UNIVERSITY OF NAIROBI
DEPARTMENT OF CIVIL ENGINEERING

Optimisation of Cost Effectiveness of Water Treatment Works:
Coagulation Processes

By: Marube Rose Kemunto, F16/41212/2011

A project submitted as a partial fulfilment for the requirement for the
award of the degree of

BACHELOR OF SCIENCE IN CIVIL ENGINEERING
2016
ABSTRACT

The process of coagulation and flocculation is one of the most important operations among the water purification process, but its effectiveness is determined by cost. The purpose of this study was to evaluate optimum conditions, effects of varying velocity gradients, times during coagulation and flocculation in water treatment to make the process cost effective. Optimum conditions include optimum pH and optimum coagulant dosage. Test water was obtained from Chiromo River during a dry season. The turbidity of raw water was found to be 46 NTU.

Coagulation and flocculation tests using jar test procedures were performed using aluminium sulphate (alum) to determine optimum pH, optimum dosage and mixing regime that would yield optimum removal of turbidity. Turbidity, colour, alkalinity and pH were measured before and after tests. The optimum pH was found by adjusting pH of jars using lime and same coagulant dose of 10 mg/l. Optimum pH was found to be 6.5. The optimum aluminium sulphate dose was found to be 39 mg/l. Tests to demonstrate effects of varying velocity gradients (for both flash and slow mixing speeds) and mixing time (for both flash and slow mixing times) were performed. Among the analytical parameters, turbidity gave the most reliable results as to the determination of efficient velocity gradients and mixing times. Tests indicated that results were successful in reducing colour and turbidity to suitable concentrations using relatively low levels of aluminium sulphate. The study enables cost reduction of coagulation process.
DEDICATION

To my parents Mr. and Mrs. Marube, for all the selfless love, prayer and support in my education, thank you so much.

To my brothers and sisters, your love and constant encouragement during the studies made my education at the university a success.

God bless you.
ACKNOWLEDGEMENTS
I wish to express my profound gratitude to Dr. P.K Ndiba for his guidance, ideas, moral support and encouragement for the success of this project. His objectivity and suggestions were helpful throughout the project period.

My sincere gratitude also goes to the laboratory technicians for providing me with necessary guidance and equipment to perform various tests in this project and for the endurance during all the laboratory experiments.

Above all, this project will not be complete without giving thanks and adoration to the Almighty God for his divine health provision and knowledge he has granted to me throughout my study at the University of Nairobi.
Table of Contents

ABSTRACT .................................................................................................................. i

DEDICATION ........................................................................................................... ii

ACKNOWLEDGEMENTS ......................................................................................... iii

Table of Contents ...................................................................................................... iv

LIST OF ABBREVIATIONS ...................................................................................... vi

LIST OF FIGURES ................................................................................................... vii

LIST OF TABLES ...................................................................................................... viii

CHAPTER ONE ........................................................................................................... 1

1 INTRODUCTION ..................................................................................................... 1

1.1 Background information ..................................................................................... 1

1.2 Problem statement .............................................................................................. 2

1.3 Objectives ............................................................................................................ 3

CHAPTER 2 .................................................................................................................. 4

2 LITERATURE REVIEW .......................................................................................... 4

2.1 Introduction .......................................................................................................... 4

2.2 Coagulation ......................................................................................................... 4

2.3 Scientific theories for coagulation ...................................................................... 6

2.4 Need for coagulation .......................................................................................... 7

2.5 Coagulant chemicals ......................................................................................... 8

2.6 Mechanism of coagulation ................................................................................ 13

2.7 Satisfactory dispersal ......................................................................................... 15

2.8 Coagulation and flocculation test ..................................................................... 16

2.9 Design of chemical mixing .............................................................................. 16

2.10 Factors affecting the process .......................................................................... 19
CHAPTER 3 .................................................................................................................. 21

3  METHODOLOGY ...................................................................................................... 21
   3.1  Introduction ......................................................................................................... 21
   3.2  Sampling of Water .............................................................................................. 21
   3.3  Jar tests ............................................................................................................... 21

CHAPTER 4 .................................................................................................................. 25

4  RESULTS AND DISCUSSION .................................................................................. 25
   4.1  Introduction ......................................................................................................... 25
   4.2  Optimum pH ....................................................................................................... 25
   4.3  Optimum alum dosage ...................................................................................... 26
   4.4  Effect of velocity gradients (mixing intensities) ............................................... 26
   4.5  Effect of time of flocculation ........................................................................... 28
   4.6  Sizing of flocculation tanks .............................................................................. 29

CHAPTER 5 .................................................................................................................. 30

5  CONCLUSION AND RECOMMENDATIONS ......................................................... 30
   5.1  Conclusion ......................................................................................................... 30
   5.2  Recommendations ........................................................................................... 31

REFERENCES ............................................................................................................. 32

APPENDICES ............................................................................................................... 33

APPENDIX 1: LABORATORY TEST PROCEDURES ....................................................... 34
APPENDIX 2: COAGULATION AND FLOCCULATION SHEETS ................................ 38
APPENDIX 3: FIGURES .............................................................................................. 41
**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBP</td>
<td>Disinfection by-products</td>
</tr>
<tr>
<td>EC</td>
<td>Enhanced coagulation</td>
</tr>
<tr>
<td>G</td>
<td>Velocity gradient value</td>
</tr>
<tr>
<td>NOM</td>
<td>Natural organic matter</td>
</tr>
<tr>
<td>NTU</td>
<td>Nephelometric turbidity unit</td>
</tr>
<tr>
<td>SCD</td>
<td>Streaming current detectors</td>
</tr>
<tr>
<td>TOC</td>
<td>Total organic carbon</td>
</tr>
<tr>
<td>TSS</td>
<td>Total suspended solids</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2.1: Schematic representation of water treatment process (www.aabergclaims.com)........ 4
Figure 2.3: Zeta potential (www.intechopen.com).......................................................... 7
Figure 2.4: Destabilization by charge neutralization (www.slideshare.net)....................... 10
Figure 2.5: Sludge lagoons for sludge disposal (William and Kawamura, 2008)............... 11
Figure 2.6: Rapid mixing and slow mixing (chemistry.wustl.edu)................................. 16
Figure 3.1: Sampling point on River Chiromo ................................................................. 21
Figure 3.2: Jar test apparatus ......................................................................................... 22
Figure 4.1: Graph of residual turbidity vs pH............................................................ 25
Figure 4.2: Graph of residual turbidity vs alum giving optimum alum dosage............. 26
Figure 4.3: Effects of rapid mixing intensity on removal of turbidity. 1 min mixing, 20 rpm slow mixing for 20 mins. Settle for 30 min............................................................. 27
Figure 4.4: Effects of slow mixing intensity on removal of turbidity. 120 rpm for 1 min and slow mixing for 20 min, settle for 30 min.......................................................... 28
Figure 4.5: Effects of varying slow mixing times on turbidity removal using jar test with 120 rpm for 1 min ad slow mixing speed of 20 rpm for 20 min. 30 mins settling time................. 29
Figure 10.1: researcher in the laboratory preparing for tests......................................... 41
Figure 10.2: Jar test apparatus ....................................................................................... 41
Figure 10.3: Floc formation during mixing ................................................................... 42
Figure 10.4: Settling of flocs after mixing ................................................................... 42
Figure 10.5: Researcher measuring color ...................................................................... 43
Figure 10.6: Researcher measuring turbidity ............................................................... 43
Figure 10.7: Researcher measuring pH......................................................................... 44
**LIST OF TABLES**

Table 5.1: Raw water parameters.................................................................................................................. 38
Table 5.2: Effect of pH using same coagulant dose to determine optimum pH .............................. 38
Table 5.3: Effect of alum dosage on same pH to determine optimum dosage ............................... 38
Table 5.4: Effects of varying rapid mixing intensity on turbidity removal, mixing time of 1 min, flocculation at 20 rpm for 20 min and 30 min settling time ............................................................ 39
Table 5.5: Effects of varying slow mixing intensity on turbidity removal, 120 rpm for 1 min, mixing time of 20 mins and 30 min settling time .................................................................................. 39
Table 5.6: Effect of flocculation mixing time on turbidity removal ....................................................... 40
CHAPTER ONE

1 INTRODUCTION

1.1 Background information

Surface water supplies contain organic and inorganic particles. Organic particles may include algae, bacteria and cysts of protozoa, oocysts, and detritus from vegetation that has fallen into the water. Erosion produces inorganic particles of clay, silt, and mineral oxides. Surface water will also include particulate and dissolved organic matter, collectively referred to as natural organic matter (NOM) that is a product of decay and leaching of organic detritus. NOM is important because it is a precursor to the formation of DBPs. Colloidal suspensions are stable and must be destabilised before it is possible to aggregate them into bigger floc particles that can be removed by sedimentation and filtration. Destabilisation is effected by coagulation, and aggregation by flocculation. Coagulation and flocculation are essential components of conventional water treatment systems that are designed to remove infectious agents, remove toxic compounds that have adsorbed to the surface of particles, remove precursors to the formation of disinfection by-products, and make the water palatable. (Water research commission, 2006)

The conventional water treatment plant consists of coagulation, flocculation, sedimentation, filtration and disinfection units. Depending on water quality influent, each unit can be optimized to achieve the desired water quality effluent, both in design and operation stages. A typical water treatment plant has the combination of processes needed to remove undesirable materials in the raw water. The presence of organic or mineral substances causes some problems in obtaining water quality. Understanding these phenomena requires taking into account the physical and chemical natures of the water to be treated. Optimization of conventional water treatment plant means “to attain the most efficient or effective use” of a water treatment plant regarding some principles: achievement of consistently high quality water on a continuous basis and the importance to focus on overall plant performance. The study focuses on the coagulation process to minimize the overall water treatment costs.

The object of coagulation (and subsequently flocculation) is to turn the small particles into larger particles called flocs, either as precipitates or suspended particles. The flocs are readily removed in subsequent processes such as settling, dissolved air flotation (DAF), or filtration. For the
purpose of this discussion coagulation means the addition of one or more chemicals to condition the small particles for subsequent processing by flocculation. Flocculation is the process of aggregation of the destabilized particles and precipitation products. (M.L Davis, 2010).

Mostly in water treatment, chemical coagulant is used to remove turbidity before the water can be consumed by the users. The chemicals used for water treatment often are inorganic substances such as aluminium. Aluminium can be costly as it is needed in a large quantities for water treatment and it is associated with human health and can affect the environment. The jar test is a common laboratory test used to determine the optimum dosage requirement for chemicals added to remove suspended particles in water sample. This method allows adjustments of pH value of water, variety in sorts of coagulant utilized, testing different coagulant dose or alternating mixing speeds. A jar test simulates the coagulation and flocculation processes encouraging the removal of suspended colloids and organic matters, which can prompt to turbidity, odour and taste problems. Jar test involve slow mixing and rapid mixing. During rapid mixing, the coagulant is quickly mixed with water to create efficient and effective conditions for water treatment. In slow mixing, the mixture is stirred to encourage the particles to clump together to form flocs so that the flocs can settle faster. Slow mixing is required to ensure that the flocs formed will not break. (Gasim, 2015)

1.2 Problem statement
Water treatment industry is faces the challenge to produce higher quality treated water at lower cost. The coagulation-flocculation process is a major step in the production of potable water, allowing the removal of colloidal particles. There is need to determine the optimum coagulant dosage related to the influent of raw water. Excessive coagulant overdosing leads to increased treatment costs and public health concerns, while under dosing leads to a failure to meet the water quality targets and less efficient operation of the water treatment plant. For the moment, both manual and automatic methods are available to predict optimum coagulant dosage rate. Manual methods mainly include jar testing which involves taking a raw water sample and applying different quantities of coagulant to each sample. After a short period of time each sample is assessed for water quality and the dosage that produces the optimal result is used as a set point. Operators change the dose and make a new jar test if the quality of treated water changes. Disadvantages associated with jar testing are the necessity to perform manual intervention, and the
limitation to feedback control. Automatic coagulant control is ensured mainly by streaming current detectors (SCD), which measure the residual charge on colloids, color and turbidity particles in the water.

### 1.3 Objectives

The overall objective is to minimize water treatment costs through optimization of stages of water treatment.

The specific objectives of the study are to:

1) Determine the optimum pH and optimum suitable coagulant doses at coagulation stage following the standard methods.
2) Evaluate effect of time of coagulation.
3) Establish effect of velocity gradient, G.
CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction
The water treatment process consists of coagulation, flocculation, sedimentation, filtration and disinfection units. Focus is on the coagulation and flocculation stages shown below.

![Water Treatment Process Diagram](www.aabergclaims.com)

Figure 2.1: Schematic representation of water treatment process (www.aabergclaims.com)

2.2 Coagulation
Coagulation is the process by which particles (colloids) become destabilized by addition of chemicals that neutralize the negative charges and begin clumping together. It is one of the most important processes in water treatment. It is an effective method for the removal of colloidal particles in surface water. It has been used to treat highly turbid water and natural organic matter present in surface water. The process has the ability to eliminate many pollutants from surface and drinking water, the success of the process has a direct impact on the reliability of treatment
Plant operations and final water quality. It is well established that the choice of coagulants used, the dosing and the operational pH applied in a coagulation process make a significant contribution to the operational cost of the treatment plant. Wastewater has finely divided particles. They are classified as suspended and colloidal particles for practices reasons.

Suspended particles range in size from about 0.1 m to about 100 m in diameter. Suspended solids are defined as solids that are relatively large and settle easily under quiescent conditions. Suspended solids are normally determined by filtering the suspended solids from a water sample of known mass, and determining the mass of the dried solids.

Colloidal particles are in the size range between dissolved substances and suspended particles. They are in solid state and can be removed by physical means such as very high-force centrifugation or by passage of the liquid through filters with very small pore spaces. Colloidal particles on the other hand are too small to settle and they also carry an electrical charge that prevents them from settling. They can actually remain in suspension for days without settling. A colloidal system is defined as a system in which particles in a finely divided state are dispersed in a continuous medium. Colloidal particles are not limited to any particular group of substances but are defined by size. The colloidal size range is generally regarded to extend in size from about 10 nanometre (nm) to 1 micrometre (μm).

Colloidal particles impart undesirable properties to water:
Turbidity is most often caused by inorganic clay minerals in surface water. Most turbidity particles are hydrophobic (water repelling). Turbidity can be readily removed from water by coagulation-flocculation and separation.
Colloidal organic substances, i.e. humic and fulvic acids which generally cause colour in natural water. Colloidal metal hydroxides (e.g. iron) also cause colour in water. Most of the particles responsible for colour are hydrophilic (water attractive) and more difficult to remove by coagulation than turbidity particles.
Bacteria, viruses and micro-algae are also colloidal in nature. They consist of polar organic molecules, are hydrated and hydrophilic.
2.3 **Scientific theories for coagulation**

Coagulation is the electrochemical process of aggregating small particles into larger particles or “flocs” that settle more rapidly than individual particles due to their increased weight. It is the most common first step in water treatment prior to treatment whereby removal of impure particulates can be achieved. In this process, coagulants are added to turbid water in order to destabilize particles and reduce inter-particle repulsion forces. Destabilization increases the tendency of particles to coalesce on contact, resulting in heavier agglomerated particles. The heavier particles will then start settling out of solution. There are two theories that attempt to explain the transformation between stable and unstable particles:

The physical theory is based on the presence of electrical double layers surrounding a particle and counter-ion adsorption. It proposes that reduction in electrostatic forces, such as the zeta potential, is responsible for destabilization. The chemical theory assumes that suspended particles, or colloids, are aggregates of chemical structural units. Therefore, specific chemical reactions between colloidal particle and chemical coagulant are responsible for destabilization (Culp et al).

The physical theory, the electrical double layer comprises of ions that counterbalance charges developing at particle-water interface. The ions surround a colloidal particle to preserve its electro-neutrality. The inner layer of counter-ions are a compact layer on the colloid surface while the remaining counter-ions make up a diffuse layer extending into the solution. At the plane of shear within the diffused layer, the zeta potential is measured. The zeta potential’s magnitude describes the colloidal particle stability. Low potentials correlate to easily coagulate unstable systems while high potentials relate to strong forces of separation and stability, difficult to coagulate systems (Culp et al). See Figure 2-1 for a visual schematic of the relationship between zeta potential and distance from particle surface (Van Olphen, 1977).
2.4 Need for coagulation

With relatively few exceptions, surface waters require some kind of treatment before distribution to customers. Contaminants resulting from land erosion, dissolution of minerals, and the decay of organic vegetation have always been present in widely varying proportions. The need for such treatment is ever increasing due to the additional pollution contributed by an expanding industrial complex and a burgeoning human population.

Natural waters polluted either by man or by nature, are likely to contain dissolved inorganic and organic substances, biological forms such as bacteria and suspended inorganic material. To remove these substances, the usual unit processes include plain sedimentation, removal by coagulation generally followed by filtration. Other processes such as adsorption, aeration, ion exchange, oxidation, and distillation are also important for the removal of dissolved substances.
Coagulation followed by filtration is by far the most widely used process to remove substances producing turbidity in water. Substances producing color, as distinct from turbidity, consist either of colloidal metallic hydroxides, iron for example, or of organic compounds having a much smaller particle size. These substances too can be removed by coagulation, which serves to agglomerate the very small particles into sizes which are settleable or can be removed by filters.

The process of coagulation may also find use, although not always, in the softening of hard water with lime or with lime and soda ash. Softening is more properly a precipitation process, and coagulation is used to obtain a more rapid and complete settling of the precipitated hardness components.

2.5 Coagulant chemicals
Coagulants chemicals are used to cause particles or colloids to become destabilized and begin to clump together. Colloids have a net negative surface charge. Electrostatic force prevents them from agglomeration. Brownian motion keeps the colloids in motion preventing settling by gravity. Two major forces acting on colloids are electrostatic repulsion and intermolecular forces. Coagulants are hence used to reduce this forces by addition of countercharged ions (neutralization). Colloids aggregate and start settling. The most commonly used coagulants are Alum (aluminium sulphate), Al₂(SO₄)₃ • 14H₂O. The most common coagulant, it is often used in conjunction with cationic polymers. Polyaluminum chloride, AL (OH) x (C1) y. This is efficient in some waters, requiring less pH adjustment and producing less sludge. Ferric chloride, FeCl₃. This may be more effective than alum in some applications. Ferric sulfate, Fe₂(SO₄)₃. It is effective in some waters and more economical in some locations. Cationic polymers may also be used as primary coagulants.

2.5.1 Alum
Aluminium can be purchased as either dry or liquid alum [Al₂(SO₄)₃.14H₂O]. Commercial alum has an average molecular weight of 594. Liquid alum is sold as approximately 48.8 percent alum (8.3 percent Al₂O₃) and 51.2 percent water. If it is sold as a more concentrated solution, there can be problems with crystallization of the alum during shipment and storage. A 48.8 percent alum
solution has a crystallization point of -15.6° C. A 50.7 percent alum solution will crystallize at +18.3° C. The alternative is to purchase dry alum. However, dry alum costs about 50 percent more than an equivalent amount of liquid alum so that only users of very small amounts of alum purchase it in this form.

When alum is added to a water containing alkalinity, the following reaction occurs:

$$\text{Al}_2\text{(SO}_4\text{)}_3 \cdot 14\text{H}_2\text{O} + 6\text{HCO}_3^- \leftrightarrow 2\text{Al(}\text{OH})_3 \cdot 3\text{H}_2\text{O(s)} + 6\text{ CO}_2+ \text{H}_2\text{O} + \text{SO}_4^{2-}$$

Such that each mole of alum added uses six moles of alkalinity and produces six moles of carbon dioxide. The above reaction shifts the carbonate equilibrium and decreases the pH. However, as long as sufficient alkalinity is present and CO$_2$ (g) is allowed to evolve, the pH is not drastically reduced and is generally not an operational problem. When sufficient alkalinity is not present to neutralize the sulphuric acid production, the pH may be greatly reduced:

$$\text{Al}_2\text{(SO}_4\text{)}_3 \cdot 14\text{H}_2\text{O} \leftrightarrow 2\text{Al(}\text{OH})_3 \cdot 3\text{H}_2\text{O(s)} + 3\text{H}_2\text{SO}_4 + 2\text{H}_2\text{O}$$

If the second reaction occurs, lime or sodium carbonate may be added to neutralize the acid formed because the precipitate will dissolve. (M.L Davis, 2010).

Although alum is by far the most widely used coagulant chemical. Alum may react in different ways to achieve coagulation. When used at relatively low doses (<5 mg/L), charge neutralization (destabilization) is believed to be the primary mechanism involved while at higher dosages, the primary coagulation mechanism tends to be entrapment. In this case, aluminium hydroxide precipitates forming a “sweepfloc” that tends to hold suspended solids as they settles out of suspension.

Cost should also considered when selecting chemicals. An economic analysis should be performed when comparing chemicals and not just comparing unit cost. For instance, a polymer may cost more per unit than alum, but less polymer may be needed than alum. Therefore, the total cost for polymer may not be much different than the total cost for alum. The following issues may be evaluated as options to consider for treatment process enhancement.
The pH of the water has an important role when alum is used for coagulation because the solubility of the aluminium species in water depends on pH. If the pH of the water is between 4 and 5, alum is generally present in the form of positive ions (\(\text{Al(OH)}^2^+\), \(\text{Al}_8\ (\text{OH})^4^+\), and \(\text{Al}^{3^+}\)). However, optimum coagulation occurs when positively charged forms of alum predominate, which occurs when the pH is between 6 and 8. When alum is used and charge neutralization is the primary coagulation mechanism, effective flash mixing is important to the success of the process. When the primary mechanism is entrapment, effective flash mixing is less critical.

### 2.5.2 Coagulant aids

Insoluble particulate materials such as clay, sodium silicate, pure precipitated calcium carbonate, diatomite, and activated carbon have been used as coagulant aids. They are used in waters that have low concentrations of particles and, thus, have few nucleating sites to form larger floc. Because their density is higher than most floc particles, floc settling velocity is increased by the addition of coagulant aids. The dosage must be carefully controlled to avoid lowering the water quality. (Davis, 2010).
2.5.3 Adjustment of pH

Control of pH and alkalinity is an essential aspect of coagulation. The optimum pH for coagulation varies but is generally within the following ranges for turbidity removal using alum: pH 5.5 to 7.5; typical pH 7.0. It can be necessary to adjust the pH of some source waters to achieve optimum coagulation. The pH is often lowered by adding carbon dioxide or an acid. Alum consumes alkalinity and can lower pH; however, reducing pH by adding more chemical than is required for coagulation should be avoided as it increases overall chemical costs and sludge production costs. There are several ways to handle the high sludge production including sludge lagoons, gravity thickening tanks, and dissolved air flotation tanks. Each process will produce a different percentage of solids and have different construction and operations costs. It may be possible to transfer the cost of solids handling simply by adding the sludge to the local sewer connection. Sludge lagoons are those which liquid seeps into the ground leaving the solids at the surface. Lagoons are by far the cheapest from both a construction and operating cost view. If there is sufficient land available and this type of system is permitted, it is a very cost-effective solution. (William and Kawamura, 2008).

Figure 2.4: Sludge lagoons for sludge disposal (William and Kawamura, 2008)
In some source waters with low pH or low alkalinity, it may be necessary to add caustic soda or lime to raise pH and to offset the acidity of metal-ion coagulants, even in an enhanced coagulation mode of operation.

For waters that require EC to remove organic matter, the pH of coagulation should be lowered as compared to coagulation for turbidity removal only. Typically, the optimum pH for organics removal with alum is between 6.0 and 6.5. There are a number of secondary impacts of utilizing the higher coagulant dosages and lower pH values for enhanced coagulation. A few of these impacts include the following:

Increased solids. The higher coagulant dosages directly result in increased sludge volumes.

Poorer dewatering characteristics. The increased metal (Al^{3+} or Fe^{2+} or 3+) concentrations typically result in poorer dewatering characteristics. As a result, a change to enhanced coagulation may result in lower ultimate, dewatered solids concentrations.

Increased concrete-metal corrosion. The lower pH of the coagulated water for TOC removal will be significantly more aggressive on concrete and metals as compared to the more neutral pH of water that has been coagulated for turbidity removal.

If pH is lowered to improve coagulation, it is typically necessary to raise the pH in the final effluent from the plant to provide a less corrosive finished water. The pH may be adjusted at one or more points in the treatment, including rapid mixing, pre-filtration, and post-filtration. If the pH is lowered to improve coagulation and organics removal, it is often recommended to readjust the pH after the filtration process as compared to pre-filtration. This is due to the fact that some organic matter may be adsorbed onto the floc that may carry over from the clarification process, and any pre-filtration pH adjustment may then result in the "release" of this organic matter, which could pass through the filters and contribute to subsequent DBP formation. For plants where only a small increase in pH is required, liquid caustic soda is most commonly used because of its ease of handling. When a large increase in pH is required, lime is normally the most economical choice. Lime, however, may add turbidity to a finished water; therefore, if lime is used for post-filtration pH adjustment, it is generally best to use a lime saturator to minimize the potential of turbidity addition. Also, in some waters, the utilization of soda ash for pre-coagulation alkalinity adjustment often helps the overall coagulation process.
When lime is added, the following reactions take place

\[
\text{Ca (OH)}_2 + \text{H}_2\text{CO}_3 \leftrightarrow \text{CaCO}_3 + 2\text{H}_2\text{O} \\
\text{Ca (OH)}_2 + \text{Ca (HCO}_3)_2 \rightarrow \text{CaCO}_3 + 2\text{H}_2\text{O}
\]

2.6 **Mechanism of coagulation**

2.6.1 **Rapid mixing and flocculation**

With the development of rapid sand filtration, it was immediately realized that with this method of filtration clear water could not be produced without flocculation. The objective of coagulation and flocculation is to attain almost complete envelopment of suspended particles within floc particles, and to condition the floc particles so that they will readily be removable in the subsequent processes of sedimentation and filtration.

Water practitioners used the word coagulation to refer to an entire process that included addition of chemical coagulants, dispersions, flocculation and settling. Today the definition of coagulation used is: it is the driving together of colloidal particles by chemical forces. The process is speedy and occurs within seconds of the application of the coagulating reagent to water. Because of this, intense mixing is necessary at the point of chemical application in order to ensure uniform chemical distribution and exposure of the fine particles in the water to the coagulating agent before coagulation reaction is completed. This is the work of the rapid mix.

2.6.2 **Flocculation**

Flocculation comes after coagulation and is usually regarded as part of one process: coagulation-flocculation. The main purpose of flocculation is to cause the individual destabilised colloidal particles to collide with each other and with the precipitate formed by the coagulant so as to form flocs that can easily be removed by means of sedimentation or flotation. Flocculation involves the mixing of water to which a coagulant has been added at a slowly, causing the individual particles to “collide”. Flocculation takes place in different types of equipment. A simple mechanical stirrer can be used for flocculation or a specially designed channel with baffles to create desired flow conditions that can also be used to flocculate the particles in water. The basis of the design of a
flocculation channel is that the flow velocity of the water has to be reduced from a high initial value to a much lower value to enable large, strong aggregates to be form. If the flow velocity is too high, the aggregates may break up again causing settling of the broken flocs to be incomplete. In water treatment practice, typically the velocity gradient from 15 to 80 s\(^{-1}\) and the detention time from 10 to 60 minutes are normal ranges for flocculation design (AWWA Manual M37, 1992). Flocculation is controlled through the introduction of energy into the water (through paddles or by means of baffles in the flocculation channel) to produce the required conditions (required velocity gradient) for flocs to grow to the optimum size and strength. The velocity gradient (or G-value) is an extremely important factor that determines the probability of particles to collide and form flocs. If G values are too low, the probability of collisions is low and poor floc formation results. If too high, shear forces become large and this may result in break-up of aggregates. Aggregates and flocs are removed from water by means of separation processes, i.e. sedimentation and sand filtration; or flotation and sand filtration. Coagulation and flocculation are greatly influenced by physical and chemical forces such as electrical charges on particles, exchange capacity, particle size and concentration, pH, water temperature, and electrolyte concentrations. These and other factors vary widely from place to place, and their influence and effects are not fully understood. Because of this, it is important to secure information on the behavior of the water to be treated in a proposed plant. This may be done by examination of records of adjacent plants treating similar water, and by laboratory testing using jar test techniques followed by laboratory filtration.

### 2.6.3 Flocculation aids

Uncharged and negatively charged polymers are used as flocculant aids. Their purpose is to build a stronger floc. They are added after the coagulants are added and the particles are already destabilized. These chemicals are normally added after the application of coagulants, from 5 to 600 s after mixing. In processes where these are added, called ballasted flocculation, micro-sand is added after chemical coagulation but before flocculation to act as a nucleus for floc formation. The sand has a higher density than the floc and increases its settling velocity. The advantage of these organic polymers is that they have a high positive charge and are much more effective at small dosages. Even though they may be more expensive, a smaller amount may be needed, thereby saving money. Organic polymers also typically produce less sludge. Typical additives used for flocculation aids are high molecular weight anionic or non-ionic polymers, activated silica and
Bentonite. If the water to be treated with a flocculent aid is already in the flocculation stage, the chemical should be added so that it can be spread across the flocculation basin. (Willis, 2005).

2.7 Satisfactory dispersal

Coagulation and mixing also depends on satisfactory dispersal of coagulation chemicals and appropriate application points. Where only a coagulant is used, rapid mixing may be obtained by injection of the chemicals into a point of high-velocity flows, such as the suction of a low-lift pump or hydraulic jump. More commonly however, rapid mixing chambers are used. Where feasible, these should have at least two compartments so as to enable sequential application and dispersion of each reagent. Ordinarily, rapid mix chambers are fitted with vertical-shaft rotary mixing devices such as paddle agitators or turbines. Where practicable, underwater bearings are avoided. The sequence of addition of chemicals for coagulation is often important, and unpredictable; multiple points of application of the chemicals are therefore required. The chemicals used are a pH-adjusting compound, such as lime or an acidic substance, the coagulant (alum in this case) and a coagulant or flocculation aid.

There is a range of optimum dosages for which a coagulant at maximum settling and removal of suspended particles is most efficiently and effectively achieved. Below this range, the amount of coagulant added is insufficient to adequately destabilize the particles. Above this range, the coagulant essentially acts as a chemical coating which re-stabilizes the particle. The window of acceptable dosages varies with different coagulants and with many of these factors, making some less sensitive to imprecisely measured dosages.

Similarly, there is an optimum range of mixing times that effectively aids removal of particulate matter. There are typically three phases of mixing in a coagulation process: rapid mix, gentle mix, and no mix. The rapid mixing phase is a short period of extremely turbulent mixing that allows coagulants contact with suspended particles. (K Luu, 2000).
2.8 Coagulation and flocculation test

Jar test is utilized for obtaining the required information and data on coagulation and flocculation treatment. Those information include following items:

1) Selection of suitable coagulant and flocculants, and their dosages,
2) Determination of optimum pH,
3) Prediction of treated water quality and sludge volume generated.

The test conditions, such as rotation speed of stirrer and stirring time, have to be determined according to the conditions of actual treatment system.

2.9 Design of chemical mixing

Chemical mixing can be accomplished by several different types of equipment designed to mix the applied chemicals with the source water as quickly as possible.
2.9.1 Mixing intensity

The intensity of agitation required for optimum rapid mixing and flocculation is measured by the G value. The G value concept, developed by Camp and Stein in 1943, is widely used in designing rapid mixing and flocculation processes and is defined by the equation

\[ G = (P/\mu V)^{0.5} \]

Where, \( G \) = root-mean-square velocity gradient, or rate of change of velocity, (ft/s)\(^2\)
\( P \) = power input, ft • lb/s
\( \mu \) = dynamic viscosity, lb • sift 2
\( V \) = volume, ft 3

Different velocity gradients are appropriate for different processes. Coagulation requires very high velocity gradients. Flocculation requires a velocity gradient high enough to cause particle contact and to keep the flocs from settling but low enough to prevent the flocs from tearing apart. In addition, different chemicals require different velocity gradients. (Metcalf and Eddy, 1991)

In practice, the recommended G-value for rapid mixing is 1500 s\(^{-1}\), at a minimum. Two different mixing systems can be applied:

- mechanical mixing
- static mixing

After coagulation the colloids and humic acid are destabilized and many small particles are present in the water. Mixers that are placed in the floc formation chambers dissipate energy in the water, resulting in the collision of neutral particles and the formation of flocs. The degree of energy dissipation is expressed, like for coagulation, in the velocity gradient. The velocity gradient is mainly created by mixers. Alternatively, hydraulic floc formation can be applied where the head loss between two chambers delivers the energy for the formation of flocs. The drawback of hydraulic flocculation is the uneven energy input.
2.9.2 Mixing time

Experimental work has revealed that coagulant reactions are very fast. Alum hydrolyses to Al (OH)\(^{2+}\) within 10\(^{-5}\) s (Base and Mesmer, 1976). Hahn and Stumm (1968) found the time to form mono- and polynuclear hydroxide species was on the order of 10\(^{-3}\) s, and the time of formation of polymer species was on the order of 10\(^{-2}\) s.

This work along with field observations implies that nearly instantaneous and intense mixing of metal salts is of critical importance. This is especially true when the metal salts are being used to lower the surface charge of the particles. Mixing times of less than 1 s are recommended in this case. The formation of the aluminium-hydroxide precipitate is slower and occurs in the range of 1 to 7 s.

The time requirements for flocculation are more dependent on the requirements of downstream processes. For conventional treatment where settling follows flocculation the flocculation time ranges from 20 to 30 minutes. If direct filtration is to follow flocculation, shorter times on the order of 10 to 20 minutes are often selected (MWH, 2005). For these time-dependent reactions, the time that a fluid particle remains in the reactor affects the degree to which the reaction goes to completion. In ideal reactors the average time in the reactor (the theoretical detention time also known as hydraulic detention time, hydraulic residence time, or detention time) is defined as \( t \)

\[
t = \frac{V}{Q}
\]

- \( t \) = theoretical detention time, s
- \( V \) = volume of fluid in reactor, m\(^3\)
- \( Q \) = flow rate into reactor, m\(^3\)/s

Theoretically, given the desired detention time and the design flow rate, the liquid volume of the vessel to achieve the design detention time may be calculated. However, real reactors do not behave as ideal reactors because of density differences due to temperature or other causes, short circuiting because of uneven inlet or outlet conditions, and local turbulence or dead spots in the reactor corners. The mean detention time in real tanks is generally less than the theoretical detention time.
2.9.3 Selection of $G$ and $Gt$ values

Both $G$ and the product of the velocity gradient and time ($Gt$), serve as criteria for the design of mixing systems. The selection of $G$ and $Gt$ values for coagulation is dependent on the mixing device, the chemicals selected, and the anticipated reactions. As noted previously, coagulation occurs predominately by two mechanisms: adsorption of the soluble hydrolysis species on the colloid and destabilization or sweep coagulation where the colloid is trapped in the hydroxide precipitate. Jar test data may be used to identify whether adsorption/destabilization or sweep coagulation is predominant using the following procedure:

- Determine the optimum pH and dose from plots of settled turbidity.
- Plot the optimum pH and dose.
- Determine which the predominant mechanism from the plotted position is.

Determining optimum $G$, $t$, and $Gt$ values can be supported with residual turbidity measurements. Turbidity removal is an important factor used to investigate the state of aggregation since microfloc structure and size distribution are the main parameters determining residual turbidity. $G$ values in the range of 3,000 to 5,000 s$^{-1}$ and detention times on the order of 0.5 s are recommended for adsorption/destabilization reactions. For sweep coagulation, detention times of 1 to 10 s and $G$ values in the range of 600 to 1,000 s$^{-1}$ are recommended.

2.10 Factors affecting the process

1) Dose of the coagulant.

Sufficient chemical has to be added to more or less neutralise the surface charge on the clay and silica. The sign to look for is the appearance of the water between the flock particles. A clear water rather than a murky one is the desired result, at the end of the flocculation stage.

2) pH.

pH is defined as the negative log of the hydrogen ion concentration. It is one of the important raw water quality parameters for coagulant selection. During the coagulation process, the pH of the water affects the chemistry of the coagulant, such as solubility and speciation, as well as the charge
on the particles and NOM. pH is controlled by the equilibrium achieved by dissolved coagulants in water. Generally speaking, the coagulation process performs better if the practical pH is close to the pH of minimum solubility of the coagulant. Alkalinity is a measure of water’s capacity to neutralize acids and is expressed in terms of CaCO3. It is related to pH. Higher alkalinity water has higher pH. Since metal coagulants are acid, coagulant addition consumes alkalinity. High alkalinity water may need more coagulant addition to decrease the pH to a favourable value for effective coagulation (Tseng et al., 2000). Higher alkalinity consumption is observed after addition of alum than PACl (Pernitsky and Edzwald, 2003).

3) **Intensity of stirring**

As measured by G.

4) **Time (t).**

The effect of G on the time to give a constant turbidity can be directly measured. At high G values (100 or more), the turbidity falls rapidly but the resultant constant turbidity is generally high, while at G of 20 or 30 it takes longer to get there but the constant turbidity is much lower. Between these limits there is space for more in-between values of G, either stepwise or gradual, giving tapered flocculation, starting with high G and ending with low G. (Shutte, 2007)
CHAPTER 3

3 METHODOLOGY

3.1 Introduction
The study was limited to the optimization of coagulant dosage, rapid mix velocity gradient, rapid mix time, slow mix velocity gradient, slow mixing time.

3.2 Sampling of Water
Water sampling was conducted at Chiromo River. Water was collected from one station on February 17, 2016. All water samples were collected using 5 litre containers. Samples were stored in the public health laboratory in a refrigerator until analysed. Parameters tested include alkalinity, turbidity, pH, and colour.

![Sampling point on River Chiromo](image)

Figure 3.1: Sampling point on River Chiromo

3.3 Jar tests
A multiple-bladed 4 paddle stirrer Phipps and Byrd programmable jar test apparatus. The speed was variable from 10 to 160 rpm. In addition, a laboratory stirrer was needed for rapid mixing.
A pH meter to measure pH. The meter was adjusted at the start of each test session. Beakers: size 1000 ml, Graduated pipettes: 2, 5, 10 and 25 ml, Measuring cylinder: 500 or 1000 ml. Turbidity meter. (Hach 2100 A)

Figure 3.2: Jar test apparatus

Jar tests were performed on the collected samples using 1.0 L samples, on a six stirrer Phipps and Byrd programmable jar test apparatus. The initial parameters of the river water were tested and results recorded. Jar test were performed as follows:

3.3.1 Determination of optimum pH
pH of the jars were adjusted while using NaOH/lime to pH: 5.0; 5.5; 6.0; 6.5; 7.0; 7.5 while mixing. Same dose of the alum coagulant was added to each jar (Coagulant dose: 10 mg/L) and Rapid mixed at 150 rpm for 1 minute. The rapid mix helped to disperse the coagulant throughout each container. The stirring speed was then reduced to 30 rpm and mixing continued for 20 minutes. The slower mixing speed helped to promote floc formation by enhancing particle collisions, which lead to larger flocs formation. Mixers were turned off to allow flocs to settle for one hour. The final residual turbidity was measured in each jar. The goal of the testing was to plot residual turbidity against pH.
3.3.2 Dose of alum coagulant which was found to be optimum
The pH of all jars were adjusted to optimum pH (found from first test) while mixing using NaOH/lime. The appropriate amount of 1,000 mg/l alum stock to provide doses of 10, 20, 30, 40, 45; and 50 mg/L were added to each sample, and flash mixed at 150 rpm for 1 minute, then followed by flocculation at 40 rpm for 15 minutes. The samples were then allowed to settle for one hour until all of the floc had fully settled. Before and after treatment samples were measured for pH, temperature, turbidity, alkalinity and colour. The goal of the testing was to identify the optimum dose of alum required to achieve a turbidity of less than 1.0 NTU by plotting residual turbidity against coagulant dosage.

3.3.3 Test to examine effect of varying rapid mixing intensity (velocity gradients)
Each jar was filled with 1.0 L samples and coagulant doses (10, 20, 30, 35, 40, 45, and 50 mg/l) carefully measured and added. The speed was set to rapid mixing intensities (velocity gradients) 4000s\(^{-1}\) (100 rpm), 5300s\(^{-1}\) (120 rpm), 6700s\(^{-1}\) (140rpm), and 8100s\(^{-1}\) (160 rpm). Flash mixing was done for 1min followed by slow mixing 20 rpm for 20 mins and allowed to settle for 30 mins. Curves were then plotted for residual turbidity against alum doses for each flash mix speed.

3.3.4 Test to examine effect of varying slow mixing intensity (velocity gradient)
Each jar was filled with 1.0 L samples and coagulant doses (10, 20, 30, 35, 40, 45, and 50 mg/l) carefully measured and added. The speed was set to slow mixing of 120 rpm for 1 min. Mixing speed was then switched to slow mix intensities of 400s\(^{-1}\) (20 rpm), 700s\(^{-1}\) (30 rpm), 1000s\(^{-1}\) (40 rpm) and 1400s\(^{-1}\) (50 rpm) for 20 mins and allowed to settle for 30 mins. Curves were then plotted for residual turbidity against alum doses for each slow mix speed.

3.3.5 Tests to examine the influence of rapid mixing time
The test utilized a 1L water sample contained within a glass beaker, to which was added lime to adjust the pH to optimum. The optimum 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 (0, 5, 10, 15, 20, 30 and 45) with a constant 120 rpm rapid mixing speed, and then at a slower rate of 20 rpm for 20 minutes to accommodate the agglomeration of flocs

3.3.6 Tests to examine the influence of slow mixing time
The test utilized a 1L water sample contained within a glass beaker, to which was added lime to adjust the pH to optimum. The optimum coagulant was subsequently added to the water sample.
Once a pH of 6.5 was reached, the sample was mixed rapidly at 120 rpm for 1 min followed by slow mixing of 20 rpm for a range of times (0, 5, 10, 15, 20, 30 and 45) to accommodate the agglomeration of flocs.
CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 Introduction
The coagulation and flocculation tests were carried out following the standard practice for coagulation flocculation testing of wastewater to evaluate the results for chemicals, dosages and conditions necessary to achieve optimum results presented in this chapter.

4.2 Optimum pH
A plot of turbidity against pH (Figure 8) found optimum pH to be 6.5. The optimal pH range for alum is approximately 5.5 to 6.5 with adequate coagulation between pH 5.0 to 6.5 under certain conditions. Therefore, the observed optimum pH was within the typical range. If the pH is lower or higher than this optimum, then problems of high residual colour and aluminium or disinfection by-products may occur in the finished water. pH value gives an indication of how acidic or alkaline a solution is. It’s a very important parameter in water treatment, especially in determining effective coagulation.

![Optimum pH](image.png)

Figure 4.1: Graph of residual turbidity vs pH
4.3 Optimum alum dosage

A plot of turbidity against alum dosages (Figure 9) found optimum alum dose to be 39mg/l. From the graph pattern it is evident that with increasing alum dosage the residual turbidity decreases to the optimum value and starts increasing. The residual turbidity at optimum alum dose is 6.1 NTU, hence the alum dose efficiency was calculated and found to be 88% which resulted with clear water. Coagulants contributes significantly to operating costs and thus it is important to use them efficiently. Coagulant management includes stock preparation, testing stock concentrations, dosing with the chemical dose controller, and injection of the coagulant into the raw water.

![Optimum alum dosage](image)

Figure 4.2: Graph of residual turbidity vs alum giving optimum alum dosage

4.4 Effect of velocity gradients (mixing intensities)

A number of tests were performed to examine the effect of rapid mixing intensity and the slow mixing intensity to removal of turbidity. Figure10 and 11 show the results of the tests respectively.

**Rapid mixing intensity variation**

The results of these jar tests using alum are shown in Figure 10, over a range of dosages from 10 to 50 mg/l for mixing intensities of 4000s⁻¹ (100 rpm), 5300s⁻¹ (120 rpm), 6700s⁻¹ (140 rpm) and 8100s⁻¹ (160 rpm). In the turbidity data, a significant difference was seen for mixing intensity of 5300s⁻¹ and 6700s⁻¹. In practice, the recommended G-value for rapid mixing is 1500 s⁻¹, at a
minimum. The lower mixing intensity of 5300s\(^{-1}\) may improve the removal of turbidity at lower concentrations, due to reduced shearing of the floc during initial formation. A high-energy, rapid-mix allows proper dispersal of coagulant and promote particle collisions is needed to achieve good coagulation. Over-mixing does not affect coagulation, but insufficient mixing will leave this step incomplete. Contact time in the rapid-mix chamber is typically 1 to 3 minutes.

Figure 4.3: Effects of rapid mixing intensity on removal of turbidity. 1 min mixing, 20 rpm slow mixing for 20 mins. Settle for 30 min.

**Slow mixing velocity variation**

The results of these jar tests using alum are shown in Figure 11, over a range of dosages from 10 to 50 mg/l for flocculation intensities of 400s\(^{-1}\) (20 rpm), 700s\(^{-1}\) (130), 1000s\(^{-1}\) (40 rpm) and 1400s\(^{-1}\) (50 rpm). But for the normalized turbidity data, no significant difference was seen for all flocculation speeds. The lower mixing intensity of 400s\(^{-1}\) may improve the removal of turbidity at lower concentrations of alum due to reduced shearing during the flocculation phase.
4.5 Effect of time of flocculation

Figure 12 shows the effect of flocculation mixing times of 0, 5, 10, 15, 20, 25 and 30 mins on the removal of turbidity at the optimum alum coagulant dosage of 39 mg/l. The curve indicates that after the first five minutes there is very little change in amount of turbidity available. While detention time (mixing time) is not usually a critical factor in the coagulation or flash-mixing process, in the flocculation process detention time is very important. The minimum detention time recommended for flocculation, where separate flocculation chambers are provided, ranges from about 5 to 20 minutes for direct filtration systems and up to 30 minutes for conventional filtration. The size and shape of the flocculation facility also influence the detention time needed for optimum floc development. (EPA, 2002)
Figure 4.5: Effects of varying slow mixing times on turbidity removal using jar test with 120 rpm for 1 min ad slow mixing speed of 20 rpm for 20 min. 30 mins settling time.

4.6 Sizing of flocculation tanks

Conventional design characterize a flocculator with a laminar velocity gradient, G, and residence time, t (Tambo and Watanabe, 1979). Although Gt doesn’t apply to turbulent flow flocculators, it is an appropriate parameterization of laminar flow flocculator. A series of flocculation chambers is usually employed rather than a single basin. A stepped-down mixing intensity is utilized in each successive chamber. Inlet and outlet design must be such as to prevent short-circuiting and destruction of floc. The flow-through velocity shall not be less than 0.5 and not greater than 1.5 ft/min with a detention time of at least 30 minutes. Mixing devices are driven by variable speed drives with the peripheral speed of paddles ranging from 0.5 to 2.0 ft per second. Allowances must be made to minimize turbulence at bends and changes in direction. The common mechanical mixing devices are paddle flocculators, flat-bed turbines, and vertical-turbine mixers. (JN Ramaswamy, 2009).
CHAPTER 5

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

After completion of tests and analysis, the following conclusions were deduced:

1. The jar test experiments performed on turbid waters from Chiromo River using aluminium sulfate gave an optimum pH of 6.5 resulting in the maximum turbidity removal.
2. The optimum alum dosage was found to be 39 mg/l. The turbidity removal efficiency for alum at this optimal dosage was 88%.
3. Residual turbidity of test water was 4.15 NTU which shows a decrease from its initial turbidity of 46 NTU. This residual turbidity was sufficient to meet national drinking water limit of 5 NTU at optimum alum dose.
4. At optimum alum dosage of 39 mg/L the colour is removed by 80%, concentrations higher than 39 mg/L had little significance in colour removal after this point.
5. Rapid mixing parameters, time and intensity of mixing, as well as slow mixing parameters on turbidity removal by alum showed that rapid mixing is an important step for particle growth because sound flocs were observed forming. This growth of particles observed during rapid mixing affects (in a negative way if the rapid mixing period was excessive, and in a positive way if it was not excessive) the flocculation process as well as the sedimentation process.
5.2 Recommendations

Based on the investigations of the study, the following recommendations are offered;

1. Alum (low cost coagulant) needs pH-adjustment for optimum performance. The usage of alum coagulant is recommended since its performance is more than satisfying and disinfection step would also benefit from a pH-adjustment.

2. Coagulant should be dispersed rapidly (ideally in a few seconds) and effectively throughout the process flow. The effectiveness of dispersion is supported by dilution and application at a point of turbulence.

3. Turbidity removal was used as an indicator for optimal conditions. However, its removal rate increased with higher alum dosage hence further steps such as disinfection and filtration should be done.

4. Further studies should be
REFERENCES


APPENDICES
APPENDIX 1: LABORATORY TEST PROCEDURES

Jar test

**Apparatus**

Phipps and Byrd programmable

Beakers

Stop watch

Pipette

**Reagents**

Coagulant, Aluminium sulfate (alum)

Coagulant aid, pH adjuster (lime)

Liquid sample

**Procedure**

The water from the river was prepared. The lime was used to stabilize the PH of the waste water to the neutral. The temperature, pH, color, alkalinity and turbidity of the synthetic water sample were measured. 1L was filled into six different beakers. The prescribed dose of coagulant was added to each jar by using a pipette. One jar has no coagulant since a control sample was required. If a coagulant aid is required, it is added to each jar (except for control sample) during the last 15 seconds of the rapid mix stage. Start stirring rapidly (60 to 80 rpm) for 3 minute (Rapid mix stage). After the rapid mix stage, reduce the speed to 30 rpm for 20 minutes. 500mL of settle water was separate out into another beaker. The temperature, pH, color, alkalinity and turbidity of the clarified water were determined. A graph of turbidity versus coagulant dose (mg/L) was plotted. The most effective dose of coagulant (or with the present of coagulant aid) that gives the least turbid results also determined. The qualitative characteristics of floc as bad, moderate, good and very good were recorded. Cloudy samples indicate bad coagulation while good coagulation refers to rapid floc formation resulting in clear water formation on the upper portion of the beaker.
The following graph: turbidity versus pH, turbidity versus coagulant dose, etc. were plotted. These graphs assist in the interpretation of the coagulation-flocculation process.

**Alkalinity**

**Apparatus**

Pipette
Burette
Conical flask
Tripod stand

**Reagents**

Water Sample
Phenolphthalein Indicator
N/50 Sulphuric Acid
Methyl Orange

**Procedure**

100ml of the sample was titrated into a conical flask and a few drops of phenolphthalein indicator added.
This was followed by titrating N/50 Sulphuric Acid until the solution turned colorless. The volume of acid used was recorded then a few drops of methyl orange added and titration continued until the final orange-red color appears. The total amount of acid was then recorded.

a) Readings and Calculations:

Reading 1 (before titration) = 0 ml
Reading 2 (when solution turned colourless) = 6.8 ml
Reading 3 (Final Reading) = 16.0 ml

Phenolphthalein alkalinity = (reading 2 − reading 1) × 10 = 68 mg CaCO$_3$/l
Total alkalinity = (reading 3 − reading 1) × 10 = 160 mg CaCO$_3$/l
**Turbidity**

**Apparatus**

Turbidimeter  
Cell riser  
Light Shield  
Sample cell

**Reagents**

30ml of the water sample  
Formazin

**Procedure**

The turbidimeter was allowed to warm up for approximately 110 minutes. 30ml of the water sample was then pipetted into a clean sample cell and the sample compared with the given standards. The standard with a value of turbidity closest to, but higher than the water sample was chosen. The standard chosen (FTU) was found to be in the range of 0 – 100 FTU, thus a cell riser was inserted into the cell holder assembly.

The standard was then inserted into the cell holder and the instrument standardized while taking care to use the light shield. This was followed by removing the standard and replacing it with the sample also taking care to use the light shield. The turbidity is then read (in FTU) using the correct range.

**pH**

**Apparatus**

pH Meter

**Reagents**

Distilled water
Procedure

The pH meter electrodes were carefully raised out of their container and rinsed with distilled water. Drops of water were wiped from the electrodes. Approximately 75 ml of sample was placed in a 100ml beaker and the electrodes were immersed in the beaker containing the sample. The selector switch was turned to ‘pH’. The pH was read directly from meter. The electrodes were raised, rinsed with distilled water and replaced in a beaker of distilled water.

Colour

Apparatus

Lovibond nessleriser

Hazen disc no. NSA

Nessler cylinder

Reagents

A sample of un-distilled water

Distilled water in beaker

Procedure

A Nessler cylinder is filled with the water sample (previously filtered if turbid) up to the mark and transferred to the right hand compartment of a Lovibond nessleriser used in conjunction with a white light cabinet. The color is then matched against the standard Hazen disc No. The color is then read off directly in Hazen.
### APPENDIX 2: COAGULATION AND FLOCCULATION SHEETS

#### Table 5.1: Raw water parameters

<table>
<thead>
<tr>
<th>Raw Water Parameters</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkalinity</td>
<td>143</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colour</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 5.2: Effect of pH using same coagulant dose to determine optimum pH

<table>
<thead>
<tr>
<th>Coagulant dosage (mg/l)</th>
<th>pH</th>
<th>Turbidity (NTU)</th>
<th>Alkalinity (mg/l)</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5.00</td>
<td>8.9</td>
<td>138</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>5.50</td>
<td>7.5</td>
<td>129</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>6.00</td>
<td>7.1</td>
<td>122</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>6.50</td>
<td>6.4</td>
<td>115</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>7.00</td>
<td>6.8</td>
<td>109</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>7.50</td>
<td>7.6</td>
<td>97</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>10</td>
<td>7.50</td>
<td>7.9</td>
<td>94</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

#### Table 5.3: Effect of alum dosage on same pH to determine optimum dosage

<table>
<thead>
<tr>
<th>Coagulant dosage (mg/l)</th>
<th>pH</th>
<th>Turbidity (NTU)</th>
<th>Alkalinity (mg/l)</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.50</td>
<td>8.8</td>
<td>141</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>6.50</td>
<td>7.9</td>
<td>137</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>6.50</td>
<td>7.0</td>
<td>133</td>
<td>10</td>
</tr>
<tr>
<td>35</td>
<td>6.50</td>
<td>6.4</td>
<td>127</td>
<td>10</td>
</tr>
<tr>
<td>40</td>
<td>6.50</td>
<td>6.2</td>
<td>120</td>
<td>5</td>
</tr>
<tr>
<td>45</td>
<td>6.50</td>
<td>7.5</td>
<td>118</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>6.50</td>
<td>7.9</td>
<td>108</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>
### Table 5.4: Effects of varying rapid mixing intensity on turbidity removal, mixing time of 1 min, flocculation at 20 rpm for 20 min and 30 min settling time

<table>
<thead>
<tr>
<th>Rapid Mixing speeds</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coagulant dosages</td>
<td>Turbidity(NTU)</td>
<td>Turbidity(NTU)</td>
<td>Turbidity(NTU)</td>
<td>Turbidity(NTU)</td>
</tr>
<tr>
<td>10</td>
<td>15.3</td>
<td>12.6</td>
<td>11.8</td>
<td>13.5</td>
</tr>
<tr>
<td>20</td>
<td>10.2</td>
<td>11.9</td>
<td>10.6</td>
<td>12.7</td>
</tr>
<tr>
<td>30</td>
<td>8.8</td>
<td>10.4</td>
<td>9.2</td>
<td>12.1</td>
</tr>
<tr>
<td>35</td>
<td>7.5</td>
<td>9.8</td>
<td>8.4</td>
<td>10.5</td>
</tr>
<tr>
<td>40</td>
<td>6.2</td>
<td>8.2</td>
<td>7.5</td>
<td>9.2</td>
</tr>
<tr>
<td>45</td>
<td>5.2</td>
<td>7.1</td>
<td>6.1</td>
<td>8.1</td>
</tr>
<tr>
<td>50</td>
<td>3.2</td>
<td>6.2</td>
<td>4.7</td>
<td>5.3</td>
</tr>
</tbody>
</table>

### Table 5.5: Effects of varying slow mixing intensity on turbidity removal, 120 rpm for 1 min, mixing time of 20 mins and 30 min settling time

<table>
<thead>
<tr>
<th>Slow Mixing speeds</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coagulant dosages</td>
<td>Turbidity(NTU)</td>
<td>Turbidity(NTU)</td>
<td>Turbidity(NTU)</td>
<td>Turbidity(NTU)</td>
</tr>
<tr>
<td>10</td>
<td>14.2</td>
<td>15.4</td>
<td>14.8</td>
<td>15.2</td>
</tr>
<tr>
<td>20</td>
<td>8.2</td>
<td>8.5</td>
<td>7.9</td>
<td>7.8</td>
</tr>
<tr>
<td>30</td>
<td>7.5</td>
<td>7.2</td>
<td>7.1</td>
<td>6.9</td>
</tr>
<tr>
<td>35</td>
<td>6.2</td>
<td>6.9</td>
<td>6.5</td>
<td>6.1</td>
</tr>
<tr>
<td>40</td>
<td>5.1</td>
<td>5.5</td>
<td>5.2</td>
<td>5.5</td>
</tr>
<tr>
<td>45</td>
<td>4.6</td>
<td>4.2</td>
<td>4.6</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>2.1</td>
<td>3.2</td>
<td>3.9</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Table 5.6: Effect of flocculation mixing time on turbidity removal

**VELOCITY GRADIENT CALCULATIONS**

\[ FD = \frac{CDApVP^2}{2} \]

\[ P = FD \times VP \]

Where, \( C_D \) = Drag coefficient

\[ A_P = \text{Cross-sectional area of paddles, m}^2 \]

\[ V_P = \text{Relative Velocity of paddle tip to water usually 0.6 to 0.75 of velocity.} \]

\[ F_D = \text{Drag Force,} \]

\[ P = \text{Power, W} \]

\[ \rho = \text{Density of water, kg/m}^3 \]

\[ G = (P/\mu V)^{0.5} \]

Where, \( G \) = root-mean-square velocity gradient, or rate of change of velocity, (\( /s \))

\[ P = \text{power input, Pa} \]

\[ \mu = \text{dynamic viscosity, lb \cdot s/ft}^2 \]

\[ V = \text{volume, m}^3 \]
APPENDIX 3: FIGURES

Figure 5.1: researcher in the laboratory preparing for tests.

Figure 5.2: Jar test apparatus
Figure 5.3: Floc formation during mixing

Figure 5.4: Settling of flocs after mixing
Figure 5.5: Researcher measuring color

Figure 5.6: Researcher measuring turbidity
Figure 5.7: Researcher measuring pH