. This does not happen when using positive pressure. This result and hypothesis need further investigation to ensure their validity.

6.6 The Influence of water composition on SRF value

The CST results for raw water and wastewater indicated that sludge dewaterability is unaffected by water composition. In contrast, the floc size investigation revealed that the wastewater had larger particle sizes than the raw water. According to the floc size investigation, the CST value of domestic wastewater should be lower than the CST value of raw water. To verify or contradict these results, SRF was used with different water samples. The results are presented in Figure 43.


CST
a)
40
35
30
25
20
15
10
5
0
CST (s)
60
70
80
90
100
Rapid mixing velocity (rpm)
Radial synt. raw water
Axial synt. raw water
Wheel synt. raw water
Magnetic synt. raw water
3-blades synt. raw water
Radial synt. dom ww
Axial synt. dom ww
Wheel synt. dom ww
Magnetic synt. dom ww
3-blades synt. dom ww

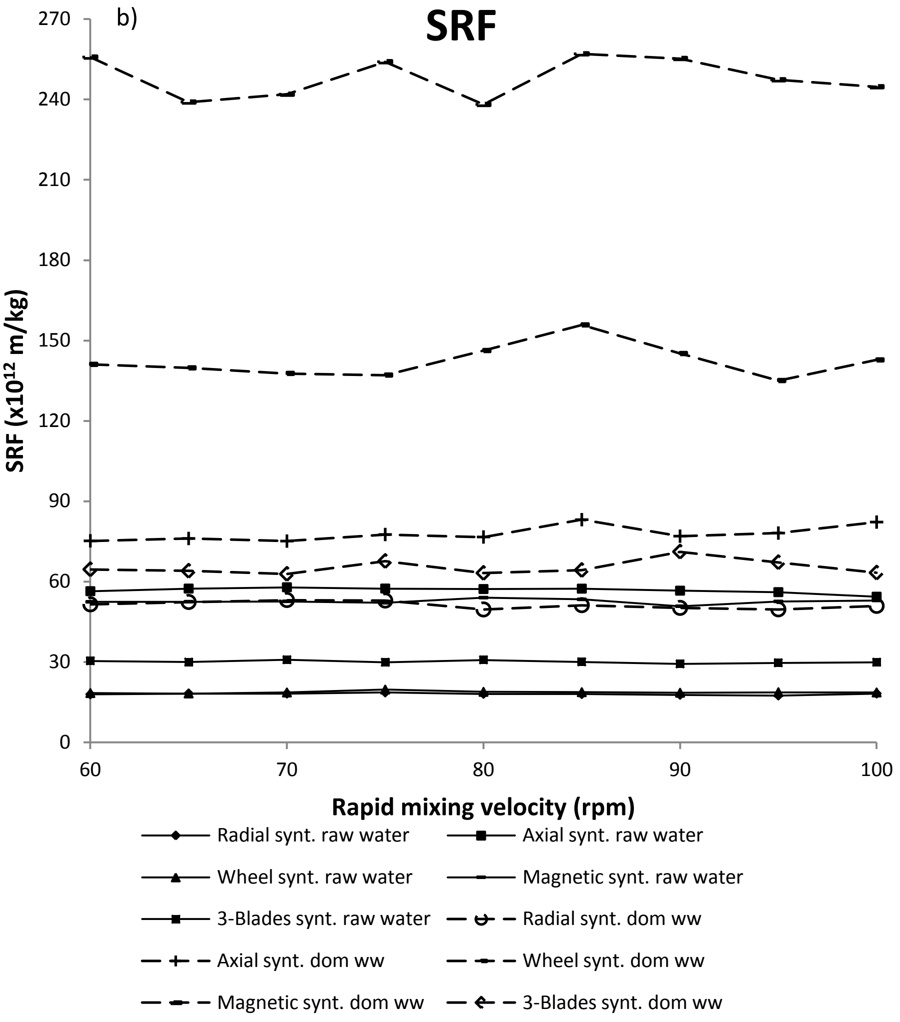


Figure 43. Influence of water composition on CST and SRF results

The SRF results indicate that synthetic raw water is in general more readily dewatered than synthetic domestic wastewater. The comparison shows different trends from the CST results; with CST, these two recipes do not produce a significant variation in the degree of sludge dewaterability. Again, the results of the test with water composition confirm that the CST and SRF results are poorly correlated, influenced by the factors under consideration.

6.7 Correlation between CST and SRF results

It is evident that the CST and SRF results are interrelated for some factors, but are not correlated or are poorly correlated for others. SRF and CST results agree that the gradually increasing rapid mixing velocity and rapid mixing time are not beneficial to sludge dewaterability.

In the case of the effect of different mixer shape, coagulant, temperature and different water sample composition, the comparison of the results of the CST and SRF tests show distinctive trends. Investigating the different shapes of mixer the CST results show that only the magnetic stirrer has a different impact on sludge dewaterability; the other mixers have a similar degree of influence to each other. The SRF results show that the influence of each mixer shape on the sludge dewaterability varies or inconsistent to CST, turbidity and floc size values.

The CST test results indicated that ferric was the most effective coagulant with the lowest sludge dewaterability, followed by alum and *Moringa oleifera*, where alum and *Moringa oleifera* had a similar influence to each other. In contrast, using the SRF test, alum appears to be the most effective coagulant, followed by *Moringa oleifera* and ferric. In addition, the CST test results were unaffected by temperature when using the coagulant ferric. However, the SRF test indicates that temperature does influence sludge dewaterability. The SRF results correlate well with temperature change, where a lower temperature produced a higher SRF value, and a higher temperature produced a lower SRF value.

From the results of the experimental work, it appears that for mixer shape, coagulant, temperature and water composition, the correlation between CST and SRF is poor. There has been limited work investigating the relationship between

CST and SRF which compare about different materials i.e mixer shapes, rapid mixing velocity and time, coagulants and temperature. Investigations by Smollen (1986), Chang et al. (2001), Lee and Liu (2001) also found that CST and SRF are not correlated in responding to different water and polymer compositions. The relationship between these two tests is undoubtedly influenced by the difference in test equipment and the difference in test methodology (Chang et al., 2001; Lee & Liu, 2001).

The overall study outcome is supported by Smollen (1986), Chang et al. (2001) and Lee and Liu (2001), who also found that CST and SRF do not correlate well for different water and polymer compositions. This has been explained by the differences in test equipment and methodology (Chang et al., 2001; Lee and Liu, 2001).

Lee and Liu (2001) observed that the difference in results between CST and SRF can be directly linked to the different pressures adopted in their respective tests. All CST tests are carried out at atmospheric pressure and SRF tests at negative pressure of 80 kPa.

The processes immediately before measuring the sludge dewaterability by CST and SRF also differ. Before measuring with the CST equipment, the floc settles and is then separated from the supernatant. Thus, only separated sludge was measured for its dewaterability. Concerning SRF, the full solution is used for dewaterability measurement.

The CST operation only requires the sludge to be poured into a funnel. A filter paper subsequently filters the sludge and drains off the water. In comparison, when applying the SRF test, the sludge is poured into a Buchner funnel in which the filter paper has been placed, and a vacuum suction is then applied to facilitate the filtration process. The SRF value is a function of the vacuum filtration pressure intensity, the area of the filter paper, the slope of the curve relating volume of filtrate and filtration time, filtrate volume, filtered weight, and filtrate viscosity. The SRF test considers not only water running time but also many other parameters which influence the result.

Concerning process complexity, the CST test is more stable than the SRF apparatus in responding to variability in the coagulation process. The CST value is a function of the filter paper properties (depth and thickness), instrument characteristics (diameter of the open part of the solar and sensor location) and sludge-related properties (solid concentration, filtrate viscosity, sludge cake permeability and deposit cake thickness) according to Sanin et al. (2011). The equipment and measurement procedure are simpler than those for SRF (Scholz, 2005; Peng et al., 2011). The CST time requirement is simply the time to flow through the filter between two electrodes (Scholz, 2005).

Despite many investigations showing that the CST and SRF are inter-related (e.g. Scholz, 2005; Sawalha, 2010, Sawalha & Scholz, 2010), this investigation found that the CST and SRF are inter-related for some parameters, but are not related for all the water treatment process variables.

Relating to the floc size and turbidity, it seems that CST is more favourable for measuring sludge dewaterability than SRF. The CST value has been verified by floc size and turbidity results. CST is also quicker to measure, easier to operate and cheaper than SRF. Other worker also said the same thing that CST provides a simple, rapid and inexpensive method to measure sludge dewaterability (Scholz 2005, 2006). In contrast, SRF test is a more difficult to execute, time consuming, and expensive test and no specific standard device to measure the SRF is available (Ayol and Dentel, 2005; Li et al, 2005; Teoh et al, 2006 and Yukseler et al, 2007).

6.8 Summary

Different parameters were used in this investigation. Different shapes of mixer, different coagulants, different temperatures and different water composition had different effects on sludge dewaterability. The influence of these different parameters was not constant, especially for mixer shape. If other parameters are changed, the effect of different mixer shapes also changes. So, no conclusion can be reached about the comparison of different mixer shapes in sludge dewaterability. The trend of rapid mixing velocity and rapid mixing time are constants and the former has a more significant impact on sludge dewaterability than the latter.

In using rapid mixing velocity and rapid mixing times as the process variable, the CST and SRF test results can be correlated. When using different mixer shapes, different coagulants, different temperatures, the coagulant ferric and different water sample compositions, the CST and SRF test results are not well correlated. This is probably because of differences in test procedures and equipment. CST is more appropriate to measure sludge dewaterability because it has more stable results, and is quicker, easier and cheaper than the SRF apparatus.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

In this final chapter, the conclusions are directly aligned with the objectives presented in Chapter 1, and are explained in accordance with the results of the literature review and the experimental research. This chapter discusses the conclusions relating to:

- The influence of mixer shape on sludge dewaterability
- The influence of rapid mixing velocity on sludge dewaterability
- The influence of rapid mixing times on sludge dewaterability
- The influence of types of coagulant on sludge dewaterability
- The influence of temperature on sludge dewaterability
- The influence of water composition on sludge dewaterability.

Some recommendations for further study are also identified and presented within this chapter.

7.2 The Influence of Different Shapes of Mixer on Sludge Dewaterability

The CST investigation results show that of the five mixer shapes, the magnetic stirrer had the lowest CST value, indicating that this mixer has both the greatest influence on sludge dewaterability and the only distinctive results. This is because the magnetic stirrer produces the optimum G value for floc formation.

The turbidity meter and the particle size indicate similar trends with CST value. These three tests indicated that the magnetic stirrer is the most effective in terms of sludge dewaterability, producing the lowest turbidity value and the largest floc size. The SRF test results, unlike the CST test results, showed that all five shapes of mixer produced different degrees of sludge dewaterability; at the same time, the magnetic stirrer did not yield the lowest SRF value. This investigation reveals that the CST results correlate well with the results from the turbidity meter and the particle size analyzer, but showed poor correlation with the SRF test results because of the different equipment and different procedures.

7.3 The Influence of Different Rapid Mixing Velocity on Sludge Dewaterability

Rapid mixing velocity itself plays an essential role in CST values, but different velocities do not have a significant impact, as confirmed by the coefficient of correlation. This means that low rapid mixing velocity is sufficient to decrease sludge dewaterability. The floc size, turbidity and SRF results compare favourably with the CST results, so that the CST, floc size, turbidity and the SRF values are inter-related in terms of rapid mixing velocity .

7.4 The Influence of Different Rapid Mixing Times on Sludge Dewaterability

In general, rapid mixing time is significant for the CST value, although this increasing does not have a significant impact on the CST test results; this is supported by the turbidity and floc size analysis. Again, the coefficient of correlation confirms this observation. It is plausible that there is an optimum time for the coagulation process, beyond which the rapid mixing time is largely irrelevant to the process. Based on the results of the CST, turbidity meter and particle size analyzer, a relatively short rapid mixing time might be sufficient to produce contact between the coagulant and the colloidal material. This investigation reveals, therefore, that there is no difference between the extended and shorter rapid mixing times. The SRF results indicate the same trend as the CST results, suggesting that for rapid mixing time, CST and SRF are related. This is due to using the same preparatory sludge methodology for both CST and SRF.

7.5 The Influence of Different Coagulants on Sludge Dewaterability

The coagulants alum, ferric and *Moringa oleifera* had different effects on the CST test results, the effect of alum and ferric being similar to each other. Alum and ferric have the lowest CST value, while *Moringa oleifera* produced the highest when correlated with the rapid mixing velocity. When considering the rapid mixing time, CST values for the three different coagulants were consistent. Alum and ferric were affected more by rapid mixing velocity than by rapid mixing time; in contrast, *Moringa oleifera* was affected by rapid mixing time more than by rapid mixing velocity. The turbidity and median floc size data verified the CST test results. The coagulant ferric produced the lowest turbidity value and the largest median floc size, followed by alum and *Moringa oleifera*. The SRF test results indicate that alum was the most effective coagulant, followed by *Moringa oleifera* and ferric, in producing lower sludge dewaterability. This indicates that the CST and the SRF test results are not well correlated when using different coagulants as the test variable.

7.6 The Influence of Different Temperature on Sludge Dewaterability

A comparison of coagulant efficiency at different temperatures indicated that the performance of alum and *Moringa oleifera* was sensitive to temperature. Experimental results showed that higher temperatures produced lower CST values and vice versa. Changes in temperature with ferric as a coagulant produced consistent with CST test results, suggesting that ferric is insensitive to temperature.

The turbidity and median floc size data supported the CST result that the coagulants alum and *Moringa oleifera* are sensitive to temperature. The data also confirmed the relative insensitivity of ferric to temperature changes. However, the SRF test results indicated that the performance of the coagulant ferric was sensitive to temperature, 26℃ producing the lowest SRF test results, followed by 20℃ and 16℃. The results of these experiments indicate a lack of correlation between the SRF and CST tests.

7.7 The Influence of Different Water Sample Composition on Sludge Dewaterability

The synthetic raw water and the synthetic domestic wastewater samples resulted in almost the same the CST values. The turbidity and median floc size showed different trends in the CST values, being higher with synthetic raw water and lower with synthetic domestic wastewater. The SRF result was also different from the CST value, with the synthetic raw water producing the lowest sludge dewaterability. The use of different water composition thus yields an uncorrelated relationship between CST and SRF.

7.8 Recommendations

The magnetic stirrer produced the lowest CST and turbidity values, but the largest median size in this investigation. Along with optimum G value, only the magnetic stirrer had a different mixer position in the coagulation chamber compared to other mixer shapes. The mixer companies state that the mixer shapes work at specific heights from the bottom of coagulation chamber. As a result of this research, it is recommended that companies manufacturing industrial-scale mixers should consider those mixer types that best emulate the conditions produced by the magnetic stirrer. The coagulation process will therefore produce a better quality of treated water and, at the same time, improved sludge dewaterability.

For the treatment of high turbid water, it would be more effective and economic if a lower rapid mixing intensity were used in the coagulation process. This research has shown that low mixing intensity is sufficient to achieve appropriate coagulation and lower sludge dewaterability. Similarly, a short rapid mixing time is sufficient to produce appropriate contact between the coagulant and the colloid material. The role of rapid mixing velocity is more important than rapid mixing time, so that in designing the coagulation process, it should be given greater consideration.

The effectiveness of *Moringa oleifera* is influenced more by rapid mixing time than by rapid mixing velocity, unlike the coagulants alum and ferric which are affected more by rapid mixing velocity. *Moringa oleifera* should be allowed to have a longer time for the rapid mixing stage, because this investigation showed that this results in a lower CST value and better correlation.

If the temperature varies between 16°C and 26°C in water and wastewater treatment plants, it is more appropriate to use ferric as the coagulant, as this investigation has proven that ferric is hardly affected by temperature within this range.

The organic content in synthetic domestic wastewater decreases the dewaterability of the sludge. In order to increase the efficiency of the coagulation process and sludge dewaterability, it is necessary to introduce a preliminary treatment to remove or decrease the organic content from wastewater before continuing the coagulation process in water and wastewater treatment plants.

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Appendices

Appendix 1

List of research in Coagulation Mixing Area

No	Author and Title of Journal	Rapid Mixing Parameter										Conclusion
		Mixing Velocity		Mixing Time	Coagulants			Mixer Shape and Type	Tank Geometry	Based on Industry	Sludge Dewater-ability	
		Coagulation	Flocculation		Alum	Ferric	MO					
1	Black & Rice, 1933 "Formation of floc by aluminium sulfat"	√		√	√							Continuous stirring is necessary in the conduct of jar test which will check each other and give accurate data for plant operation
2	Leentvaar & Ywema, 1980 "Some dimensionless parameter of impeller power in coagulation-flocculation"	√						√	√			The removal of colloidal compounds at a given *G* value differs with the type of stirrer and vessel applied in square tanks
3	Amirtharajah and Mills, 1982 "Rapid mixing design for alum coagulation"	√			√							High-intensity rapid mixing does make a significant difference in the quality of the settled water produced only for a specific region of the alum stability diagram
4	McConnachie, 1989 " Turbulence intensity of mixing in relation to flocculation"		√		√			√				Turbulence intensity is shown to be an alternative measure of flocculation efficiency to velocity gradient or power input. A stirrer that extends throughout the volume of the reactor and has sharp-edged blades is shown to be more versatile than the other types.
5	Torres et.al, 1990 "Floc Structure and Growth Kinetics for Rapid Shear Coagulation	√		√								Analysis of the model suggests hydrodynamic interactions can be neglected in kinetics calculations and, further, that a sticky-floc attraction

	of Polystyrene Colloids”											suffices for our purposes.
6	Rossini et.al, 1990 “Optimization of the coagulation-flocculation treatment: Influenced of rapid mixing parameters”	√		√	√	√						Rapid mix time and velocity have a strong influence on coagulation results.
7	Mhaisalkar et.al, 1991 “Optimizing physical parameter of rapid mixing design for coagulation-flocculation on turbid water”	√	√	√	√				√			The physical parameters of rapid mix such as velocity gradient, duration of mixing and the container geometry have a great influence on the flocculation process and that their optimum combination is dependent on the turbidity of suspension
8	Clark & Flora, 1991 “Floc Restructuring in Varied Turbulent Mixing”		√		√							Floc properties did not vary monotonically with increasing breakup mixing intensity
9	M.R. Wiesner, 1992 “Kinetics of aggregate formation in rapid mix”	√			√							Mixing conditions in most full scale installations are likely to favor the formation of aggregate of precipitated coagulant particles that are sufficiently large for breakup and aggregate restructuring to control the size distribution of materials leaving the rapid mixing basin.
10	Muyibi & Evison, 1995 “Optimizing physical parameters affecting coagulation of turbid water with *moringa oleifera* seeds”	√	√				√					When *M. oleifera* was used in coagulating kaolin suspension, the following factors were found to be highly significant: the initial turbidity of the water and *M. oleifera* dose. So also were the interactions between initial turbidity and *M. oleifera* dosage, initial turbidity and rapid mix, initial turbidity and slow mix,*M. oleifera* dose and rapid mix, slow mix and time of slow mix.

11	Jiang & Logan, 1996 “Fractal dymensions of aggregates from shear devices”	√										The lack of correlation between fractal dimension and ionic strength in the paddle mixer is caused by the characteristics of aggregate restructuring or breakup and reaggregation into more dense aggregate from high shear rates
12	Spicer & Pratsinis, 1996 “ The effect of impeller type on floc size and structure during shear induced flocculation”		√					√				The steady state average floc size is shown to depend on the frequency of recirculation to the impeller zone and its characteristic velocity gradient
13	Torres et.al, 1997 “Coagulation-flocculation pretreatment of high-load chemical-pharmaceutical industry wastewater: mixing aspects”	√			√	√		√				It was shown that the selection of the right propeller for the coagulation and flocculation stages is crucial in determining the quality of the treated water, as well as the quantity and quality of the residual sludges generated in the process.
14	Hobbs & Muzzio, 1998 “Optimization of a static mixer using dynamical systems techniques”							√				Three geometric parameters of static produce different mixing efficiency
15	Biggs & Lant, 1999 “Activated sludge flocculation: on-line determination of floc size and the effect of shear”		√	√								The median floc size was found to increase until an equilibrium between therates of aggregation and breakage was reached. At this point, a steady-state floc size was maintained
16	McConnachie & Liu, 1999 “Design of baffled hydraulic channels for turbulence-induced flocculation”		√						√			Coagulation baffled influence the coagulation efficiency
17	Biggs & Lant, 1999 “activated sludge		√	√	√							The median floc size was found to increase until an equilibrium

	flocculation: on-line determination of floc size and the effect of shear”											between the rates of aggregation and breakage was reached. At this point, a steady-state floc size was maintained.
18	Rauline, et.al., 2000 “A comparative assessment of the performance of the kenics and smx static mixers”							√				Different shape of mixers produce different mixing efficiency
19	Kan & Pan, 2001 “Time requirement for rapid mixing in coagulation”	√			√							Different time in coagulation process give a significant impact on charge neutralization and sweep flocculation
20	Heyouni et.al. 2002 “Hydrodynamics and mass transfer in gas–liquid flow through static mixers”							√				Different hydrodynamics and mass transfer of a static mixer with different arrangements of mixers inside the contactor produce different pressure drop, bubble diameters and mass transfer coefficient
21	Schuetz & Piesche, 2002 “A model of the coagulation process with solid particles in a turbulent flow “	√										For the steady state the results represent different floc size distributions dependent on the solid concentration and the energy charge.
22	Chakraborti et.al, 2003 “Changes in fractal dimension during aggregation”	√	√	√	√							For aggregation of an initially monodisperse suspension, the fractal dimension was found to decrease over time in the initial stages of floc formation
23	Park et.al, 2003 “ Examining the effect of hydraulic turbulence in rapid mixer on turbidity	√			√				√			In most effective turbidity removal, non-identical impeller rotating speeds and G values in different shapes of jar has been found as the most important factor

	removal with CFD simulation and PIV analysis”											
24	Niamnuy & Devahastin, 2003 “Effects of geometry and operating conditions on the mixing behavior of an in-line impinging stream mixer”	√						√				Mixer geometry and rapid mixing intensity affect the mixing efficiency
25	Yukselen & Gregory, 2004 “The effect of rapid mixing on the break-up and re-formation of flocs”	√		√	√							For the aluminium-based coagulants it was found that, with shorter times of rapid mix, larger flocs were formed, but only limited re-growth occurred in all cases, indicating a significant irreversibility of the floc break-up process. For cationic polyelectrolytes, the re-growth of flocs occurred to a much greater extent and with longer rapid mix times floc breakage was almost fully reversible
26	Yukselen & Gregory, 2004 “The reversibility of floc breakage”	√		√								Floc strength and recovery factors were found to decrease with increased breakage time for most of the coagulants tested. It was also found that the floc size tends to a nearly constant value after an initial abrupt fragmentation, with only a very slow size reduction over several minutes
27	Coufort et.al, 2005 “Flocculation related to local hydrodynamics in a Taylor–Couette reactor and in a jar”	√	√						√			The floc size distributions obtained at the end of each stage are different even though the hydrodynamic conditions are identical. The strong influence of the initial population conditions (elementary particles or flocs formed during break-up stages) is highlighted.

28	Colomer et.al, 2005 “Experimental analysis of coagulation of particles under low-shear flow”	√		√								shear provided a means to keep the particle number count high for collisions to occur but it is small enough that the aggregation–breakup balance is dominated by aggregation
29	Bouyer et.al, 2005 “Experimental analysis of floc size distributions in a 1-L jar under different hydrodynamics and physicochemical conditions”	√		√	√							floc size depends on the history of hydrodynamics conditions experienced by the flocs
30	Regner, et.al., 2006 “Effects of geometry and flowrate on secondary flow and the mixing process in static mixers—A numerical study”							√				Different shape of mixers produce different mixing intensity
31	Kilander et. al, 2007 “Scale-upbeha viour in stirred square flocculation tanks”		√		√				√			The floc structure,strength and thus the temporal and spatial evolution of thefloc size distribution are inherently affected by the flocculation mechanisms present in the system.
32	Cheng et.al, 2008 “A novel method for on-line evaluation of floc size in coagulation process”	√	√	√								Shorter slow mixing time did not favor the formation of flocs
33	Xiao et.al, 2008 “Effects of low temperature on coagulation of kaolinite suspensions”	√	√	√	√							A greater mixing intensity (38s^{-1}) was not able to increase the CR anymore, but slightly increased the residual turbidity. The appropriate slow-mixing (flocculation) time can counterbalance the slowness of slow coagulation at low temperature
34	Serra et.al, 2008 “Efficiency of different		√									an increase in the shear rate caused a reduction in the mean particle size

	shear devices on flocculation”											
35	Ormeci & Ahmad, 2009 “Measurement of additional shear during sludge conditioning and dewatering”	√		√							√	When the mixing speed used was higher, it took shorter timesto deflocculate the contaminant. and due to the low mixing intensity, the sample was not fully disintegrated even after the extended time of mixing
36	Meroney & Colorado, 2009 “CFD simulation of mechanical draft tube mixing in anaerobic digester tanks	√							√			It was noted that tank mixing may deviate from ideal behavior for a variety of reasons associated with placement of inlets,outlets, stratification, and tank geometry
37	Sawalha, 2010 “ CST: Developments in testing methodology and reliability of results”										√	Sufficient mixing is needed to increase sludge dewatering
38	Rojas et.al, 2010 “Influence of velocity gradient in a hydraulic flocculator on NOM removal by aerated spiral-wound ultrafiltration membranes (ASWUF)”		√			√						a suitable adjustment of the velocity gradient applied in the hydraulic flocculation can create an optimum floc size, permitting an improvement in NOM removal yields without exacerbating problems of membrane clogging
39	Wang & Dentel, 2010 “The effect of polymer doses and extended mixing intensity on the geometric and rheological characteristics of conditioned anaerobic digested sludge (ADS)”	√	√								√	The results revealed that polymer doses had a distinct effect on the CST values of conditioned ADS, but that extended mixing intensity (EMI) did not show such effect at specific polymer dosage. Higher extended mixing intensities higher than 180rpm can lead to stronger shear and deflocculation occurrence

40	Wu, 2011 “CFD investigation of turbulence models for mechanical agitation of non-Newtonian fluids in anaerobic digesters”							√				Through comparing power and flow numbers for the PBT impeller obtained from computational fluid dynamics (CFD) with those from the lab specifications, the realizable ke3 and the standard keu models are found to be more appropriate than the other turbulence models
41	Yu et. al, 2011 “The role of mixing conditions on floc growth, breakage and regrowth”	√	√	√	√							Increasing the rapid mix time led to a decrease in the final floc size and the steady-state floc size decreased with increasing slow stirring rate
42	Zhan et.al, 2011 “Influence of velocity gradient on aluminum and iron floc property for NOM removal from low organic matter surfacewater by coagulation”	√			√							Different rapid mixing velocity produces different size and strength flocs

APPENDIX 2

Preliminary Testing Result

1. Optimum Coagulant Dosage

Table A1

Sample : synthetic raw water
Coagulant: alum

Dose (mg Al/l)	CST (s)
3.6	24.8
7.2	25.9
10.8	26.1
14.4	23.4
18.0	22.3
21.6	20.1
25.2	20.0
28.8	19.8

Table A2

Sample : synthetic raw water
Coagulant: ferric

Dose (mg Fe/l)	CST (s)
3.4	25.9
6.9	24.8
10.3	23.6
13.8	22.9
17.2	19.8
20.7	19.2
24.1	19.0
27.5	18.8

Table A3

Sample : synthetic raw water
Coagulant: Moringa Oleifera

Dose (mg MO/ml)	CST (s)
10	31.7
20	25.3
30	25.0
40	24.4
50	23.8
60	23.0
70	22.0
80	21.0
90	21.2
100	21.0

2. Optimum Rapid Mixing Velocity

Table B1

Sample : synthetic raw water

Coagulant : alum

Parameter : velocity

Mixer : radial

Mixing Velocity (rpm)	CST (s)	Mixing Velocity (rpm)	CST (s)
0	37.0	1050	18.5
100	17.2	1100	17.0
150	16.9	1150	16.1
200	17.0	1200	16.1
250	17.2	1250	17.8
300	17.7	1300	15.6
350	16.8	1350	17.2
400	17.4	1400	17.1
450	17.8	1450	17.1
500	15.8	1500	18.2
550	16.3	1550	16.2
600	17.1	1600	16.4
650	17.3	1650	16.5
700	15.9	1700	15.5
750	16.2	1750	17.0
800	17.4	1800	16.2
850	16.9	1850	15.3
900	16.1	1900	16.7
950	16.7	1950	16.2
1000	15.9	2000	16.2

Table B2

Sample : synthetic raw water

Coagulant : alum

Parameter : velocity

Mixer : axial

Mixing Velocity (rpm)	CST (s)	Mixing Velocity (rpm)	CST (s)
0	37.0	1050	28.4
100	24.0	1100	27.8
150	28.0	1150	26.5
200	28.3	1200	25.2
250	28.9	1250	23.9
300	30.3	1300	21.6
350	32.0	1350	20.2
400	32.0	1400	19.0
450	32.3	1450	16.4
500	32.6	1500	15.1
550	32.4	1550	16.2
600	32.2	1600	17.7
650	31.0	1650	17.4
700	30.7	1700	18.1
750	30.5	1750	18.2
800	30.6	1800	18.8
850	30.6	1850	17.6
900	29.7	1900	18.0
950	29.1	1950	17.6
1000	28.5	2000	18.1

Table B3

Sample : synthetic raw water
Coagulant : alum
Parameter : velocity
Mixer : wheel

Mixing Velocity (rpm)	CST (s)	Mixing Velocity (rpm)	CST (s)
0	39.85	1050	20.80
100	23.00	1100	20.90
150	20.00	1150	21.00
200	19.65	1200	21.05
250	19.25	1250	21.40
300	18.40	1300	21.40
350	18.60	1350	21.30
400	18.20	1400	21.00
450	18.10	1450	20.90
500	18.00	1500	20.80
550	18.40	1550	20.60
600	19.40	1600	20.80
650	20.05	1650	20.50
700	19.60	1700	20.50
750	19.50	1750	20.60
800	19.70	1800	20.60
850	19.40	1850	20.60
900	19.80	1900	20.60
950	20.00	1950	18.30
1000	20.20	2000	17.10

Table B4

Sample : synthetic raw water
Coagulant : alum
Parameter : velocity
Mixer : magnetic

Mixing Velocity (rpm)	CST (s)
0	37.0
100	19.3
150	23.3
200	25.2
250	25.5
300	25.9
350	26.1
400	28.6
450	31.9
500	19.8
550	20.4
600	20.9
650	21.2
700	22.2
750	24.0
800	26.0
850	27.0
900	28.0
950	23.7
1000	20.7
1050	20.2
1100	20.0
1150	19.7
1200	19.4

3. Optimum Rapid Mixing Time

Table C1

Sample : synthetic raw water
Coagulant : alum
Parameter : time
Mixer : radial

Mixing Time (s)	CST (s)
0	37.00
60	17.28
90	18.28
120	20.30
150	21.36
180	22.20
210	22.00
240	21.90
270	21.00
300	21.18
330	21.50
360	19.64
390	18.93
420	18.90
450	19.20
480	19.40
510	18.76
540	17.86
570	16.00
600	16.00

Table C2

Sample : synthetic raw water
Coagulant : alum
Parameter : time
Mixer : axial

Mixing Time (s)	CST (s)
0	37.00
60	24.02
90	18.44
120	18.36
150	16.40
180	16.92
210	17.20
240	17.24
270	17.30
300	18.40
330	19.44
360	21.60
390	22.20
420	21.30
450	21.66
480	20.44
510	19.77
540	19.40
570	17.78
600	16.73

Table C3

Sample : synthetic raw water
Coagulant : alum
Parameter : velocity
Mixer : magnetic

Mixing Time (s)	CST (s)
0	37.00
60	19.30
90	14.22
120	15.96
150	16.74
180	16.28
210	16.27
240	16.60
270	17.66
300	16.60
330	16.46
360	16.34
390	16.72
420	17.95
450	18.56
480	17.56
510	18.26
540	18.32
570	20.84
600	21.78

Table C4

Sample : synthetic raw water
Coagulant : alum
Parameter : time
Mixer : 3-blades

Mixing Time (s)	CST (s)
0	37.00
60	21.00
90	22.50
120	19.50
150	20.45
180	20.75
210	19.30
240	16.70
270	20.80
300	18.45
330	20.50
360	19.50
390	19.60
420	18.70
450	20.50
480	20.90
510	20.30
540	20.40
570	20.30
600	20.00

Primary Testing Result

1. CST Synthetic raw water

Table C5. The Influence of Mixer Shape, Rapid Mixing Velocity on CST (synthetic raw water)

Velocity (rpm)	CST Value (s)					Coagulant
	Radial	Axial	Wheel	Magnetic	3-blades	
0	37.00	37.00	37.00	37.00	37.00	Alum
60	24.00	23.50	28.50	22.60	21.23	
65	22.30	23.10	31.10	19.60	19.60	
70	22.80	20.90	23.00	17.40	21.73	
75	21.60	22.80	19.20	15.40	21.60	
80	19.83	25.60	22.80	18.20	24.10	
85	22.47	23.30	21.20	18.50	20.15	
90	21.23	22.40	20.10	19.00	20.50	
95	22.03	20.30	24.00	17.40	22.60	
100	22.67	24.70	20.90	15.10	20.25	
% removal	**40.26**	**37.95**	**36.69**	**50.99**	**42.41**	
0	39.85	39.85	39.85	39.85	39.85	Ferric
60	26.53	21.00	19.70	20.00	21.37	
65	21.50	20.50	22.37	20.60	19.53	
70	21.00	21.40	19.27	17.13	19.43	
75	22.83	19.83	20.53	18.83	20.53	
80	24.90	20.90	20.63	18.50	20.17	
85	21.10	21.13	21.00	19.03	21.73	
90	21.97	21.43	20.57	18.97	21.16	
95	23.06	22.63	19.77	19.06	20.53	
100	29.26	19.73	20.13	19.37	20.83	
% removal	**40.84**	**47.42**	**48.70**	**52.18**	**48.33**	
0	29.30	29.30	29.30	29.30	29.30	Moringa
60	30.87	30.27	32.76	24.26	32.37	
65	31.76	28.97	31.60	21.90	30.70	
70	28.67	28.80	30.70	22.60	32.07	
75	29.13	31.16	29.26	25.03	30.17	
80	30.57	33.17	32.70	23.80	33.73	
85	30.90	30.97	27.20	25.30	29.63	
90	30.27	31.80	32.73	25.73	29.33	
95	28.76	28.67	30.00	26.33	29.60	
100	29.70	27.17	29.87	23.60	30.97	
% removal	**-2.62**	**-2.76**	**-4.97**	**17.12**	**-5.63**	

Table C37. The impact of mixer shape, time and coagulant on CST value

Time (s)	CST Value (s)					Coagulant
	Radial	Axial	Wheel	Magnetic	3-blades	
0	37.00	37.00	37.00	37.00	37.00	Alum
10	26.80	23.00	25.20	18.60	23.70	
20	20.60	22.10	25.10	19.00	22.00	
30	20.60	23.00	21.00	17.30	21.30	
40	22.90	20.20	20.40	17.70	23.00	
50	22.70	20.20	19.80	16.70	20.30	
60	21.40	24.70	20.90	18.00	23.50	
70	20.80	24.00	20.50	17.20	23.20	
80	18.80	21.20	19.80	14.20	22.50	
90	18.28	18.44	19.00	16.30	21.00	
% removal	**42.07**	**40.88**	**42.43**	**53.45**	**39.78**	
0	39.85	39.85	39.85	39.85	39.85	Ferric
10	25.07	19.80	25.83	17.48	22.40	
20	21.50	20.33	23.53	19.03	23.40	
30	23.50	21.57	23.73	20.15	21.40	
40	21.93	21.43	23.43	18.97	20.57	
50	22.30	19.87	22.30	17.77	19.97	
60	22.30	21.57	19.87	18.10	20.80	
70	22.13	19.30	20.63	17.68	21.13	
80	22.13	21.47	19.40	19.73	20.93	
90	22.43	19.55	21.87	18.30	21.50	
% removal	**43.31**	**48.44**	**44.07**	**53.37**	**46.43**	
0	29.30	29.30	29.30	29.30	29.3	Moringa
10	22.47	27.17	26.50	14.93	25.03	
20	22.53	23.27	19.87	15.37	24.60	
30	26.70	22.50	19.90	16.07	19.37	
40	20.77	23.40	23.07	15.97	23.00	
50	23.00	22.93	20.53	15.10	20.10	
60	20.00	25.07	22.57	14.33	23.13	
70	21.40	22.47	25.07	14.77	25.67	
80	18.23	20.43	19.80	17.30	25.13	
90	22.03	25.40	22.03	15.23	26.93	
% removal	**25.24**	**19.36**	**24.40**	**47.26**	**19.24**	

Table C7. The influence of temperature on CST value (alum)

Velocity (rpm)	CST Value (s)					Temperature (°C)
	Radial	Axial	Wheel	Magnetic	3-blades	
0	37.00	37.00	37.00	37.00	37.00	20
60	24.00	23.50	28.50	22.60	21.23	
65	22.30	23.10	31.10	19.60	19.60	
70	22.80	20.90	23.00	17.40	21.73	
75	21.60	22.80	19.20	15.40	21.60	
80	19.83	25.60	22.80	18.20	24.10	
85	22.47	23.30	21.20	18.50	20.15	
90	21.23	22.40	20.10	19.00	20.50	
95	22.03	20.30	24.00	17.40	22.60	
100	22.67	24.70	20.90	15.10	20.25	
% removal	**40.26**	**37.95**	**36.69**	**50.99**	**42.41**	
0	24.05	24.05	24.05	24.05	24.05	26
60	16.80	16.90	14.75	15.85	17.00	
65	16.60	19.70	18.80	16.35	18.15	
70	16.60	21.20	19.40	17.10	18.25	
75	17.20	20.50	17.10	16.00	19.25	
80	15.00	21.10	20.90	14.00	18.70	
85	15.80	19.00	16.40	12.80	17.60	
90	17.90	19.30	20.80	14.50	18.80	
95	18.60	16.60	18.60	15.50	18.65	
100	20.10	15.40	15.00	16.10	19.10	
% removal	**28.57**	**21.59**	**25.27**	**36.15**	**23.53**	

Table C8. The influence of temperature on CST value (ferric).

Velocity (rpm)	CST Value (s)					Temperature (°C)
	Radial	Axial	Wheel	Magnetic	3-blades	
0	39.85	39.85	39.85	39.85	39.85	20
60	26.53	21.00	19.70	20.00	21.37	
65	21.50	20.50	22.37	20.60	19.53	
70	21.00	21.40	19.27	17.13	19.43	
75	22.83	19.83	20.53	18.83	20.53	
80	24.90	20.90	20.63	18.50	20.17	
85	21.10	21.13	21.00	19.03	21.73	
90	21.97	21.43	20.57	18.97	21.16	
95	23.06	22.63	19.77	19.06	20.53	
100	29.26	19.73	20.13	19.37	20.83	
% removal	**40.84**	**47.42**	**48.70**	**52.18**	**48.33**	
0	39.00	39.00	39.00	39.00	39.00	26
60	16.60	18.70	18.10	18.80	28.50	
65	17.00	22.20	22.30	20.80	21.20	
70	17.40	24.60	20.40	19.20	20.90	
75	22.60	21.00	19.70	18.00	18.90	
80	24.40	20.70	18.30	17.70	22.60	
85	20.50	19.60	19.00	17.80	19.40	
90	20.20	18.10	20.90	14.60	20.80	
95	21.90	24.50	16.90	19.30	21.40	
100	24.40	21.00	21.70	15.70	23.50	
% removal	**47.29**	**45.75**	**49.48**	**53.87**	**43.81**	

Table C9. The Influence of temperature on CST value (Moringa oleifera)

Velocity (rpm)	CST Value (s)					Temperature (℃)
	Radial	Axial	Wheel	Magnetic	3-blades	
0	29.30	29.30	29.30	29.30	29.30	20
60	30.87	30.27	32.76	24.26	32.37	
65	31.76	28.97	31.60	21.90	30.70	
70	28.67	28.80	30.70	22.60	32.07	
75	29.13	31.16	29.26	25.03	30.17	
80	30.57	33.17	32.70	23.80	33.73	
85	30.90	30.97	27.20	25.30	29.63	
90	30.27	31.80	32.73	25.73	29.33	
95	28.76	28.67	30.00	26.33	29.60	
100	29.70	27.17	29.87	23.60	30.97	
% removal	**-2.62**	**-2.76**	**-4.97**	**17.12**	**-5.63**	
0	25.00	25.00	25.00	25.00	25.00	26
60	24.40	24.50	21.70	11.20	23.70	
65	25.40	19.80	18.80	14.90	22.20	
70	22.90	23.80	23.40	16.30	25.10	
75	20.10	23.20	16.70	16.10	20.60	
80	22.20	25.50	25.00	13.80	19.20	
85	25.00	18.60	27.00	13.90	20.30	
90	21.50	21.60	23.00	15.40	17.70	
95	20.70	23.80	21.80	13.40	23.80	
100	18.10	23.30	19.50	15.20	23.20	
% removal	**10.97**	**9.28**	**12.48**	**42.13**	**12.97**	

2. CST Synthetic domestic wastewater

Table C10. Influence of mixer shape, velocity and coagulant on CST value.

Velocity (rpm)	CST Value (s)					Coagulant
	Radial	Axial	Wheel	Magnetic	3-blades	
0	18.30	18.30	18.30	18.30	18.30	Alum
60	20.07	19.47	19.73	14.73	18.17	
65	21.77	17.83	20.87	16.10	18.77	
70	18.73	22.33	16.83	17.40	16.53	
75	18.67	20.43	20.13	16.00	15.47	
80	19.67	20.57	17.80	16.60	17.70	
85	18.83	21.40	22.10	16.03	17.73	
90	18.70	22.75	21.70	16.13	19.53	
95	20.23	19.05	22.73	15.20	20.97	
100	21.10	19.97	24.23	14.60	19.23	
% removal	**-7.94**	**-11.59**	**-13.00**	**13.30**	**0.36**	
0	29.90	29.90	29.90	29.90	29.90	Ferric
60	21.70	26.70	19.80	19.50	22.60	
65	21.60	23.60	19.50	17.70	22.90	
70	19.80	20.70	24.40	16.20	21.90	
75	19.10	21.00	22.60	17.00	20.60	
80	21.10	23.60	22.50	17.50	21.40	
85	19.50	15.20	21.40	16.80	22.10	
90	20.40	19.20	26.50	17.30	23.90	
95	18.90	17.30	20.80	18.10	25.00	
100	22.40	19.50	22.70	18.40	24.20	
% removal	**31.43**	**30.58**	**25.60**	**41.09**	**23.96**	
0	23.23	23.23	23.23	23.23	23.23	Moringa
60	25.47	23.90	22.87	21.30	21.47	
65	23.60	24.37	22.77	21.50	24.07	
70	24.03	26.07	23.73	23.03	22.53	
75	24.73	26.87	24.83	23.20	24.20	
80	21.70	24.10	23.70	22.63	21.33	
85	26.80	24.00	25.47	25.23	19.80	
90	21.97	23.70	25.53	24.10	21.47	
95	25.87	24.53	24.60	23.67	22.00	
100	23.77	24.23	25.33	23.57	22.47	
% removal	**-4.24**	**-6.07**	**-4.66**	**0.40**	**4.65**	

Table C11. Influence of mixer shape, velocity and coagulant on turbidity.

Velocity	Turbidity (NTU)					Coagulant
(rpm)	Radial	Axial	Wheel	Magnetic	3-blades	
0	339.00	339.00	339.00	339.00	339.00	Alum
60	565.00	501.00	598.00	431.00	554.33	
65	541.33	506.33	489.00	429.33	530.00	
70	541.00	557.33	479.33	460.00	524.00	
75	549.00	519.00	505.00	441.33	519.67	
80	538.67	531.67	496.67	445.33	570.00	
85	552.33	509.67	539.00	450.00	547.00	
90	592.00	502.50	543.67	436.00	519.67	
95	742.67	641.50	501.67	427.67	560.00	
100	713.67	505.00	509.33	424.33	533.00	
% removal	**-74.88**	**-56.47**	**-52.79**	**-29.30**	**-59.21**	
0	486.00	486.00	486.00	486.00	486.00	Ferric
60	703.00	477.00	548.00	439.00	488.00	
65	663.00	467.00	605.00	481.00	451.00	
70	592.00	512.00	595.00	488.00	694.00	
75	595.00	621.00	541.00	417.00	728.00	
80	599.00	651.00	531.00	430.00	723.00	
85	542.00	686.00	545.00	458.00	677.00	
90	624.00	636.00	538.00	452.00	804.00	
95	571.00	673.00	511.00	471.00	741.00	
100	597.00	642.00	479.00	434.00	886.00	
% removal	**-0.25**	**-0.22**	**-0.11**	**0.06**	**-0.41**	
0	415.00	415.00	415.00	415.00	415.00	Moringa
60	412.00	424.33	446.33	377.00	471.00	
65	365.33	388.33	432.00	397.00	406.00	
70	370.67	395.33	428.00	407.33	411.67	
75	392.67	439.33	434.33	396.33	481.00	
80	358.00	381.33	398.33	353.67	405.33	
85	372.00	368.67	385.00	411.33	407.67	
90	371.67	415.00	431.67	362.67	454.33	
95	338.67	373.67	375.00	375.00	392.33	
100	328.33	372.33	422.67	332.00	394.67	
% removal	**11.39**	**4.73**	**-0.49**	**8.63**	**-2.38**	

3. Floc size

Table C12. The influence of mixer shape and rapid mixing velocity on CST value (synthetic raw water)

Velocity (rpm)	CST Values (s)			Coagulant
	Radial	Axial	Magnetic	
0	39.85	39.85	39.85	Ferric
60	26.53	21.00	20.00	
65	21.50	20.50	20.60	
70	21.00	21.40	17.13	
75	22.83	19.83	18.83	
80	24.90	20.90	18.50	
85	21.10	21.13	19.03	
90	21.97	21.43	18.97	
95	23.06	22.63	19.06	
100	29.26	19.73	19.37	

Table C13. The influence of mixer shape and rapid mixing velocity on floc sizes (synthetic raw water)

Velocity (rpm)	Median Flocs Sizes (µm)			Coagulant
	Radial	Axial	Magnetic	
0	5.98	5.42	5.98	Ferric
60	7.06	5.98	6.06	
65	5.68	5.17	5.04	
70	6.36	6.38	5.39	
75	6.23	7.29	5.80	
80	6.24	6.54	6.89	
85	6.99	7.53	7.20	
90	5.35	7.35	6.91	
95	5.48	7.51	9.50	
100	5.64	7.33	6.45	

Table C14. The influence of mixer shape and rapid mixing velocity on floc standard deviation (synthetic raw water)

Velocity (rpm)	Standard Deviation			Coagulant
	Radial	Axial	Magnetic	
0	0.71	9.10	0.71	Ferric
60	0.83	0.71	0.72	
65	0.66	0.59	0.56	
70	2.59	0.79	2.66	
75	2.61	4.98	4.79	
80	2.35	4.14	4.57	
85	1.41	0.95	2.18	
90	4.36	0.98	3.71	
95	2.81	1.02	1.67	
100	2.82	4.10	1.61	

The Influence of Different Mixer Shapes

Table D1

Sample : synthetic domestic wastewater
Coag: ferric
Mixer shape : radial

Rpm	CST (s)	Turbidity (NTU)	Floc size
0	29.9	486	5.4
60	21.7	703	9.1
65	21.6	663	5.7
70	19.8	592	9.1
75	19.1	595	10.8
80	21.1	599	7.3
85	19.5	542	9.4
90	20.4	624	7.2
95	18.9	571	9.0
100	22.4	597	8.4

Table D2

Sample : synthetic domestic wastewater
Coag: ferric
Mixer shape : axial

Rpm	CST (s)	Turbidity (NTU)	Floc size
0	29.9	486	5.4
60	26.7	477	7.7
65	23.6	467	12.6
70	20.7	512	8.6
75	21	621	8.1
80	23.6	651	8.1
85	15.2	686	11.0
90	19.2	636	11.7
95	17.3	673	11.9
100	19.5	642	10.5

Table D3

Sample : synthetic domestic wastewater
Coag: ferric
Mixer shape : wheel

Rpm	CST (s)	Turbidity (NTU)	Floc size
0	29.9	486	5.4
60	19.8	548	8.7
65	19.5	605	8.4
70	24.4	595	5.8
75	22.6	541	9.8
80	22.5	531	8.2
85	21.4	545	7.8
90	26.5	538	8.6
95	20.8	511	11.1
100	22.7	479	6.1

Table D4

Sample : synthetic domestic wastewater
Coag: ferric
Mixer shape : magnetic

Rpm	CST (s)	Turbidity (NTU)	Floc size
0	29.9	486	5.4
60	19.5	439	13.0
65	17.7	481	11.4
70	16.2	488	13.3
75	17	417	12.9
80	17.5	430	10.8
85	16.8	458	12.0
90	17.3	452	11.4
95	18.1	471	10.7
100	18.4	434	10.0

Table D5

Sample : synthetic domestic wastewater
Coag: ferric
Mixer shape : 3-Blades

Rpm	CST (s)	Turbidity (NTU)	Floc size
0	29.9	486	5.4
60	22.6	488	9.8
65	22.9	451	11.9
70	21.9	694	7.9
75	20.6	728	7.6
80	21.4	723	7.7
85	22.1	677	5.9
90	23.9	804	7.3
95	25	741	8.5
100	24.2	886	8.2

The Influence of Rapid Mixing Velocity and Time

Table E1

Sample : synthetic domestic wastewater
Coag: alum
Parameter : velocity
Mixer shape : magnetic

Rpm	CST (s)	Turbidity (NTU)	Floc size
0	29.9	486	5.4
60	25.6	1006	7.2
65	26.8	1011	4.2
70	28.7	1042	8.1
75	27.5	962	7.3
80	29.0	988	7.3
85	30.1	630	7.2
90	26.2	672	8.2
95	25.2	583	7.9
100	25.0	764	6.9

Table E2

Sample : synthetic domestic wastewater
Coag: alum
Parameter : time
Mixer shape : magnetic

Time (s)	CST (s)	Turbidity (NTU)	Floc size
0	29.9	486	5.4
10	23.5	557	7.9
20	22.3	566	7.3
30	23.7	471	8.7
40	24.0	655	8.8
50	27.2	966	8.9
60	28.2	843	8.8
70	24.4	558	8.9
80	25.1	665	9.3
90	24.9	629	8.6

Table F1

Sample : synthetic domestic wastewater
Coag: ferric
Parameter : velocity
Mixer shape : magnetic

Rpm	CST (s)	Turbidity (NTU)	Floc Size
0	29.9	486	5.4
60	19.5	439	13.0
65	17.7	481	11.4
70	16.2	488	13.2
75	17.0	417	12.9
80	17.5	430	10.8
85	16.8	458	11.9
90	17.3	452	11.3
95	18.1	471	10.7
100	18.4	434	10.0

Table F2

Sample : synthetic domestic wastewater
Coag: ferric
Parameter : time
Mixer shape : magnetic

Time (s)	CST (s)	Turbidity (NTU)	Floc Size
0	29.9	486	5.4
10	14.9	450	8.4
20	17.9	512	8.0
30	17.5	500	8.2
40	15.5	557	9.6
50	18.1	465	10.6
60	18.4	607	7.6
70	15.9	677	8.2
80	15.0	487	10.6
90	18.2	566	8.8

Table G1

Sample : synthetic domestic wastewater
Coag: Moringa oleifera
Parameter : velocity
Mixer shape : magnetic

Rpm	CST (s)	Turbidity (NTU)	Median
0	29.9	486	5.4
60	25.6	1006	7.2
65	26.8	1011	4.2
70	28.7	1042	8.1
75	27.5	962	7.3
80	29.0	988	7.3
85	30.1	630	7.2
90	26.2	672	8.2
95	25.2	583	7.9
100	25.0	764	6.9

Table G2

Sample : synthetic domestic wastewater
Coag: moringa
Parameter : time
Mixer shape : magnetic

Time (s)	CST (s)	Turbidity (NTU)	Floc Size
0	29.9	486	5.4
10	23.5	557	7.9
20	22.3	566	7.3
30	23.7	471	8.7
40	24.0	655	8.8
50	27.2	966	8.9
60	28.2	843	8.8
70	24.4	558	8.9
80	25.1	665	9.3
90	24.9	629	8.6

4. Specific Resistance to Filtration (Synthetic raw water)

Table H1

Specific Resistance to Filtration
Sample : synthetic raw water
Coagulant : ferric
Parameter : velocity
Mixer : radial

Rpm	SRF x10^{12} (m/kg)
0	40871.39
60	17.89
65	18.19
70	18.17
75	18.60
80	18.08
85	17.98
90	17.71
95	17.44
100	18.18

Table H2

Specific Resistance to Filtration
Sample : synthetic raw water
Coagulant : ferric
Parameter : velocity
Mixer : axial

Rpm	SRF x10^{12} (m/kg)
0	40871.39
60	56.39
65	57.37
70	57.85
75	57.38
80	57.19
85	57.34
90	56.58
95	56.03
100	54.33

Table H3

Specific Resistance to Filtration
Sample : synthetic raw water
Coagulant : ferric
Parameter : velocity
Mixer : wheel

Rpm	SRF x10^{12} (m/kg)
0	40871.39
60	18.35
65	18.20
70	18.57
75	19.65
80	18.80
85	18.68
90	18.47
95	18.67
100	18.58

Table H4

Specific Resistance to Filtration
Sample : synthetic raw water
Coagulant : ferric
Parameter : velocity
Mixer : magnetic

Rpm	SRF x10^{12} (m/kg)
0	40871.39
60	52.42
65	52.47
70	52.61
75	52.06
80	53.98
85	53.34
90	50.79
95	52.56
100	52.93

Table H5

Specific Resistance to Filtration
Sample : synthetic raw water
Coagulant : ferric
Parameter : velocity
Mixer : 3-blades

Rpm	**SRF x10^{12} (m/kg)**
0	40871.39
60	30.37
65	29.94
70	30.79
75	29.85
80	30.73
85	29.99
90	29.21
95	29.66
100	29.89

Specific Resistance to Filtration (Synthetic domestic wastewater)

Table I1

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : velocity
Mixer : radial

Rpm	**SRF x10^{12} (m/kg)**
0	40990.49
60	51.47
65	52.36
70	53.09
75	52.90
80	49.57
85	51.18
90	50.16
95	49.62
100	50.90

Table I2

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : velocity
Mixer : axial

Rpm	**SRF x10^{12} (m/kg)**
0	40908.67
60	75.18
65	76.07
70	75.10
75	77.55
80	76.63
85	83.09
90	76.94
95	78.09
100	82.19

Table I3

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : velocity
Mixer : wheel

Rpm	**SRF x10^{12} (m/kg)**
0	40908.67
60	141.08
65	139.77
70	137.70
75	137.08
80	146.24
85	155.81
90	145.12
95	135.04
100	142.74

Table I4

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : velocity
Mixer : magnetic

Rpm	SRF (x10^{12} m/kg)
0	40908.67
60	255.81
65	239.02
70	241.95
75	254.08
80	238.13
85	257.02
90	255.28
95	247.33
100	244.73

Table I5

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : velocity
Mixer : 3-blades

Rpm	SRF x10^{12} (m/kg)
0	40908.67
60	64.54
65	63.97
70	62.83
75	67.63
80	63.17
85	64.26
90	71.13
95	67.18
100	63.29

Specific Resistance to Filtration (time)

Table J1

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : time
Mixer : radial

Rapid Mixing Time (s)	SRF x10^{12} (m/kg)
0	40908.67
10	384.38
20	421.51
30	386.73
40	375.09
50	392.60
60	422.63
70	388.09
80	374.27
90	372.81

Table J2

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : time
Mixer : axial

Rapid Mixing Time (s)	SRF x10^{12} (m/kg)
0	40908.67
10	13.37
20	13.37
30	12.72
40	12.74
50	13.14
60	12.88
70	12.60
80	13.09
90	13.93

Table J3

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : time
Mixer : wheel

Rapid Mixing Time (s)	**SRF x10^{12} (m/kg)**
0	40908.67
10	161.27
20	157.99
30	168.31
40	167.38
50	178.91
60	206.13
70	183.45
80	189.79
90	190.15

Table J4

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : time
Mixer : magnetic

Rapid Mixing Time (s)	**SRF x10^{12} (m/kg)**
0	40908.67
10	21.64
20	21.66
30	26.05
40	23.16
50	22.39
60	22.72
70	21.93
80	20.66
90	21.75

Table J5

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : ferric
Parameter : time
Mixer : 3-blades

Rapid Mixing Time (s)	SRF x10^{12} (m/kg)
0	40908.67
10	101.09
20	103.51
30	110.12
40	99.65
50	101.36
60	105.31
70	104.29
80	103.17
90	113.97

Specific Resistance to Filtration (alum)

Table K1

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant : alum
Parameter : velocity
Mixer : radial

Rpm	SRF x10^{12} (m/kg)
0	40908.67
60	540.39
65	509.19
70	515.88
75	513.08
80	507.49
85	525.08
90	526.48
95	530.42
100	496.18

Table K2

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant :alum
Parameter : velocity
Mixer : axial

Rpm	SRF x10^{12} (m/kg)
0	40908.67
60	405.81
65	390.15
70	348.65
75	353.89
80	359.80
85	357.48
90	405.05
95	354.79
100	385.38

Table K3

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant :alum
Parameter : velocity
Mixer : wheel

Rpm	SRF x10^{12} (m/kg)
0	40908.67
60	189.06
65	201.54
70	196.39
75	193.29
80	203.50
85	181.77
90	189.93
95	198.54
100	225.13

Table K4

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant :alum
Parameter : velocity
Mixer : magnetic

Rpm	**SRF x10^{12} (m/kg)**
0	40908.67
60	25.07
65	27.33
70	24.26
75	25.50
80	26.17
85	25.11
90	24.51
95	24.66
100	25.89

Table K5

Specific Resistance to Filtration
Sample :synthetic domestic waste water
Coagulant :alum
Parameter : velocity
Mixer : 3-blades

Rpm	**SRF x10^{12} (m/kg)**
0	40908.67
60	310.75
65	335.40
70	320.16
75	315.44
80	311.87
85	314.20
90	311.75
95	294.84
100	306.84