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FACULTY OF CIVIL AND GEOMATIC ENGINEERING**

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**EFFECTS OF POLYALUMINIUM CHLORIDE DOSING ON THE
PERFORMANCE OF COAGULATION
(A CASE STUDY OF BAREKESE WATER TREATMENT PLANT)**

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ENVIRONMENTAL SANITATION**

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DECLARATION

It is hereby declare that this submission is my own work towards the MSc and that, to the best of my knowledge, is neither in part nor whole been presented for another degree elsewhere. Any references made have been duly acknowledged.

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DEDICATION

This research work is dedicated to my parents Mr. Martin Kwame Nti and Madam Florence Ama Kintoh Mensah, who have supported me in every way in my academic pursuit.

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I thank the Almighty God for granting me the strength and knowledge in carrying out this research.

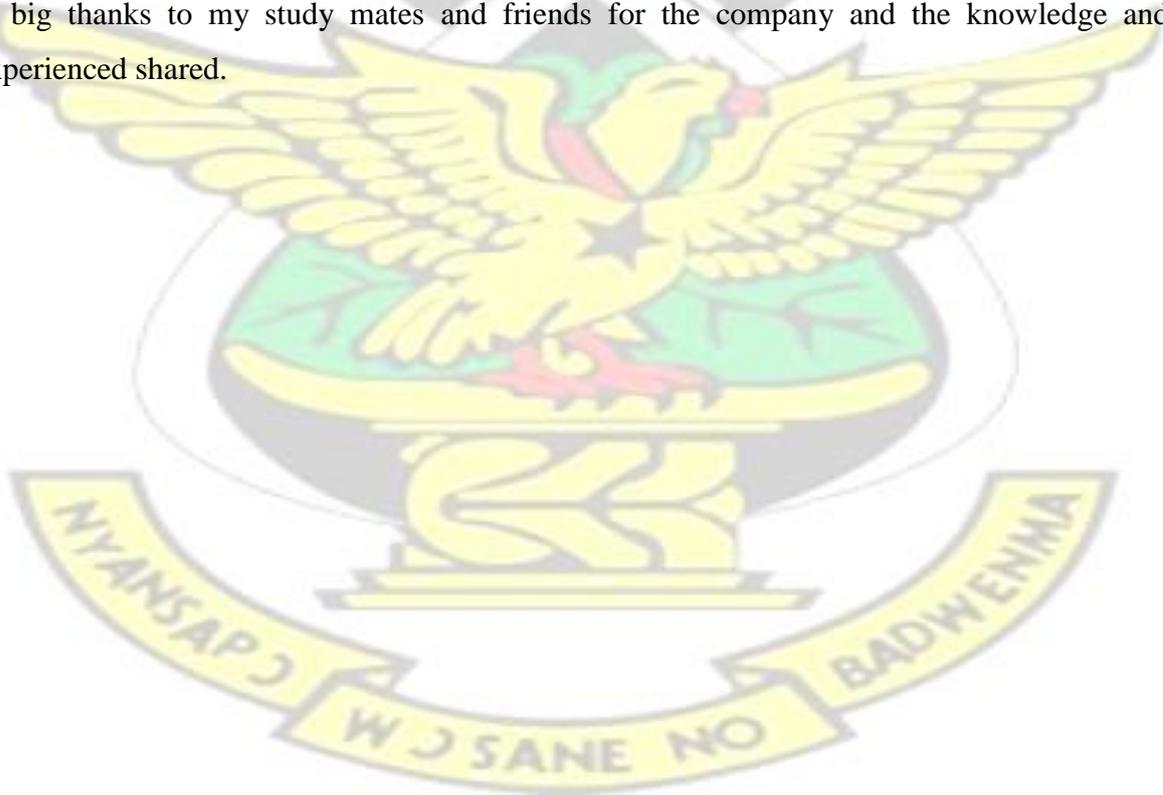
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ABSTRACT

In Ghana, the commonly used coagulant in water treatment processes is the Alum. However, its use has been associated with a number of disadvantages including the production of large volumes of post-treatment sludge, high post-treatment iron residue, reduction of water pH (requiring pH adjustment using lime), limited coagulation pH range of 5.5 to 6.5, etc. These shortfalls on the use of Alum have led to the synthesis of improved Aluminium-based chemicals, called polyelectrolyte (polymer), as alternative coagulant. Among the many polymers synthesized, what has been adopted for use at the Barekese Water Treatment Plant is the Polyaluminium Chloride (PAC). However, information obtained from the BWTP indicates that no detailed preliminary studies was conducted to determine optimal operational conditions such as the coagulant dose, mixing speed, mixing time, retention time and pH of the raw water that influence effective performance of the PAC. This study is thus concerned with identifying such optimum operational conditions necessary to enhance efficient performance of the PAC in water purification. The effects of three different mixing speeds on the purification process were investigated (i.e 180:40, 180:25 and 150:25 revolutions per minute). The 180 and 150 rpm in the later parenthesis represent the fast mixing speeds while the 40 and 25 rpm represent the slow mixing speeds. The duration of mixing the dosed PAC with the water (mixing time) was also varied to ascertain its effects on the contaminant removal. In one set of the experiment, the fast mixing time was 5 minutes and the slow mixing time, 10 minutes (i.e 5:10). In the other set, the fast mixing time was reduced to 2 minutes and the slow mixing time, 5 minutes (2:5). The pH range within which this study was carried out was 6.0 to 8.5, at interval of 0.5. From the study, the mixing speed that was found to promote efficient coagulation was the 150 rpm as fast mixing speed and 25 rpm as the slow mixing speed (i.e 150:25). Using the reduced mixing time (2 minutes) for the fast speed and 5 minutes for slow mixing speed, the treated water recorded a better water quality. The optimum dose of the PAC that promoted best contaminant removal was 15 ppm. Within the raw water pH range of 6.0 to 8.5 tested it was realized that the effect of pH changes on the performance of the PAC was minimal. At pH 6.0, the PAC-treated water had a turbidity of 4.0 NTU was obtained while at pH 8.5; the treated water recorded a turbidity of 3.11. Generally, it was realized that 15 minutes settling time was adequate to sufficiently remove turbidity, colour and iron from the raw water samples. The recorded residual Aluminium in the flocculated water was below the acceptable guideline value of 0.2 mg/l. The cost benefit analysis conducted revealed that the production cost can be reduced by 50% when this optimal PAC dose determined and the conditions recommended are applied. It is therefore proposed that before PAC is adopted as the key coagulant at any water treatment plant, a thorough preliminary study be conducted to determine the optimal operational conditions and dosage.

Keywords: Coagulation-flocculation, mixing speed, mixing time, PAC, coagulant dosage, settling time, pH, turbidity, colour, iron and residual Aluminium.

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LIST OF ABBREVIATIONS AND UNITS

ANOVA	-	Analysis of Variance
BWTP	-	Barekese Water Treatment Plant
GWCL	-	Ghana Water Company Limited
HCl	-	Hydrochloric Acid
KNUST	-	Kwame Nkrumah University of Science and Technology
mg/l	-	Milligram per litre
ml	-	Milli litre
NaOH	-	Sodium Hydroxide
NTU	-	Nephelometric Turbidity Units
ppm	-	Parts per million
Pt-Co	-	Platinum Cobalt units
rpm	-	Revolutions per minute
SPSS	-	Statistical Package for Social Sciences
WHO	-	World Health Organization



CHAPTER 1

INTRODUCTION

1.1 Research Background

Freshwater is a finite resource required for the survival of humans and the ecosystem. However, freshwater resources, especially surface water bodies, have become repositories of harmful substances released into the environment by anthropogenic activities such as the discharge of industrial effluents, domestic and commercial wastes, and agricultural wastes into water bodies coupled with other natural factors such as ore formation, volcanic eruption, etc. releasing toxic substances into water bodies (Zheng *et al.*, 2017; Bulut *et al.*, 2010). If consumed without any form of treatment, it may pose detrimental effects on human health. Therefore, supply of safe drinking water is crucial to human health and economic productivity (Malik and Khan, 2016). However, it is reported in Hossain *et al.*, 2016 that about 1.4 billion people worldwide lack access to safe water and this situation has resulted to an estimated 5 million deaths per year through the contraction of water borne diseases such as diarrhoea.

In an attempt to adequately supply safe water for human consumption, raw water is subjected to thorough treatment to remove unwanted substances such as suspended and dissolved substances. Typically, drinking water treatment processes include aeration, coagulation, clarification (or sedimentation), filtration, disinfection and liming (if necessary). Among these treatment processes, what is of much interest in this study is coagulation. It is the first stage in chemical water treatment and involves the addition of chemicals (coagulant) capable of neutralizing and destabilizing charges on particles in the raw water (Sahu and Chaudhari, 2013). Coagulation is not only necessary in water treatment because it facilitates the removal of colloidal and dissolved substances, but also helps in removing pathogens attached to these particles thereby helping to improve human health (Miller *et al.*, 2008). The efficiency of the coagulation process is greatly influenced by the type of coagulant used, the dosage, operational pH, temperature, ionic strength, nature and concentration of organic matter, total dissolved solids, size, and distribution of colloidal particles in suspensions (Sher *et al.*, 2013; Zainal-Abideen *et al.*, 2012). Inorganic coagulants, especially Alum, ferric chloride and ferric sulphate, are generally the most widely used coagulants for conventional water treatment processes (Rajagopaul and Pillay, 2004). In Ghana, Alum is preferred primarily due to their application to a wide range of water types, conservative energy requirements and availability.

1.2 Problem Statement

Aluminium Sulphate ($\text{Al}_2(\text{SO}_4)_3$), commonly called (Alum), has long been used as a coagulant in water treatment. However, numerous disadvantages including the production of large volumes of post-treatment sludge, high post-treatment Aluminium residue, limited coagulation pH range of 5.5 to 6.5, etc. (Miller *et al.*, 2008 Gebbie, 2001) is associated with its use. These shortfalls on the use of Alum have led to the synthesis of improved Aluminium-based chemicals, called Polymer, as alternative coagulant. Polymer, over the last decades, has been used extensively in developed countries for treating water due to its high efficiency at lower dosages, wider pH and temperature ranges (Sahu and Chaudhari, 2013). Different varieties have been synthesised, including Polyaluminium Chloride (PAC), Aluminium Chlorohydrate (ACH) and Polyaluminium Sulfates (PAS) (Pernitsky and Edzwald, 2006). The performance of each type is limited to the characteristics of the raw water and the operational conditions. Typically, operational conditions such as the coagulant dosage, mixing speed, mixing time, retention time and the pH of the raw water greatly affect the coagulation process. However, information obtained from the Barekese Headworks indicates that no detailed preliminary investigation was conducted to determine such optimum operational conditions. Hence, the Barekese Headworks may either be overdosing or under dosing the PAC.

1.3 Justification

The Barekese Water Treatment Plant supplies portable water to Kumasi, the second largest city and the capital of the Ashanti Region of Ghana. Currently, it supplies about 80% of potable water for the city and its surrounding environs. Therefore, ensuring safe water supply to this large population (about 1.7 million) is imperative and cannot be bargained. Therefore, when favourable operational conditions are determined for the adopted polymer (PAC), it will help improve the quality of water supplied to the people. In addition to improving health through the supply of safe water, realizing better conditions could also help to reduce production cost since the PAC could be used efficiently. Thus, the outcome of this study will be critical in making good economic decisions as well as improving the health of the consumers.

1.4 Research Question

- i. What has been the trend in the quality of the Barekese raw water for the past years?
- ii. What conditions are favourable for efficient performance of the polymer (PAC)?

- iii. What is the optimum dosage of the PAC for sufficient contaminants removal?
- iv. Does the PAC-flocculated water meet WHO and GWCL requirements?

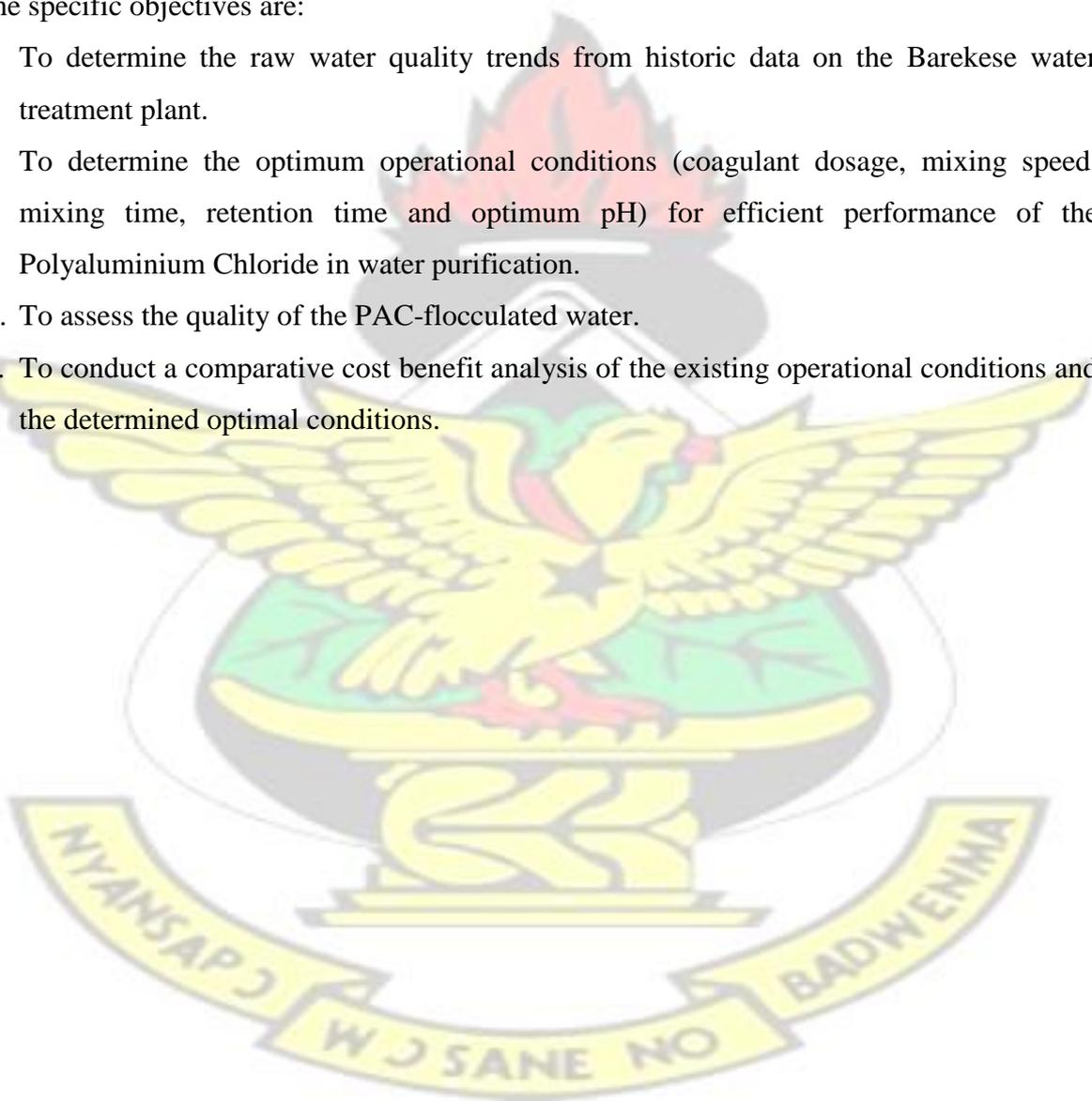
1.5 Research Objective

The main objective of this study is to assess the performance of the Polyaluminium Chloride (PAC) in water treatment process and the quality of the treated water.

1.6 Specific Objectives

The specific objectives are:

- i. To determine the raw water quality trends from historic data on the Barekese water treatment plant.
- ii. To determine the optimum operational conditions (coagulant dosage, mixing speed, mixing time, retention time and optimum pH) for efficient performance of the Polyaluminium Chloride in water purification.
- iii. To assess the quality of the PAC-flocculated water.
- iv. To conduct a comparative cost benefit analysis of the existing operational conditions and the determined optimal conditions.



CHAPTER 2

LITERATURE REVIEW

2.1 Concept and Mechanism of Coagulation – Flocculation Process

Raw water samples usually contain small suspended particles (10^{-7} to 10^{-14} cm in diameter) called colloids which cannot settle spontaneously or be removed naturally due to their light weight and stability. The presence of these colloidal particles tends to impart turbidity and colour to the water, thereby reducing its aesthetic value. There is therefore the need to add chemical agents to facilitate the settlement and subsequent removal of these colloidal materials. These chemical agents are called coagulants (Baghvand *et al.*, 2010). Colloidal particles are negatively charged and they exhibit Brownian motion in the water. As they exhibit this movement, they tend to repel one another due to the negative charges on their surfaces, and this keeps them in dispersed suspension (Sahu and Chaudhari, 2013). Chemicals agents commonly used for coagulation are mainly Aluminium salts [Aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3$)] or iron-based salts [ferric sulphate ($\text{Fe}_2(\text{SO}_4)_3$) and ferric chloride (FeCl_3)]. When introduced into water, Aluminium and iron complexes undergo dissociation (hydrolysis) to form soluble monomeric and polymeric species, as well as a solid precipitate. The Aluminium complex hydrolyses to produce five monomeric species including Al^{3+} , $\text{Al}(\text{OH})^{2+}$, $\text{Al}(\text{OH})_2^+$, $\text{Al}(\text{OH})_3$ (molecule) and $\text{Al}(\text{OH})_4^-$, and three polymeric species namely $\text{Al}_2(\text{OH})_2^{4+}$, $\text{Al}_3(\text{OH})_4^{5+}$ and $\text{Al}_{13}\text{O}_4(\text{OH})_{24}^{7+}$ and a solid precipitate $\text{Al}(\text{OH})_{3(s)}$. In the case of iron-based salts, five monomers (Fe^{3+} , $\text{Fe}(\text{OH})^{2+}$, $\text{Fe}(\text{OH})_2^+$, $\text{Fe}(\text{OH})_3$ (molecule) and $\text{Fe}(\text{OH})_4^-$), a dimer ($\text{Fe}_2(\text{OH})_2^{4+}$), a trimer ($\text{Fe}_3(\text{OH})_4^{5+}$) and a solid precipitate ($\text{Fe}(\text{OH})_3$) (Pernitsky and Edzwald, 2006; Jiang and Graham, 1998). These positively charged ions react with the stable and negatively charged particles (neutralization) through electrostatics, thereby destabilizing them. The destabilized particles are then driven toward each other by van der Waals force of attraction and the hydraulic shear force in the flocculator where there is rapid mixing of the raw water and the added coagulant (Sahu and Chaudhari, 2013; Lanciné *et al.*, 2008). This results to the formation of larger particles capable of settling from the water column as sludge by gravity or been filtered out from the water. In addition, during the hydrolysis of the coagulant, some suspended particles are occluded in the precipitates formed and these are removed as the precipitates settle out of the water. Again, the settling precipitates tend to trap other microflocs (sweep flocculation) that cannot settle by gravity (Wahid *et al.*, 2016; Miller *et al.*, 2008). Coagulation is, therefore, a process where smaller colloidal particles are transmuted into larger aggregates by addition of chemical agents. This

is followed by adsorbance of other dissolved substances onto these aggregates by a process called flocculation so that these impurities can be removed in subsequent clariflocculation/filtration processes (Betancourt and Rose, 2004).

2.2 Polymer

A polymer or polyelectrolyte, as defined in Sahu and Chaudhari (2013), is a high molecular weight organic substance produced from the polymerization of a homopolymer (same monomer type) units or copolymer (different monomers) units. In the process of polymer synthesis, the type and number of monomers units used can be varied. As a result, different polymers of varying molecular weights (usually ranging from 10^4 to 10^6 Daltons), structure (linear, branched or cross-linked), charge magnitudes and charge type can be produced (Sahu and Chaudhari, 2013). The general molecular formula for polyelectrolytes is $(Al_n(OH)_mCl_{(3n-m)})_x$, where m and n are the number of molecules of (OH) and Al species respectively, and x , the number of number of polymer units (Gebbie, 2001). A report prepared for Water Research Commission by Freese *et al.* 2004 has it that polymers can be grouped into four categories: cationic (positively charged), anionic (negatively charged), non-ionic (neutral) and amphoteric (having both positive and negative sites) polymers. The basicity (r) or the degree of neutralization of a polymer is a very significant property that cannot be overlooked. It expresses the ratio of the concentration of hydroxyl ions to that of Aluminium ions in the hydrated complex.

$$\text{Basicity, } r = [OH^-]/[Al^{3+}]$$

Where r can vary from 0 to 3, corresponding to 0 to 100% basicity.

Generally, the higher the basicity of a polymer, the greater the fraction of polymeric species up to an r value of 2.1 (equivalent to 70% basicity) and consequently the lower the consumption of alkalinity during water treatment processes. Moreover, polymers of higher basicity have less impact on the pH of the treated water since a small amount of alkalinity is consumed (Pernitsky and Edzwald, 2006; Gebbie, 2001).

Similar to the Alum, polyelectrolytes function by first neutralizing (destabilizing) the charged particles (impurities) in the water and then bridges these particles together. This, in effect, reduces the repulsive forces existing between the particles, allowing van der Waals forces to facilitate the formation of microflocs, where dense aggregated particles settle rapidly (Sahu and Chaudhari, 2013).

Among the numerous polymers commercially available, one of the most widely used is the Polyaluminium Chloride (PAC) due to its high efficiency in low dosages and wide pH

ranges, less sensitive to temperature, production of limited sludge during treatment process. Also, the PAC flocculates rapidly, and thus requires less time to react and deposit (Mirzaiy *et al.*, 2012).

2.3 Jar Test

Coagulation and subsequent flocculation are common physicochemical processes in raw water treatment that result to the destabilization of negatively charged suspended and dissolved particles in water. However, a number of factors influence the efficiency of the coagulation process. One of such factors is the coagulant dosage or optimum concentration of coagulant. The technique employed in determining the optimum concentration is referred to as the Jar Test. Jar Test is practiced in most water treatment plants (about 95%) to determine the coagulant dosage (Balcioglu and Durak, 2015). Determining the optimum concentration of the coagulant is very important both in making economic decisions and health benefits. Knowing the exact amount of coagulant to be used helps to avoid excessive application of the chemical, thereby saving cost. Also, wrong dosing due to inadequate knowledge may lead to reduced coagulation efficiency with subsequent health implications. For instance, over dosing can bring about charge reversal and re-suspension of particles, thereby resulting to increased turbidity values in the effluent. This is evident in Saritha *et al.* 2017 where turbidity removal efficiency decreased from 97.1 to 95.7 % upon increasing the coagulant dosage from 40 to 50 mg/l at a constant pH of 6. When coagulant dosage is too high, the surfaces of the colloidal particles become saturated with the coagulant ions, inhibiting agglomeration (Ezeh *et al.*, 2017). Likewise, insufficient dosing of coagulant can lead to inefficient coagulation process which consequently reduces effluent quality. When these substances contributing to turbidity, colour, etc. are consumed, they may be detrimental to human health (Haghiri *et al.*, 2018; Baghvand *et al.*, 2010).

2.4 Water Quality Parameters

Surface water is practically exposed to a quantum of environmental contaminants such as heavy metals, nutrients (e.g nitrates, phosphates), and other biological factors such the E. coli and faecal coliform resulting from both anthropogenic activities and natural factors. These contaminants have significant health impacts on human health and the ecosystem at large. World Health Organization (WHO) and other standard agencies have therefore set out permissible levels of these parameters that the human system and/or the ecosystem can

accommodate beyond which will be detrimental to health. Water quality parameters considered for this study include the following:

2.4.1 Physical Parameters

2.4.1.1 pH

pH, as defined by Sørensen in 1909, is a measure of the concentration of hydrogen ions in aqueous solution. Mathematically, pH is expressed as the negative logarithm of hydrogen ion concentration. pH values (ranging from 0 to 14) define whether a solution is acidic, neutral or basic. When the pH of a solution is equal to 7, then the solution is neutral. However, when the pH of an aqueous medium is less than 7 (< 7), the solution is acidic, otherwise (> 7) basic (Silberberg, 2000; Chang 1998). pH is a very important parameter in drinking water treatment processes. The charge on the colloidal particles and the hydrolysis of coagulants is greatly influenced by pH (Lanciné *et al.*, 2008). In most water conditions where pH ranges between 6.5 and 8.5, particles carry negative charges and the extent of the negativity increases with increased pH as a result of the ionization of the metal ion or hydroxide groups on the surfaces of the particles. High coagulant dosage will therefore be required to sufficiently neutralize the particles. As the pH of the water decreases, the negative charge on the dissolved organic carbon decreases, and hence requires only small amount of coagulant for neutralization to occur. In terms of Al speciation, the type of Al species present in solution is also dependent on pH of the water. For pH values less than 5, the predominant Al species produced from hydrolysis is Al^{3+} . However, as pH increase to about 6.5, the oxidation states of the predominant Al species are Al^{2+} and Al^{+} . For pH values greater than 6.5, Al specie present in solution is $Al(OH)_4^{-}$. Therefore, as pH increases, Al species having lower positive charges predominate until a point where negatively charged Al species predominate (Ezeh *et al.*, 2017; Pernitsky and Edzwald, 2006, Braul *et al.*, 2001).

This thus signifies that if the pH of the raw water is greater than 6.5, then pre-treatment in the form of acidification (pH correction) will be required to achieve optimum pH condition critical for the coagulant to effectively neutralize the negatively charged particles (Baghvand *et al.*, 2010). Also, at high pH values, coagulated particles can break down, resulting to re-suspension of the particles. The size of flocs formed is also significantly dependent on the pH of the water. Disinfection efficiency is also influenced by pH. The optimum range of pH required for effective disinfection is between 5.5 and 7.5. pH values above 8 have high tendency to reduce the efficiency of disinfectant, and so high chlorine dosages are required when pH is high (Ezeh *et al.*, 2017; Kale, 2016).

pH has some significant effects on aquatic organisms. When the pH of water is less than 5 (acidic), dissolution of toxic chemicals (eg. heavy metals) is enhanced and this causes some aquatic organisms to die out. At high pH levels (9 – 14) ammonia becomes toxic ammonia which can harm fishes. No concrete health-based guideline value for pH has been set by WHO (Kale, 2016).

2.4.1.2 Turbidity

The presence of suspended particles such as clay, silt, organic matter (decaying plants and animals), plankton, microorganisms and other dissolved organic compounds (dyes) in water usually impart some cloudiness or muddiness in water. A measure of this cloudiness or clarity in water is what is termed turbidity (Bouvier *et al.*, 2013). Turbidity does not measure the quantum of chemical and biological particles in the water, but the magnitude of light scattering caused by the particles present in the water (Eisnor *et al.*, 2001). Nephelometry (measurement of the extent of light scattering by particles suspended in a fluid when a beam of light is incident on it) is the most reliable technique for measuring turbidity. The common device for determining turbidity is the turbidity meter, which records the amount of light scattered in nephelometric turbidity units (NTU) (Canadian Water Quality Guidelines for the Protection of Aquatic Life, 2002). Particles responsible for turbidity of water, especially surface water, are potentially sourced from runoff from road construction sites, mining activities, agricultural activities, infrastructural developments, dredging, etc. Turbidity reduces the aesthetic value of water and much cost is incurred in treating turbid waters (Buczek *et al.*, 2018).

Research have shown that when source water is more turbid, high dosage of coagulant is required to adequately neutralize and destabilize the suspended particles. Also, since the suspended particles tend to provide some shield for most microorganisms (viruses, protozoans, bacteria, and coliforms), disinfection efficiency is reduced. This thus requires that high chlorine dosage is applied during disinfection. In treating water with high biological load (algae, zooplankton, etc.), there is a high tendency of clogging of the pores in the filter bed, reducing the efficiency of the filter media. In such cases, backwashing is done within short time intervals. Hence, the cost of treating highly turbid waters to meet quality standards may be very high (Kale, 2016; Braul *et al.*, 2001; Ogutu and Otieno, [n.d]).

Ecologically, turbidity decreases light penetration in water bodies limiting photosynthetic activities of primary producers (macrophytes, periphyton, and phytoplankton), which consequently results to anoxic conditions in the water bodies (Buczek *et al.*, 2018; Bouvier

et al., 2013) and may also increase water temperature (Kale, 2016). Increased sedimentation in surface waters also cause gill damage in fishes, impairs the visual abilities of fishes and this reduces their swimming and mating opportunities, retard growth and survival (Gray *et al.*, 2016). Generally, surface waters are more turbidity than ground water since surface water bodies are directly exposed to factors that cause turbidity. During the raining seasons, surface waters become more turbid than the dry seasons since erosions and runoffs are high during the wet seasons. Also, the extent of turbidity is affected by factors such as the concentration, size, shape, and refractive index of suspended sediments (Canadian Water Quality Guidelines for the Protection of Aquatic Life, 2002).

2.4.1.3 Colour

Another physical water quality parameter that is of greater concern to consumers is colour. Coloured water is aesthetically unpleasing to consumers. In addition to the unpleasant looks, coloured water may also be potentially detrimental to health since most of the dissolved substances may be toxic. Coloured water is also not suitable for washing clothes, dyeing, plastic production, textile industry, paper industry, beverages production, dairies and other food products. Colourless water is thus mostly preferred by consumers (Malakootian and Fatehizadeh, 2010). Colour in water may have its source from dredging, industrial wastes and runoffs from agricultural lands, construction sites, etc. Dyes, wood preservatives, antispasms, and various other dissolved organic substances from the activities of humans may also contribute to water colouration (Canadian Water Quality Guidelines for the Protection of Aquatic Life, 2001). Research has also indicated that when water contains humic substances in the presence of heavy metals, the heavy metals are able to react with the humic substances to generate colour in the water (Malakootian and Fatehizadeh, 2010).

Colour observed in water is as a result of light back scattered upward from the water after the light has passed through to various depths and undergone selective absorption (Canadian Water Quality Guidelines for the Protection of Aquatic Life, 2001). Generally, pure water looks bluish. This is because, in pure water, light is absorbed greatly in the infrared region of the light spectrum and poorly absorbed in the blue region. Hence blue light is refracted, reflected and/or re-emitted back, causing the visible colour of the water to be blue (Canadian Water Quality Guidelines for the Protection of Aquatic Life, 2001). Colour of water has been broadly categorized into true and apparent colours (Hendricks, 2011). True colour is the result of soluble chemical substances including natural minerals such as metal ions (iron and manganese), lignin, tannin, algae, peaty matters, planktons, ferric hydroxide and

dissolved organic substances such as humic or fulvic acids that cannot be separated by filtration (Malakootian and Fatehizadeh, 2010; Canadian Water Quality Guidelines for the Protection of Aquatic Life, 2001). Two common methods by which true colour can be measured are the comparator and calorimetric methods. Comparator methods rely on visual comparison of a water sample to a standard colour solution, usually containing platinum (Pt) and cobalt (Co) chloride salts, or to a set of coloured filter disks. Calorimetric methods are based on the calibration of absorbance of the water sample at various single wavelengths, usually against the Pt-Co standard (Malakootian and Fatehizadeh, 2010; Canadian Water Quality Guidelines for the Protection of Aquatic Life, 2001). Apparent colour, on the other hand, is the colour resulting from the combined effect of dissolved compounds (that is true colour) and any particulate matter or suspended materials such as organic plant debris, phyto and zooplankton, and inorganic suspended sediments. In view of this, the value obtained for true colour measurement is significantly less than the apparent colour (Australian Drinking Water Guidelines, 2013; Canadian Water Quality Guidelines for the Protection of Aquatic Life, 2001).

In water treatment, colour is known to interfere coagulation processes. There is also high chlorine demand for water with high amount of colour since chlorine also functions to remove colour from water (Hendricks, 2011). The maximum allowable colour in drinking water set by WHO is 15.0 TCU (Ezeh *et al.*, 2017).

2.4.2 Chemical Parameters

2.4.2.1 Iron

Iron is considered as one of the major impurities in the raw water treated at the Barekese Headworks. As an essential element, it is known to play significant roles in physiological processes such as helping in the transportation of oxygen in the blood and also serves as a cofactor for many tissue enzymes (Hossain *et al.*, 2016; Slaninova *et al.*, 2014, Gražulevičienė and Balčius, 2009). However, high concentrations of iron in drinking have been found to cause gastrointestinal disorder such as vomiting, diarrhoea, and abdominal pain. Aesthetically, high iron concentrations result to some reddish coloration in water, which subsequently increase water colour (Kritzberg and Ekström, 2012). Also, Vegetables and other food stuffs cooked with water rich in iron usually develops some dark coating and hence look unattractive (Hossain *et al.* 2016).

Iron is generally present in two different forms; the reduced soluble divalent ferrous (Fe^{2+}) and the oxidized trivalent ferric (Fe^{3+}). It is colorless when present in water in the ferrous

state. However, water containing the ferric form of iron usually has high colour due to the reddish- brown nature of the Fe^{3+} . Due to the negative health and aesthetic implications of iron in water, WHO recommends that the permissible level of iron in drinking water should be less or equal to 0.3 mg/l (Vasudevan *et al.*, 2009).

2.4.2.2 Residual Aluminium

Aluminium is a ubiquitous element constituting about 8% of the earth's crust. It is present in the environment in the form of oxides, silicates and hydroxides. It may also be present in the form of complexes with organic matter (WHO, 2010). Though naturally present in the environment, however, its presence in water is greatly increased by the introduction of Aluminium coagulants during water treatment processes (Tomperi *et al.*, 2013). Exposure to high concentration of residual Aluminium is known to be detrimental to human health. For instance, high levels of Aluminium are reported to be associated with neurodegenerative diseases such as dialysis encephalopathy, Alzheimer's disease, Parkinson's disease, etc (Sieliuchi *et al.*, 2010). Other disorders associated when exposed to high level of residual Aluminium in drinking water includes nausea, vomiting, diarrhea, mouth and skin ulcers, rashes and arthritic pain (Tomperi *et al.*, 2013). High concentrations of Aluminium in the human system may also react with essential elements such as zinc, iron, calcium and chromium, thereby inhibiting them to execute their functions appropriately (Sieliuchi *et al.*, 2010). Due to the toxicity of residual Aluminium when consumed, acceptable limit has been established (0.2 mg/l) for drinking water above which may pose health threats (Milind *et al.*, 2012).

CHAPTER 3

MATERIALS AND METHODS

3.1 Study Area

The construction of the Barekese Water Treatment Plant (BWTP) was completed in 1969 during the regime of the then president of the republic of Ghana, Dr. Kwame Nkrumah. The plant is located at Barekese about 22 km northwest of Kumasi, the capital of Ashanti region of Ghana. It is fed by a reservoir of about 35,300,000 m³ capacity resulting from a Dam constructed across the Offin river. The Plant was constructed to augment water supply by the Owabi Water Treatment Plant to the people of Kumasi and its neighbouring environs. In 1971, the BWTP was commissioned with initial design capacity of 12 million gallons (approximately 45, 425 m³) of water per day. Currently, the design capacity has been increased to 30 million gallons (approximately 113,562.5 m³) of water per day, supplying water to about 80% of the population in the Kumasi metropolis (GWCL, 2019).

3.1.1 Map of the Barekese Water Treatment Plant

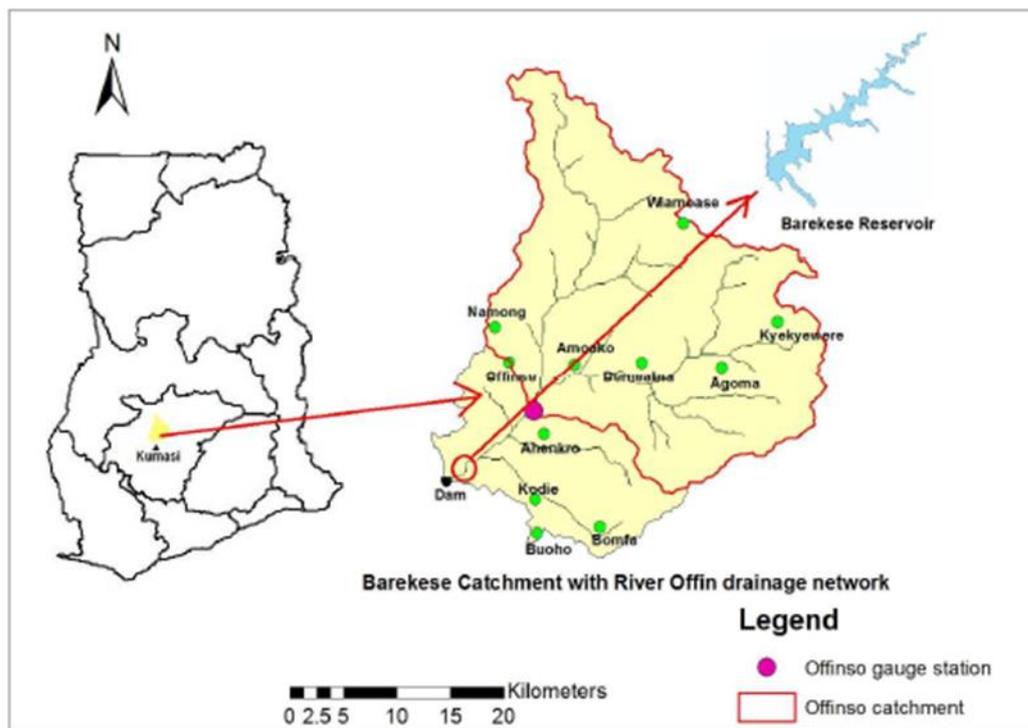


Figure 3.1 Map of Barekese Water Treatment Plant and its catchment area

3.2 Desk Study

Management of the Barekese Water Treatment Plant were first engaged in an interview to know the operational practices on the Plant. From this conversation, information such as the mixing speed, mixing time, maximum contact time employed in the Jar Test were obtained. Also, water quality records from their Water Quality Laboratory were gathered from 2013 to 2018 for analysis. Water quality parameters that were consistently available during this desk study included the pH, colour and turbidity (physical parameters) of the raw, settled, filtered and final water. The information gathered from this desk study served as the basis for this study.

3.3 Raw water Sampling

Raw water from the Barekese reservoir was sampled from the sampling tap at the aerator into well-cleaned drums/containers and covered. The initial pH, turbidity and colour of the sampled water were taken on site. The sampled water was then transported to the KNUST Civil Engineering and Environmental Quality Laboratory for Jar Test and subsequent physical and chemical analysis.

3.4 Calibration of pH Meter

The pH meter used for the pH determinations was calibrated using buffer solutions of pH 4.01, 7.00 and 10.00. The pH meter was powered and allowed to stabilize. The CAL button was pressed and the probe of the pH meter was first put into the buffer 4.01. The probe was allowed to stay in the solution until it reads 4.01. The probe was removed, rinsed with distilled water and put into another buffer of pH 7.00. Same procedure was repeated for the buffer 10. The pH meter, after this treatment, was deemed ready for use.

3.5 Calibration of Turbidity Meter

The turbidity meter used for the turbidity measurement was calibrated using standard solutions of 0, 10, 20 and 100 NTU. The meter was powered and allowed to stabilize. The sample cell was rinsed distilled water

3.6 Preparation of Solution

3.6.1 0.1N Hydrochloric Acid (HCl) Solution

8.31 ml of a stock acid solution (12.03M) was measured into a 1000 ml volumetric flask already containing reasonable volume of distilled water using a measuring cylinder. The

measuring cylinder was rinsed with enough distilled water and added to the solution in the 1000 ml flask. More distilled water was added to this mixture until the 1000 ml mark. The volumetric flask was then corked and shook gently to ensure that a uniform mixture was achieved. This acid solution was used for the pH adjustment.

3.6.2 0.1N Sodium Hydroxide (NaOH) Solution

Approximately 4.0g of NaOH pellets was weighed into a beaker using analytical weighing balance. The pellets were dissolved using distilled water and poured into a 1000 ml volumetric flask. The beaker was rinsed with enough distilled and poured into the 1000 ml flask. The solution was topped up to the 1000 ml mark using distilled water. The volumetric flask was then corked and gently shaken to ensure that a uniform mixture was achieved. This basic solution was used to raise the pH of the sampled water when necessary.

3.6.3 One Percent (1%) Polyaluminium Chloride solution

The concentration of the PAC solution adopted for the Jar Test at the Barekese Water Treatment Plant is 1%. Therefore, similar solution was prepared for this study. Exactly 1.0 ml of the stock polymer solution was measured into a 100 ml volumetric flask and topped up with distilled water while swirling to ensure uniform mixing until the 100 ml mark was reached. The flask was then corked and kept for use.

3.7 Preparation of sampled water for Jar Test

From the historic data collected from the Barekese Headworks, the predominant pH range of their raw water was found to be between 6 and 8.5. Therefore, the pH of the sampled water was adjusted from 6.0 to 8.5 at 0.5 intervals using the 0.1N HCl and NaOH solutions prepared.

3.8 Jar Test experiment

Below is the setup for the Jar Test. The device for this experiment is known as the flocculator. In it, there are six mixers (stirrers), each for a beaker. It has the speed button for adjusting the speed of mixing (revolution per minute) and a time button for setting the time or duration (minutes) for a particular mixing speed.



Plate 1 Jar Test setup (flocculator)

3.8.1 Experiment 1

A portion of the raw water sampled from Barekese Reservoir was poured into a clean rubber bucket. The pH was adjusted to pH 6.0 (see Section 3.7). Approximately 1000 ml of this prepared water sample was measured into six different one litre (1.0 L) beakers and labelled as beakers 1 to 6. Beaker number 1 was designated as the control setup. 1.5, 2.0, 2.5, 3.0, and 3.5 ml of the 1% polymer solution prepared were measured using five different cleaned syringes into beakers 2, 3, 4, 5 and 6 respectively. The measured polymer solutions were poured into their assigned samples simultaneously and the device was started immediately. The stirrers were set to achieve a revolving speed of 180 rpm for 5 minutes (fast mixing), followed by a slow mixing of 40 rpm for 10 minutes. When the mixing time elapsed, the stirrers were removed and the PAC-treated samples were allowed to stand for 15 minutes. The supernatant obtained from each sample was gently poured. The turbidity and colour of the supernatants were then determined. This procedure was repeated four more times and the mean values obtained were analysed. Another portion of this raw water sample whose pH has been adjusted to 6.0 was subjected to another Jar Test using two different revolutions per minute (180:25 and 150:25) to investigate the effect of varied mixing speeds on the performance of coagulation. The pH of the raw water sample was varied to 6.5, 7.0, 7.5, 8.0 and 8.5 and the whole Jar Test procedure described above was repeated. All determinations were done at room temperature.

NB: The choice of procedure outlined in this Jar Test experiment was based on what is practised at the Barekese Headworks.

3.8.2 Experiment 2

Raw water from the Barekese Headworks was sampled. The sampled water was subjected to the same treatment as described in Section 3.7 above. The adjusted water sample was then subjected to the Jar Test using the best mixing speed (150:25 rpm) and optimum PAC dosage (15 ppm) derived from experiment 1. The Jar Test experiment was carried out following the procedure outlined in section 3.8.1. However, with this setup, the supernatant obtained were tested every five minutes up to the 30th minute (i.e 5, 10, 15, 20, 25 and 30 minutes) to ascertain the effects of retention time on the removal of contaminants (turbidity and colour) from the treated water. All the determinations were done at room temperature.

3.8.3 Experiment 3

Raw water was sampled from the Barekese Headworks, adjusted to the desired pH as described in section 3.7 above. The prepared water sample was then subjected to the Jar Test using the optimal mixing speed (150:25) and PAC dose (15 ppm) identified in experiment 1. In this experiment, the effect of mixing time on the removal of contaminants from water was examined. The duration for the fast mixing speed was reduced from 5 minutes to 2 minutes and the slow mixing speed, from 10 minutes to 5 minutes. The supernatant obtained was examined at different retention times as mentioned in Section 3.8.2. All determinations were made at room temperature.

3.9 Determination of Water Quality Parameters

3.9.1 pH

The pH of the supernatant for each sample was determined using pH meter (see Plate 3). The probe of the pH meter was dipped into the blank solution (the sample with no polymer), the pH read on the screen of the pH meter. This was repeated for supernatants from beakers 2, 3, 4, 5 and 6. After each determination, the probe was removed and dropped into distilled water before another determination in order to avoid any potential contamination.

3.9.2 Turbidity

The turbidity of the supernatants obtained from the Jar Test was determined using the HANNA turbidity meter (see Plate 2). Before determination, the supernatant was shaken to

ensure that any settled particle was re-dispersed into the bulk solution. Aliquot of supernatants from each beaker was poured into the sample cell up to the 10 ml mark on it. The cell was corked, cleaned using tissue paper and inserted into the turbidity meter. The read button was pressed and the turbidity value was read in NTU.



Plate 2 HANNA Turbidimeter



Plate 3 pH meter

3.9.3 Colour

The colour of the PAC-flocculated water samples was determined using the HACH spectrophotometer (DR 3900 model) (see Plate 4). The device was first powered and set to colour reading at 455 nm. A 10.0 ml of distilled water was measured into one sample cell. This, serving as the blank, was used to zero the spectrophotometer. Exactly 10.0 ml of the flocculated water was then measured into another sample cell. The colour of this sample was determined by pressing the start button on the spectrophotometer.



Plate 4 HACH Spectrophotometer (DR 3900 model)



Plate 5 Photometer 7500

3.9.4 Residual Aluminium

The residual Aluminium in the flocculated water was determined using the Palintest reagents for Aluminium determination (XXAP 166 and XXAP 167) and the Interface Photometer 7500 (see Plate 5). The procedure for the measurement is as below:

- A 10.0 ml of the water sample was measured into a test tube
- One Aluminium No. 1 tablet was added to this measured sample, crushed and mixed to dissolve
- One Aluminium No. 2 tablet was then added to this solution, crushed and mixed gently to dissolve.
- The resulting solution was allowed a reaction time of five minutes
- A 10.0 ml of distilled water was measured into another test tube as the blank.
- Phot 3 was selected and the blank was first run before the analyte. The concentration of Aluminium in the sample was read in mg/l

3.9.5 Iron

Iron levels in the water samples were determined using Ferrover and the HACH spectrophotometer (DR 3900 model) (see Plate 5). The following procedure was observed for the iron determination.

- Exactly 10.0 ml of the sample was measured into two different sample cells.

- A pillow of the Ferrover was poured into one of these sample cell content, leaving the other as the blank.
- The resulting solution was allowed a reaction time of three minutes.
- The spectrophotometer was powered, set to Ferrover iron measure.
- The blank was first run before the analyte. The concentration of iron in the sample was read in mg/l

3.10 Statistical Analysis

Statistical tools such as SPSS (Statistical Package for the Social Sciences, version 16.0) and Microsoft Excel (2019) were used in the study for plotting of graphs and computation of parameters such as means and analysis of variance (ANOVA).

3.11 Contaminant Removal Efficiency

The efficiency of contaminant removal from the PAC-treated water was estimated using the formula below:

$$\text{Removal efficiency} = \frac{(\text{Initial contaminant level} - \text{final contaminant level})}{\text{Initial contaminant level}} \times 100$$

3.12 Comparative Cost Benefit Analysis

Production cost, in terms of coagulant usage, on the plant for the existing operational conditions was computed and compared with the experimentally determined optimum dosage. The difference between these two was estimated.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Historic data from the Barekese Headworks

Historic data on the quality of the raw water and the treated water were gathered from the Barekese Water Quality Laboratory. The data gathered ranged from 2013 to 2018. Information on the pH, the turbidity, colour and coagulant dosage were collected.

4.1.1 Raw Water pH from 2013 to 2018

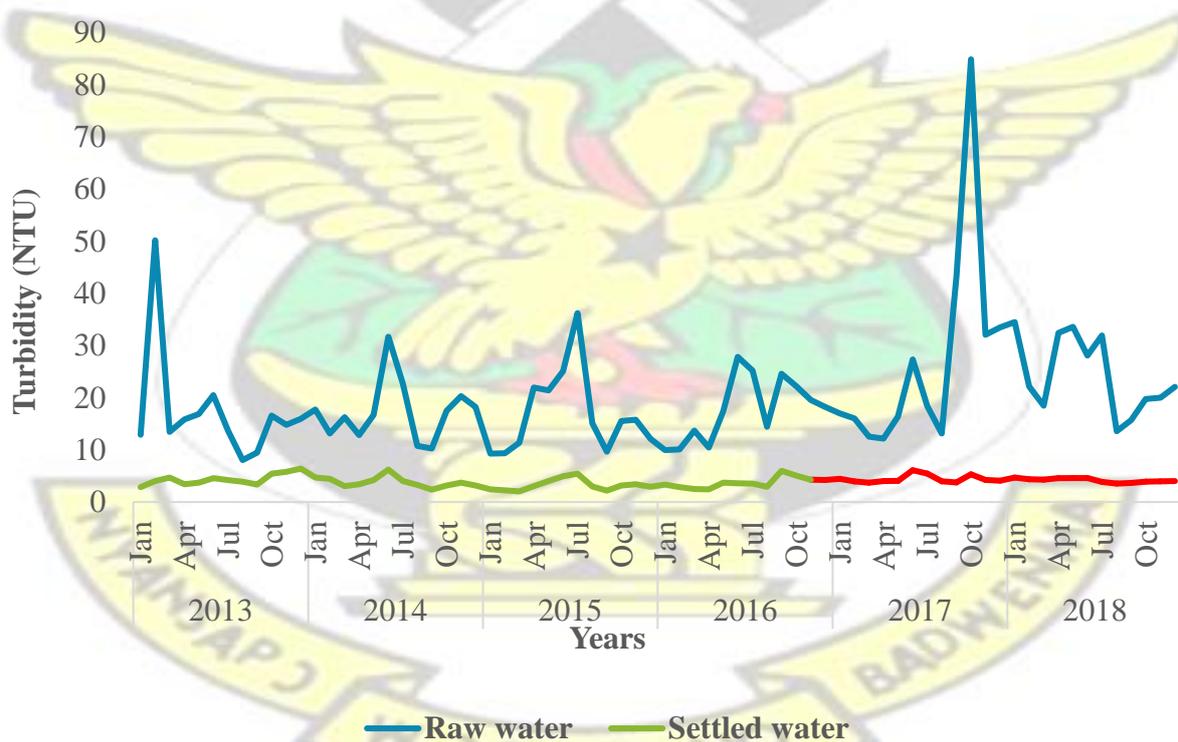
From Figure 4.1, it can be seen that the pH of the Barekese raw water lied within the normal raw water pH of 6.5 to 8.5, except in September, 2013 where a sharp drop in pH was recorded. The sharp drop in pH could possibly be due to the discharge of high loads of dissolved acidic substances from industrial effluents, surface runoff and other sources into the streams and rivers that feed the Barekese reservoir.



Figure 4.1 Trend of raw water pH from 2013 to 2018

4.1.2 Raw Water Turbidity and Settled Water Turbidity from 2013 to 2018

The average turbidity of the raw water from 2013 to 2018 is as shown in Figure 4.2. It was observed that the turbidity generally hovered around 10 to 30 NTU; however, very high turbidity values were recorded in February 2013 and October, 2017. The sharp increase in turbidity in these specific periods could be attributed to human activities such as road construction within the Kumasi Metropolis and natural factors such as high rains (with subsequent increase in runoff). Between 2013 and 2017, the average dose of the Alum applied on the Plant was 70.35 mg/l, with minimum and maximum dosages of 56.73 and 96.78 mg/l respectively. Nonetheless, the average dose of the PAC since its introduction was found to be 33.18 mg/l, within the range of 14.11 to 43.80 mg/l (see Table 4.1). This suggests that the PAC is more efficient than the Alum. It was also observed that since the introduction of the PAC in December, 2016, the turbidity of the settled water remained fairly stable within the range of 3.54 to 6.09 NTU compared to the time Alum was used as the coagulant (2.04 to 6.41 NTU).

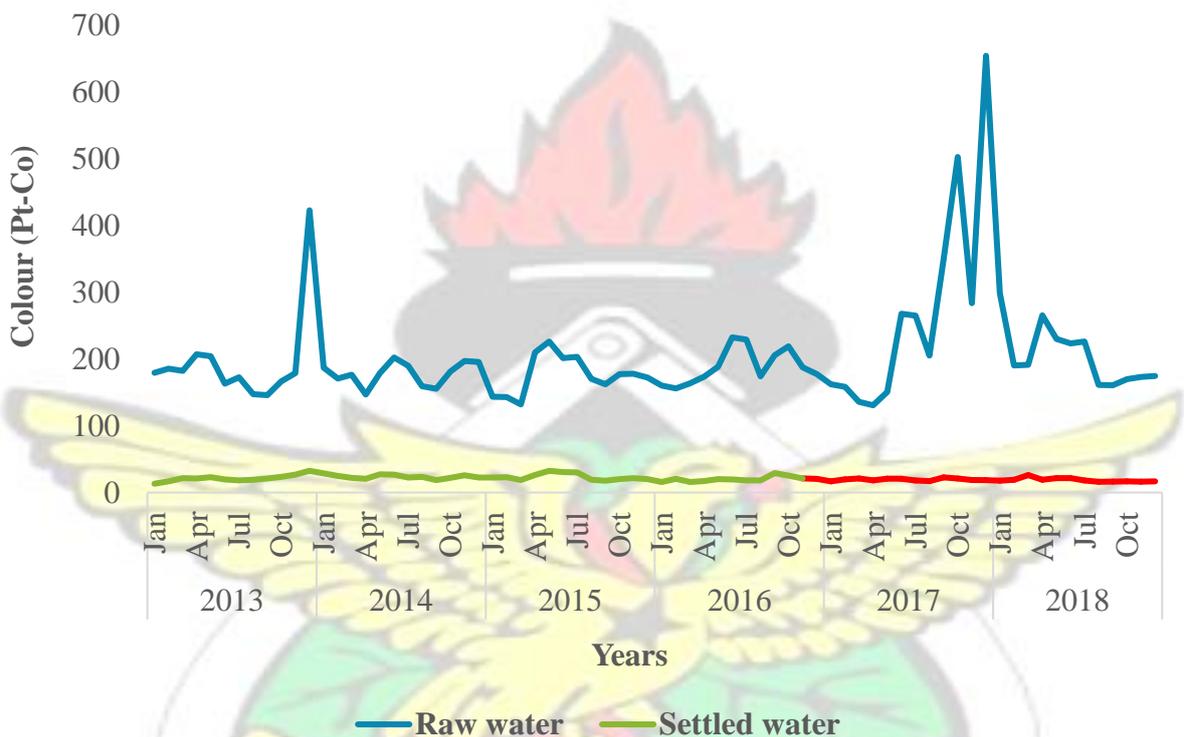


**The red line represents the settled water turbidity when PAC was applied.*

Figure 4.2 Trend of raw and settled water turbidity from 2013 to 2018

4.1.3 Raw and Settled Water Colour from 2013 to 2018

The graph below shows the trend of raw water and settled water colour from 2013 to 2018. Generally, it was observed that the colour of the raw water was averagely around 200 Pt-Co. However, in December, 2013 and late 2017, the colour of the raw water was found to be relatively high. This may be due to the presence of high concentrations of organics in effluents discharged into the water. For the settled water, the colour was found to range between 15 and 20 Pt-Co.



*The red line represents the settled water colour when PAC was applied.

Figure 4.3 Trend of mean monthly colour of raw water and settled water from 2013 to 2018

The dose of the Alum and the PAC applied here is similar to those mentioned in Section 4.1.2. It was also observed that since the introduction of the PAC in December, 2016, the colour of the settled water remained fairly stable within the range of 16.06 to 26.09 Pt-Co units compared to Alum's regime of 15.75 to 32.55 Pt-Co units. The average colour obtained since the application of the PAC was recorded as 19.10 Pt-Co units as against 22.11 Pt-Co units during the time when Alum was used.

4.1.4 Mean Coagulant Consumption (ppm) from 2013 to 2018

Table 4.1 shows the average monthly consumption of coagulant from 2013 to 2018. From the time the Barekese Water Treatment Plant was commissioned to November, 2016, Alum has been the primary coagulant for water purification. However, from December, 2016 to date (except in August and September, 2017), PAC has been adopted to improve the treatment process. The average monthly consumption over this period ranged between 14.11 and 43.22 ppm. Comparatively, the PAC was found to be more efficient for coagulation than the Alum since it requires relatively low dosage to remove contaminants from water.

Table 4.1 Mean coagulant consumption from 2013 to 2018

Month	Alum and PAC consumption (ppm)					
	2013 ϕ	2014 ϕ	2015 ϕ	2016 ϕ	2017*	2018*
January	71.13	69.63	60.42	70.98	21.40	38.27
February	63.65	66.67	56.73	67.25	42.58	35.56
March	62.09	65.34	58.18	62.86	38.68	31.43
April	68.79	62.07	65.43	69.55	37.93	42.41
May	70.88	66.52	72.97	69.60	43.22	42.08
June	70.74	70.17	73.44	89.30	34.82	34.23
July	67.93	69.67	74.47	89.77	18.30	37.25
August	72.50	64.50	67.22	85.44	82.06 ϕ	19.47
September	73.87	60.34	65.24	77.47	72.05 ϕ	33.01
October	78.24	61.35	72.99	86.24	14.11	26.24
November	67.17	62.96	70.27	96.78	39.94	28.58
December	69.56	64.67	69.95	28.90*	43.15	30.05

The ϕ represents Alum and * represents PAC

4.2 Results for Laboratory Experiment 1

The initial characteristics of the raw water sampled from the Barekese Headworks were examined. The sampled water was then subjected to the Jar Test at varied pH and the effects of mixing speed and PAC dosage on turbidity removal were assessed (see section 3.8.1). The mean turbidity and colour levels are presented in tables in appendix B.

4.2.1 Initial Raw Water Characteristics

The characteristics of the raw water sampled from the Barekese Headworks were as follows

pH = 7.76

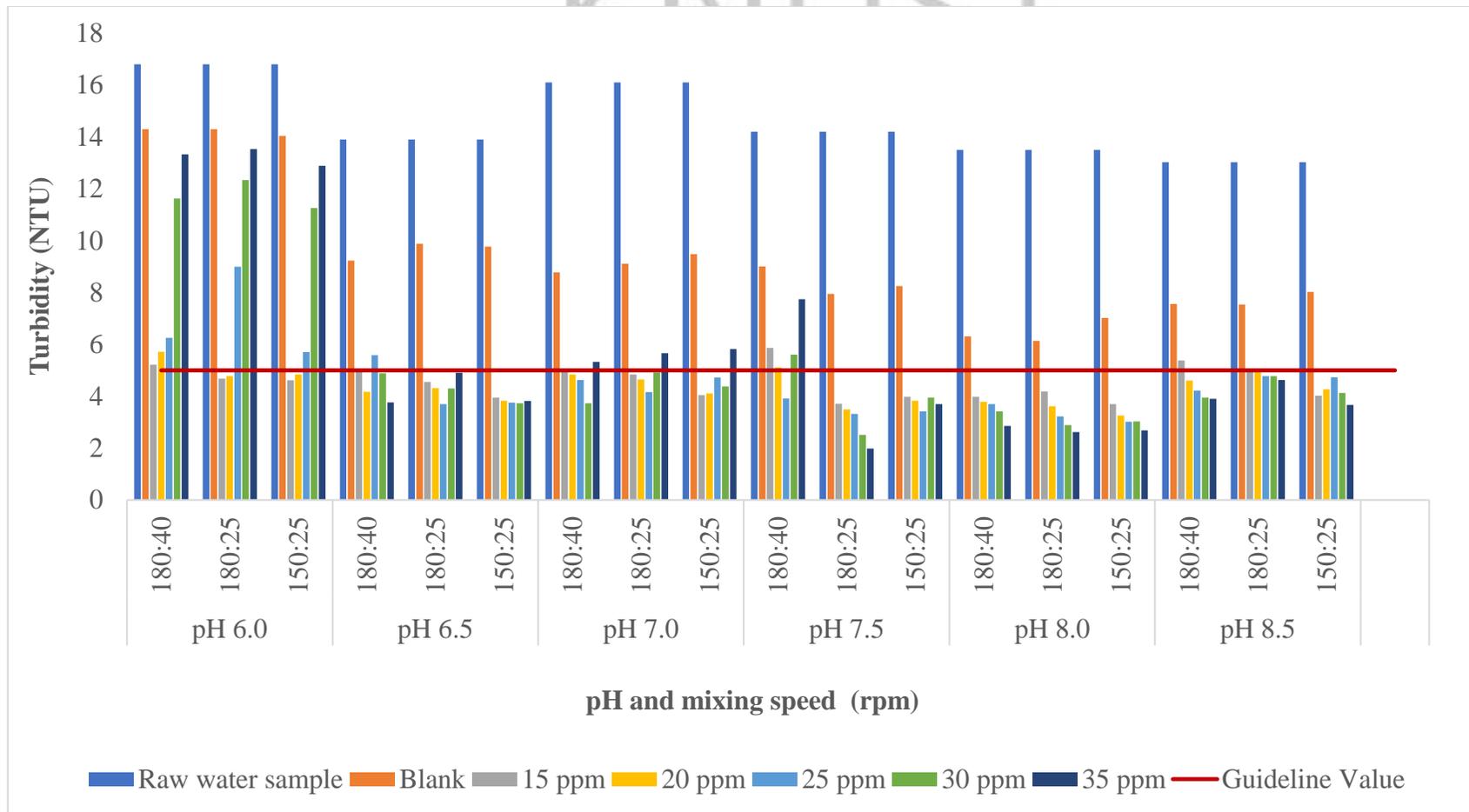
Turbidity = 24.5 NTU

Colour = 200 Pt-Co

Iron = 5.45 mg/l

4.2.2 Effect of pH, Mixing Speed and PAC Dosage on the Turbidity of Flocculated Water.

The effect of pH, mixing speed and PAC dosage on turbidity removal from raw water was assessed experimentally. Figure 4.4 shows the turbidity levels for water samples treated with different dosages of the PAC at different pH, taking into consideration three different mixing speeds (180:40 rpm, 180:25 rpm and 150:25 rpm mixing speeds). The pH of the water was adjusted from 6.0 to 8.5 at intervals of 0.5.



* Along the pH axis, the various mixing speeds (in rpm) employed in the study have been indicated. The indicated mixing speeds show the initial mixing speed and the subsequent slow mixing speed.

*The different PAC dosages and guideline value for turbidity have also been indicated with different colour bars

Figure 4.4 Mean turbidity of treated water at different pH, PAC dosage and mixing speed

1. Turbidity Levels at pH 6.0

The effects of mixing speed and PAC dosage on turbidity removal at pH 6.0 were examined the results are discussed below:

- i. 180:40 rpm mixing speed:** From Figure 4.4, it was observed that as the dosage of the Polyaluminium Chloride (PAC) increased, turbidity of the supernatants obtained also increased. The increase in turbidity signifies that the polymer in high dosages does not achieve efficient turbidity removal. This is because excess concentration of the PAC causes the surfaces of the colloidal particles to be saturated with the positively charged ions of the PAC. This, by means repulsive forces, impedes agglomeration, with consequent increase in turbidity values in the treated water. None of the dosages produced turbidity values within the GWCL settled water standard of 5.0 NTU. However, comparing their respective turbidity levels, 15 ppm dosage was found to reduce the turbidity of the flocculated water sufficiently.
- ii. 180:25 rpm mixing speed:** For this mixing speed, it was found that increasing the dose of the PAC resulted to an increase in turbidity of the treated water. The increase in turbidity with increasing PAC dosage suggests that high dosages of the PAC reduce the effectiveness of coagulation. From Figure 4.4 above, it can be seen that only the turbidities recorded for 15 ppm and 20 ppm dosages of the PAC met the GWCL guideline value of 5 NTU. Comparing the turbidity levels obtained for these two dosages, the 15 ppm was found to be better and hence the preferred dosage for this mixing speed.
- iii. 150:25 rpm mixing speed:** From Figure 4.4, it was also observed that increasing the PAC dosage increased the turbidity of the flocculated water. It was realized that only 15 ppm and 20 ppm dosages of the PAC yielded turbidity values within the acceptable limit (5.0 NTU) established by WHO and GWCL for settled water. Since 15 ppm removed turbidity better than the 20 ppm, it can be considered as the best dosage to be applied at this pH.

Summary

All the three mixing speeds employed at this pH required 15 ppm of the PAC for sufficient turbidity removal. Comparatively, the turbidity level obtained for 150:25 rpm mixing speed was best among the three mixing speeds. This may be because the prevailing velocity gradient (G) when 150:25 mixing was adopted enhanced agglomeration of the particles. From research works, high performance of coagulants is achieved in basins operating with G values between 20 and 74 S^{-1} . When G values are high, there is high tendency for formed

flocs to break apart. The higher the mixing speed, the higher the G value. Therefore, 150:25 mixing is recommended for operation.

2. Turbidity Levels at pH 6.5

The effects of the three mixing speeds and PAC dosage on turbidity removal are discussed below:

- i. **180:40 rpm mixing speed:** From Figure 4.4, a significant improvement in the treated water turbidity was observed when the dose of the PAC was increased from 15 ppm to 20 ppm. However, further increase in the dose to 25 ppm led to an increase in the treated water turbidity and began to drop gradually when the dosage was further increased to 30 ppm and 35 ppm. Of all the various dosages applied, only the 25 ppm failed to remove turbidity to acceptable level. Since 15 ppm dose of the PAC removed turbidity satisfactorily, it can be recommended for use in water treatment.
- ii. **180:25 rpm mixing speed:** All dosages of the PAC applied removed turbidity to acceptable levels. Although 25 ppm of the PAC produced relatively less turbid effluent compared to the other dosages, however, 15 ppm can be considered for application since it also removed turbidity acceptable level.
- iii. **150:25 rpm mixing speed:** For this mixing speed, all dosages of the PAC resulted to turbidity values within permissible limit (5.0 NTU). It can be seen from Figure 4.4 that as the dose of the PAC was increased, turbidity of the supernatants obtained also improved progressively. Statistically, the turbidity value obtained for the 15 ppm is not different (p value > 0.05) from the values obtained for the higher dosages. Therefore, to reduce production cost, 15 ppm is preferred.

Summary

Comparing the three mixing speeds discussed above, it is observed that all mixing speeds employed required just 15 ppm of the polymer for effective turbidity removal. However, higher efficiency was observed for 150:25 rpm mixing speed (71.63%) than the 180:40 rpm (64.39%) and 180:25 rpm (67.24%) mixing speeds. This may be because the induced shear forces when 150:25 mixing speed was employed were less. The higher the shear forces in the beakers, the higher the tendency for the formed flocs to be disintegrated.

3. Turbidity Levels at pH 7.0

The performance of the PAC in removing turbidity from the flocculated water was examined at pH 7.0 using the three mixings speeds as discussed below:

- i. 180:40 rpm mixing speed:** Increasing the PAC dosage reduced the turbidity of the treated water significantly, except the 35 ppm dosage where the turbidity increased beyond the guideline value. Although the turbidity value recorded for the 15 ppm dose (5.06 NTU) was above the GWCL guideline value (5.0 NTU), however, there is no significant difference between the two at 95% confidence (p value > 0.05). Therefore, 15 ppm can be considered in order to reduce production cost.
- ii. 180:25 rpm mixing speed:** Apart from the 35 ppm dose, all the other dosages of the PAC removed turbidity sufficiently to acceptable levels. Increasing the PAC dosage from 15 ppm to 25 ppm improved the turbidity significantly; nonetheless, further increase in the dose increased the turbidity of the treated water. Since the 15 ppm dosage of the PAC yielded acceptable turbidity value, it is recommended for application at pH 7.0.
- iii. 150:25 rpm mixing speed:** All dosages of the PAC were found to improve the turbidity of the treated water to acceptable levels, except the 35 ppm where the recorded turbidity was above the guideline value. Since 15 ppm dosage produced supernatant of acceptable turbidity level, it is recommended for application.

Summary

The 35 ppm dose of the PAC was generally found to produce supernatants of high turbidity values in all the three mixing speeds. This observation suggests that the 35 ppm was an overdose and thus, inhibited the agglomeration of the microflocs formed. All the three mixing speeds (180:40 rpm, 180:25 rpm and 150:20 rpm) required 15 ppm dose of the PAC for effective coagulation. The turbidity removal efficiencies estimated for 180:40 rpm, 180:25 rpm and 150:20 rpm mixing speeds were 68.59%, 69.92% and 74.87% respectively. Comparatively, 150:25 rpm was found to be more efficient, hence the recommended mixing speed for operation.

4. Turbidity Levels at pH 7.5

The effects of the three mixing speeds and PAC dosage on turbidity removal are discussed below:

- i. 180:40 rpm mixing speed:** It was observed that when the PAC dosage was increased from 15 ppm to 25 ppm, the turbidity of the treated water also improved accordingly. Nonetheless, further increase in the dose of the PAC resulted to increase in the treated water turbidity. The increase in the treated water turbidity may suggest that higher dosages of the PAC brought about charge reversal and re-suspension of

particles, thereby resulting to increased turbidity values. Of all the dosages of the PAC, only the 25 ppm met the GWCL guideline value for settled water. Hence, the preferred dosage when this mixing speed is practiced.

- ii. **180:25 rpm mixing speed:** Increasing the PAC dosage was found to improve the turbidity of the treated water progressively. This observation is consistent with the findings of by Zand and Hoveidi, 2015, Mirzaiy *et al.* 2012 and Yang *et al.* 2010 when coagulation performance of PAC was assessed. Turbidity values recorded for the various dosages met the guideline value of 5.0 NTU. Since turbidity values recorded for all dosages met the GWCL guideline value, 15 ppm (the lowest dosage) can be recommended for application so as to reduce production cost.
- iii. **150:25 rpm mixing speed:** A positive relationship was observed between the PAC dosage and turbidity removal. When the dose was increased, turbidity removal also increased accordingly. All PAC dosages removed turbidity satisfactorily to levels within the permissible limit of 5.0 NTU recommended by GWCL for settled water. Since 15 ppm of the PAC improved the turbidity of the flocculated water, it can be considered for application to reduce production cost.

Summary

180:40 rpm mixing speed was found to required high dose of the PAC (25 ppm) for effective coagulation. However, 180:25 and 150:25 rpm mixing speeds required just 15 ppm to effect sufficient turbidity removal from the PAC-treated water samples. Comparing the turbidity removal efficiencies for 180:25 rpm and 150:25 rpm mixing, the 180:25 was found to be more efficient (73.85%) than the 150:25 (71.97%). However, more electrical energy will be required to operate the 180:25 rpm mixing compared to the 150:25 rpm mixing. It will therefore be cheaper to operate with the 150:25 rpm mixing, hence the preferred mixing speed.

5. Turbidity Levels at pH 8.0

The effects of the three mixing speeds and PAC dosage on turbidity removal are discussed below:

- i. **180:40 rpm mixing speed:** Increasing the PAC dosage was found to progressively improve the turbidity of the treated water. All turbidity values recorded for the various dosages met the guideline value (5.0 NTU). Therefore, 15 ppm of the PAC is the preferred dose for application when this mixing speed is adopted.

- ii. **180:25 rpm mixing speed:** Increasing the PAC dosage led to a reduction in turbidity of the treated water samples. The resultant turbidities recorded for all dosages of the PAC met the GWCL guideline value (5.0 NTU). Therefore, 15 ppm is the preferred dosage for application in order to reduce production cost.
- iii. **150:25 rpm mixing speed:** It was observed from Figure 4.4 that as the dose of PAC was increased from 15 ppm to 35 ppm, the turbidity of the resulting supernatants reduced accordingly. All turbidity values recorded met the GWCL guideline value for flocculated water. Since acceptable turbidity value was recorded for the 15 ppm dosage, it can be recommended for use to achieve the production of safe water at reduced cost.

Summary

Increasing the dose of the PAC led to a progressive reduction in turbidity of the treated water. This observation was consistent with the findings of by Zand and Hoveidi, 2015, Mirzai *et al.* 2012 and Yang *et al.* 2010 when coagulation efficiency of PAC was studied. Comparing the three mixing speeds studied, it was realized that 15 ppm dose of the PAC was the maximum dose required to improve the turbidity of the Barekese raw water. However, higher efficiency was observed for the 150:25 rpm mixing speed (72.57%) than the 180:40 rpm (70.49%) and 180:25 rpm (69.04%) mixing speeds. Therefore, it can be said that 150:25 mixing speed provides optimal conditions for the PAC in removing turbid materials from the Barekese water at pH 8.0.

6. Turbidity Levels at pH 8.5

Turbidity removal efficiencies using different PAC dosages and mixing speeds at pH 8.5 are discussed below:

- i. **180:40 mixing speed:** It can be seen from Figure 4.4 that as the dosage of the PAC was increased, turbidity levels of treated water decreased significantly. Apart from the 15 ppm dose, all other dosages of the PAC produced supernatants of acceptable turbidity values (≤ 5.0 NTU). Therefore, the preferred dosage for this mixing speed at pH 8.5 is 20 ppm.
- ii. **180:25 mixing speed:** Turbidity removal from the treated water samples was found to increase while increasing the PAC dosage. All turbidity values recorded met the GWCL guideline value of 5.0 NTU, except that of the 15 ppm. Although the turbidity value recorded for the 15 ppm dose (5.06 NTU) was above the GWCL guideline value (5.0 NTU), however, there is no significant difference between the

two at 95% confidence (p value > 0.05). Therefore, 15 ppm can be considered for application in order to reduce production cost.

- iii. 150:25 mixing speed:** Figure 4.4 showed that increasing the PAC dosage from 15 ppm to 25 ppm resulted to an increase in turbidity values of the treated water samples. However, further increase in the PAC dosage from 30 ppm to 35 ppm saw a reduction in turbidity values. All turbidity values recorded were within the permissible limit (5.0 NTU) set by GWCL for settled water. Since 15 ppm produced supernatant of acceptable turbidity value, it is the preferred dose for treatment of the Barekese water at pH 8.5.

Summary

As the dose of the PAC was increased, a corresponding decrease in turbidity values was observed. A similar observation was made by Zand and Hoveidi, 2015, Mirzaei *et al.* 2012 and Yang *et al.* 2010 when the effect of PAC dose on coagulation efficiency was investigated. Comparing the three mixing speeds discussed above, 180:25 rpm and 150:25 rpm mixing speeds were found to require a maximum of 15 ppm dose of the PAC to remove turbidity sufficiently from the sampled water. However, higher turbidity removal efficiency was observed for 150:25 rpm mixing speed (70.22%) than the 180:25 rpm mixing speed (62.54%). Therefore, the recommended mixing speed and PAC dosage for pH 8.5 are 150:25 rpm and 15 ppm respectively.

Summary Table

The recommended mixing speed and PAC dosage at the various pH values are summarized in the table below:

Table 4.2 Recommended Mixing Speed and PAC Dosage at Varied pH Values

pH	Recommended mixing speed (rpm)	Recommended dosage (ppm)	Turbidity value (NTU)
6.0	150:25	15	4.61
6.5	150:25	15	3.94
7.0	150:25	15	4.05
7.5	150:25	15	3.98
8.0	150:25	15	3.70
8.5	150:25	15	4.02

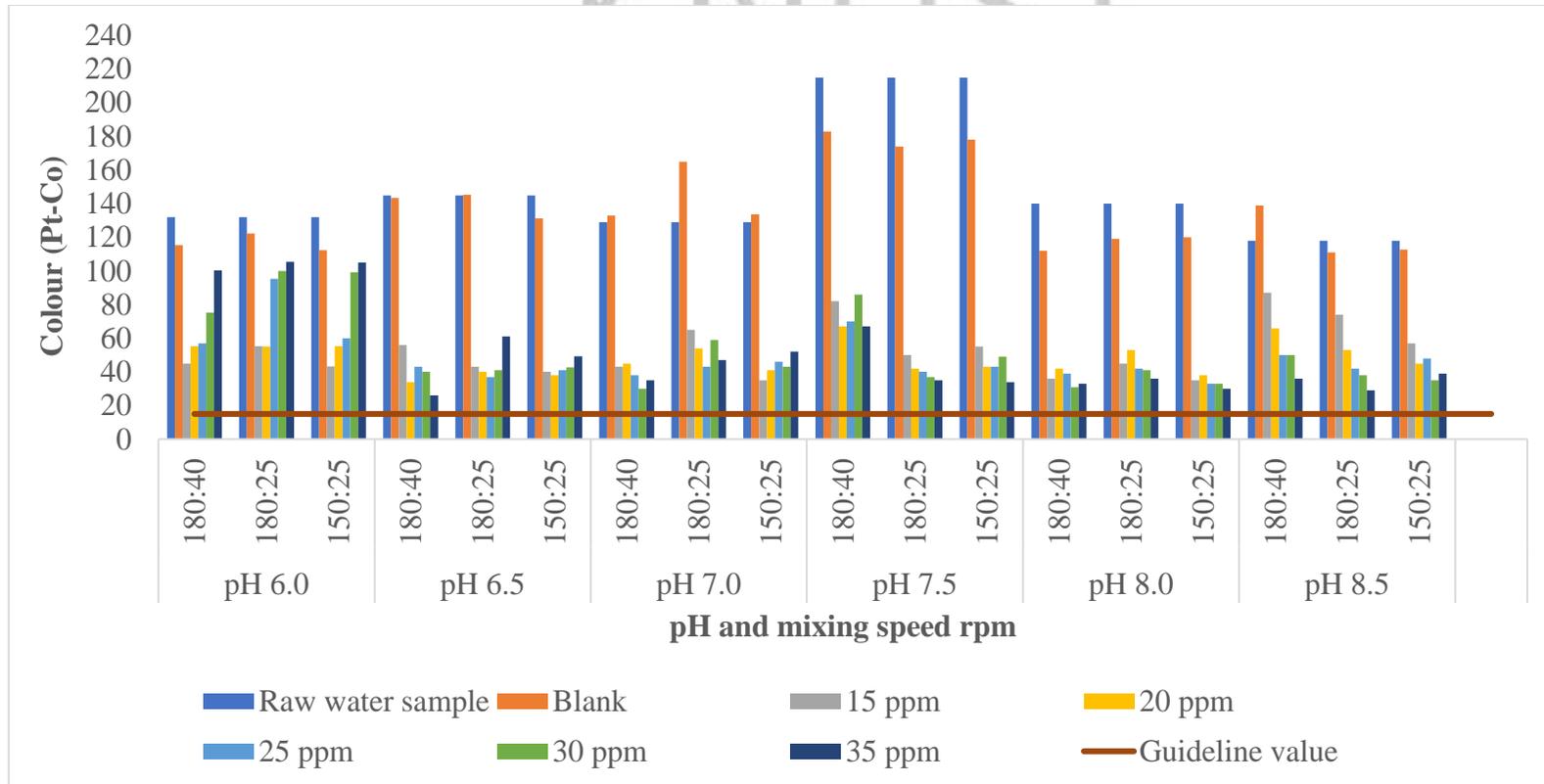
4.2.3 Effects of pH, Mixing Speed and PAC Dosage on Colour Removal

The effect of pH, mixing speed and PAC dosage on colour removal from raw water was evaluated experimentally. Figure 4.5 shows the colour values recorded for water samples dosed with different concentrations of the PAC for the three mixing speeds at different pH of the water. The pH of the water was adjusted from 6.0 to 8.5 at intervals of 0.5.

1. Colour Levels at pH 6.0

The effects of mixing speed and PAC dosage on colour removal at pH 6.0 were examined and the results discussed below:

- i. **180:40 rpm mixing speed:** The colour of the PAC-treated water was found to increase when the dose of the PAC was increased (see Figure 4.5). Dissolved organics are known to contribute greatly to water colour. However, the negative charges on the dissolved organic carbons decrease in acidic medium, and hence require only small amount of coagulant to destabilize them (Pernitsky and Edzwald, 2006). This theory explains why high dosages of the PAC led to an increase in the colour of the treated water. All colour values recorded failed to meet the standard guideline value of 15.0 Pt-Co units. However, the 15 ppm is the preferred dose since its colour level was best among the higher dosages.
- ii. **180:25 rpm mixing speed:** Increasing the dose of the increased the resultant colour of the treated water (see Figure 4.5). None of the readings met the standard requirement for settled water (15.0 Pt-Co units) set by WHO and GWCL. This observation contradicts the findings of Yuan-Shing and Ha-Manh, 2014 when Polyaluminium Chloride (PAC) was used for the decolorization of reactive dyeing wastewater. The disparity observed may be due to the difference in the characteristics of the water studied. Although none of these values met the guideline value, however, the colour value obtained for the 15 ppm was best, and hence the preferred dose.



* Along the pH axis, the various mixing speeds (in rpm) employed in the study have been indicated. The indicated mixing speeds show the initial mixing speed and the subsequent slow mixing speed.

*The different PAC dosages and guideline value for colour have also been indicated with different colour bars

Figure 4.5 Mean Colour of Flocculated Water at Different pH, PAC Dosage and Mixing Speed

- iii. 150:25 rpm mixing speed:** From Figure 4.5, it was also observed that increasing the PAC dosage from 15 ppm to 35 ppm led to an increase in the colour of the treated water. All the colour values failed to meet the recommended guideline value (15.0 Pt-Co units) set by WHO and GWCL for settled water. However, since 15 ppm resulted to relatively improved colour of the treated water, it can be said to be the maximum dosage required for sufficient colour removal.

Summary

Higher dosages of the PAC were found to increase the colour of the treated water. This may be due to the oxidation of the dissolved organics in the acidic regions, requiring less amount of coagulant to be destabilized. All the three mixing speeds studied required 15 ppm dose of the PAC to remove sufficient water colour. Although colour removal was not satisfactory, however, comparing the three mixing speeds investigated, 150:25 rpm was found to be the best. This indicates that 150:25 rpm mixing speeds provided favorable conditions for efficient use of the PAC than the other two. This finding was similar to that of Yuan-Shing and Ha-Manh, 2014 and Aziz *et al.* 2009 when the effect of mixing speed on colour removal was investigated. Hence the recommended mixing speed at pH 6.0 is the 150:25 rpm.

2. Colour Levels at pH 6.5

- i. 180:40 rpm mixing speed:** From Figure 4.5, it was observed that none of the dosages of the PAC applied could remove colour from the sampled water to acceptable levels. The 35 ppm dose was found to improve the colour sufficiently. However, the colour values record for the 20 ppm and the 35 ppm are comparable. Therefore, the 20 ppm is chosen to reduce production cost.
- ii. 180:25 rpm mixing speed:** From Figure 4.5, it was realized that increasing the PAC dose from 15 ppm to 25 ppm, the colour of the treated water improved significantly. Nonetheless, appreciable increase in colour was observed in the treated water when the dose of the PAC was further increased. This observation was found to be consistent with the findings of Aziz *et al.* 2009 when the efficiency of water colour removal was studied using PAC as coagulant. The increase in water colour at high PAC dosages suggests that excess ions of the PAC resulted to charge reversal and redistribution of organics and other colour-contributing substances, thereby rendering them suspended in the water. All colour values recorded failed to meet the standard requirement for settled water (15.0 Pt-Co units). Although 25 ppm improved the colour of the water best, however, there is no significant difference

between the colour values recorded for the 20 ppm and the 25 ppm dose. Therefore, 20 ppm is the recommended dose for this mixing speed.

- iii. **150:25 rpm mixing speed:** Increasing the PAC dosage from 15 ppm to 20 ppm decolorized the water accordingly. However, further increase in the coagulant dose increased the colour of the treated water considerably. The possible cause of this observation is as discussed in (ii) above. All dosages failed to produce colour values to acceptable levels. Nonetheless, the 20 ppm was found to produce relatively better colour value. Hence the recommended dose.

Summary

All three mixing speed examined required 20 ppm of the polymer for sufficient colour removal. The order of the performance of the three mixing speeds was 180:40 rpm > 150:25 rpm > 180:25 rpm. Analysis of variance showed no significant difference between the colour values recorded for the 180:40 rpm and 150:25 rpm mixing speeds. However, higher energy will be required to operate the 180:40 rpm mixing speed. Therefore 150:25 rpm mixing is preferred since it will be cheaper to operate with.

3. Colour Levels at pH 7.0

- i. **180:40 rpm mixing speed:** In Figure 4.5, no regular trend was observed on the removal of colour from water when different dosages of the PAC were administered. None of the resultant colour values met the standard requirement for settled water. The 30 ppm dose of the PAC was found to produce supernatant of least colour value. However, the colour readings for the 25 ppm and 30 ppm are comparable. Hence 25 ppm is preferred to the 30 ppm so as to reduce production cost.
- ii. **180:25 rpm mixing speed:** Increasing PAC dosage was observed to improve the colour of the treated water significantly, except the 30 ppm dose which may be due to chance variation. From the results shown in Figure 4.5, 25 ppm is the recommended dose for this mixing speed since its colour value was the least.
- iii. **150:25 rpm mixing speed:** From Figure 4.5, no regular trend was observed for the PAC dose and colour removal. However, 15 ppm produced supernatant with relatively better colour compared to the higher dosages. Hence, the recommended dose.

Summary

The optimum dosage identified for 180:40, 180:25 and 150:25 mixing speeds were 25 ppm, 25 ppm and 15 ppm respectively. This indicates that 150:25 rpm mixing speeds provided

favorable conditions for efficient use of the PAC than the other two. This finding was similar to that of Yuan-Shing and Ha-Manh, 2014 and Aziz *et al.* 2009 when the effect of mixing speed on colour removal was investigated.

4. Colour Levels at pH 7.5

i. 180:40 rpm mixing speed: All dosages of the polymer applied failed to produce colour values below the threshold set by WHO and GWCL for settled water (15 Pt-Co units). The recorded colour values for 15, 20, 25, 30 and 35 ppm dosages were 82, 87, 70, 86 and 120 Pt-Co units. The equivalent removal efficiencies were 62%, 60%, 67%, 60% and 40% accordingly. Although none of these recorded colour values were below the acceptable value, however, 25 ppm dosage of the PAC removed colour relatively better than the other dosages. Analysis of Variance (ANOVA) also indicated that the colour value recorded for the 25-ppm dosage is significantly different from all the other colour values. Therefore, 25 ppm is chosen as the optimum dosage required sufficient colour removal.

ii. 180:25 rpm mixing speed: From Figure 4.5, it can be seen that all the recorded colour values are above the guideline value (15.0 Pt-Co units). Generally, it was observed that, increasing the dosage of the polymer increased the colour removal efficiency. This observation was found to be consistent with the finding of Yuan-Shing and Ha-Manh, 2014 when the effect of PAC dosage on colour removal was investigated. Analysis of variance showed no significant difference between the colour value recorded for the 20, 25, 30 and 35ppm (p value < 0.05) from the other readings. Hence 20 ppm is considered as the required dosage of the PAC for sufficient water colour removal.

iii. 150:25 rpm mixing speed: Increasing PAC dose was generally found to improve water colour. However, none of the resultant colour met the recommended guideline value. A one-way ANOVA showed no significant difference between the color recorded for the 20 ppm and 25 ppm (p value > 0.05). The 20 ppm dosage comparatively gave relatively satisfactory colour of the effluent, and hence the recommended dosage for this condition.

Summary

At pH 7.5, the required dosage of the PAC to effect sufficient colour removal from the sampled water is relatively higher compared to the other pH regimes discussed above. The dose of the polymer required for the 180:40, 182:25 and 150:25 mixing speeds were 25 ppm, 20 ppm and 20 ppm respectively. Though the 180:25 rpm produced better colour than the 150:25, however, their values are not statistically different at 95% confidence. In addition,

higher electrical energy will be required to operate the 180:25 rpm than the 150:25 rpm. Therefore, 150:25 rpm is the preferred mixing speed.

5. Colour Levels at pH 8.0

- i. **180:40 mixing:** All dosages of the polymer again failed to removed colour sufficiently from the flocculated water to the acceptable level established by WHO and GWCL (15 Pt-Co). Nonetheless, increasing the PAC dosage improved the colour of the treated water. Similar observation was made by Yuan-Shing and Ha-Manh, 2014 when the effect of PAC dosage on colour removal was investigated. Colour values recorded for the 15 ppm is comparable to the values obtained for the 25, 30 and 35 ppm. Therefore, 15 ppm is chosen to reduce production cost.
- ii. **180:25 mixing:** An increase in the polymer dosage from 15 ppm to 20 ppm saw an increase in the colour of the treated water. However, upon addition higher dosages, a steady decrease in the colour was observed. One-way ANOVA showed that there is no significant difference between colour value obtained for the 15, 25 and 30 ppm (p value > 0.05). Hence, it is economically sound to opt for the 15 ppm since it sufficiently removed colour from the sampled water.
- iii. **150:25 mixing:** All dosages of the polymer applied could not remove colour from the flocculated water to acceptable level (15.0 Pt-Co). No significant difference was observed to exist between the colour values recorded for the higher dosages of the PAC. Therefore, 15 ppm of the polymer can be chosen as the optimum dosage for efficient colour removal.

Summary

The optimum dosage identified for 180:40 rpm, 180:25 rpm and 150:25 rpm mixing speeds were all 15 ppm. However, the 150:25 rpm mixing was found to improve colour of the sampled water more efficiently than the other two mixing speeds. Therefore, 150:25 is chosen as the best mixing speed.

5. Colour Levels at pH 8.5

- i. **180:40 rpm mixing speed:** All dosages of the polymer again failed to removed colour sufficiently from the flocculated water to the acceptable level established by WHO and GWCL (15 Pt-Co). Nonetheless, increasing the PAC dosage improved the colour of the treated water significantly. Similar observation was made by Yuan-Shing and Ha-Manh, 2014 when the effect of PAC dosage on colour removal was

investigated. From the results, only 35 ppm was found to improve the colour of the treated water to considerable level, hence the recommended dose.

- ii. **[180:25 mixing:** In Figure 4.5, increasing the polymer dosage sufficiently improved the colour of the treated water. However, none of the polymer dosages could reduce the sampled water colour to acceptable levels. From the results obtained, only the colour recorded for the 35 ppm is comparable to the recommended guideline value. Therefore, 35 ppm is preferred for this mixing speed.
- iii. **150:25 mixing:** Mean colour values recorded for 15, 20, 25, 30 and 35 ppm were 57, 45, 48, 35 and 39 Pt-Co units, representing 52%, 62%, 59%, 70% and 67% colour removal efficiencies respectively. Though higher dosages removed colour adequately, however, one-way ANOVA showed that there is no significant difference between the results obtained for 20, 25, 30 and 35 ppm of the coagulant. Hence 20 ppm can be recommended for use.

Summary

At pH 8.5, the efficiency of the Polyaluminium Chloride in removing colour from water was generally poor. The required dosage of the polymer for 180:40, 180:25 and 150:25 mixing speeds were 35, 35 and 20 ppm. Despite these high dosage requirements, the resulting colour values recorded were all above the threshold (15 Pt-Co) set by WHO and GWCL for settled water. Comparatively, 150:25 mixing speed was found to improve the colour of the flocculated water more than the other two mixing speeds, hence recommended for use at pH 8.5 (refer to Table 4.3).

Table 4.3 Recommended Mixing Speed and PAC Dosage at Varied pH Values

pH	Recommended mixing speed (rpm)	Recommended dosage (ppm)	Colour (Pt-Co)
6.0	150:25	15	43
6.5	150:25	15	40
7.0	150:25	15	35
7.5	150:25	20	43
8.0	150:25	15	35
8.5	150:25	20	45

4.3 Results for Laboratory Experiment 2

The initial characteristics of the raw water sampled from the Barekese Headworks were examined. The sampled water was then subjected to the Jar Test at varied pH and the effects of mixing speed and PAC dosage on turbidity removal were assessed (see section 3.8.2). The mean turbidity, colour, iron values and residual Aluminium levels are presented in tables in appendix B.

4.3.1 Initial Raw Water Characteristics

Raw water from the Barekese treatment plant was sampled at the sampling tap just by the aerators. Initial characteristics of the raw water were determined as follows:

pH = 6.6

Turbidity = 13.2 NTU

Colour = 182 Pt-Co

4.3.3: Using Changes in Turbidity to Determine the Optimal Retention Times

The effect of retention time on turbidity removal was studied at varied pH values using the optimal mixing speed (150:25 rpm) and PAC dosage (15 ppm) identified in experiments 1. In this section, turbidity levels of flocculated water samples were determined at 5, 10, 15, 20, 25 and 30 minutes.

1. Turbidity Levels at pH 6.0

From Figure 4.6, it was observed that as more time was allowed, much of the flocs formed settled, thereby reducing turbidity. This is because, as more time is allowed for settling, more flocs are bridged together to attain settleable sizes, and hence precipitate out of the bulk solution. This observation was found to be consistent with the findings of Mohammed and Shakir (2018) when the effect of retention or contact time on turbidity removal was studied using the PAC. Turbidity values for all the treated water met the guideline value for settled water. Though allowing longer retention times improved the turbidity satisfactorily, however, since 15 minutes residence time (as adopted at the Barekese Water Treatment Plant) removed turbidity to acceptable levels, it is recommended for operation at the treatment plant.

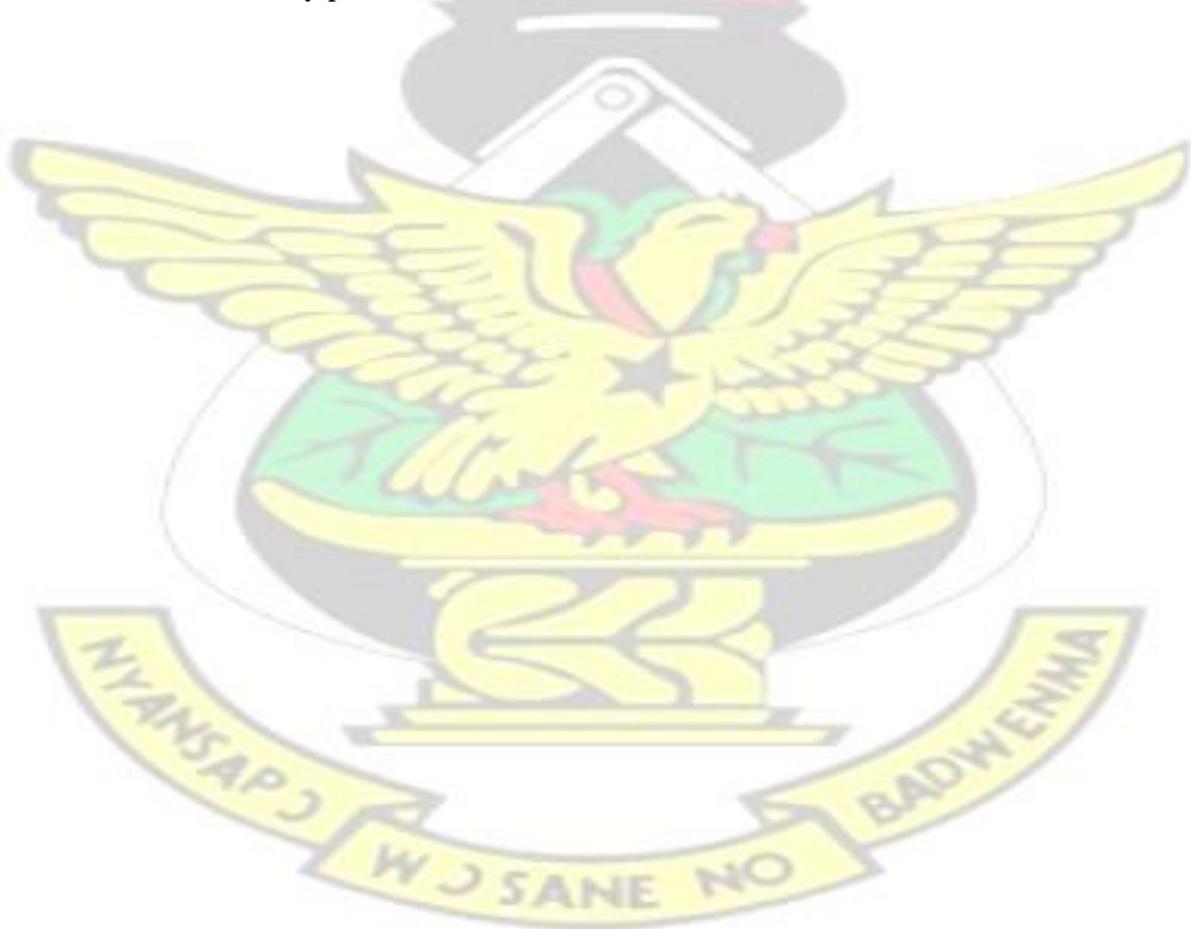
2. Turbidity Levels at pH 6.5

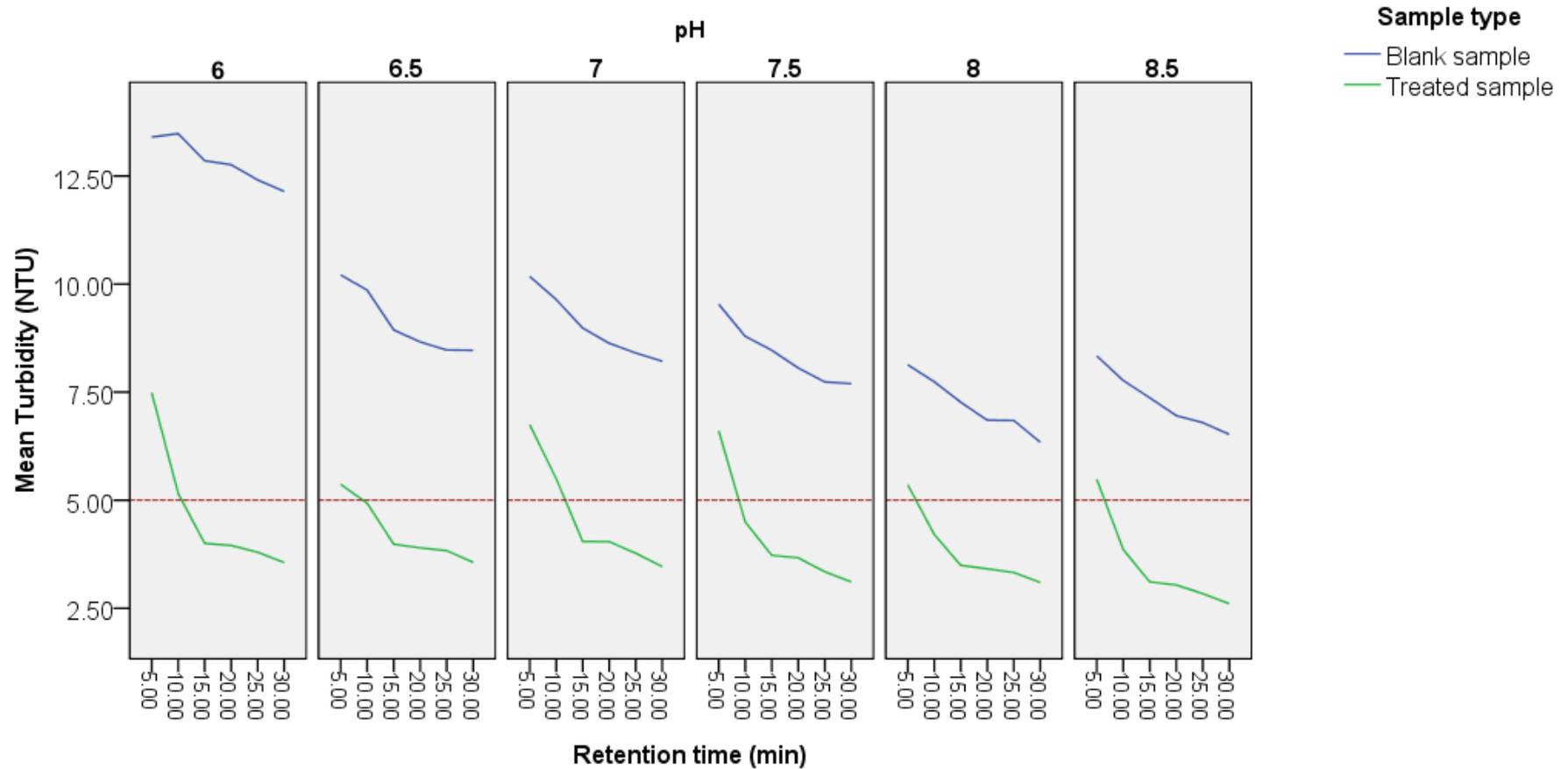
Increasing residence time was found to improve the turbidity of the treated water significantly. Similar observation was made by Mohammed and Shakir (2018). All turbidity

values recorded at this pH, except the 5th minute, met the GWCL guideline value of 5.0 NTU for settled water. Hence 15 minutes is enough for more contaminants to settle out of water.

3. Turbidity Levels at pH 7.0

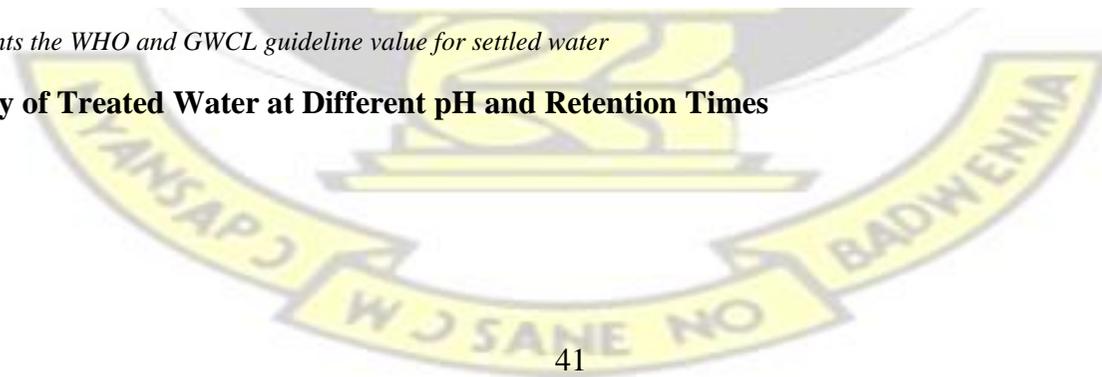
Generally, it was observed that as the retention time increased, turbidity decreased. This could be explained that as more time is allowed, agglomeration increases, thus increasing particle sizes to facilitate settling. All turbidity values recorded, apart from the 5th and 10th minutes, were within the GWCL settled water limit of 5 NTU. The high turbidities recorded for 5 and 10 minutes retention times suggest that the sizes and densities of the flocs formed were small and lighter. Although longer periods of settling improved the turbidity of the treated water, however, the values recorded for the 15 minutes and the longer residence times are comparable (p value > 0.05). Therefore, 15 minutes retention time can be adopted in order to increase daily production.





*The horizontal red line represents the WHO and GWCL guideline value for settled water

Figure 4.6 Mean Turbidity of Treated Water at Different pH and Retention Times



4. Turbidity Levels at pH 7.5

It is seen from Figure 4.6 that as the PAC-treated water samples were allowed to remain in contact with the coagulant, turbidity levels decreased. All turbidity values recorded, except the 5th minute, met the acceptable level of 5.0 NTU. It can be inferred that the rate of particle growth was high and hence greater fraction of the flocs attained settleable sizes quickly. However, after 15 minutes time, the settling rate remained virtually stable. This suggests that much of the flocs settled within the first 15 minutes.

5. Turbidity Levels at pH 8.0

Figure 4.6 showed that increasing contact time improved the turbidity of the treated water. It was observed that only the 5 minutes settling time failed to produce supernatant of acceptable turbidity. Statistically, the turbidity value recorded for the 15 minutes (the retention time adopted at Barekese Headworks) is not significantly different (p value > 0.05) from the longer periods allowed for settling. Hence 15 minutes is adequate for turbid substances to settle out of water.

6. Turbidity Levels at pH 8.5

It was observed that as more time was allowed for settling, turbidity decreased considerably. This could be explained that increasing contact time led to an increase in particle sizes, and hence attained high densities capable of settling by gravity. All turbidity values recorded, apart from the 5th and 10th minutes, were within the GWCL settled water limit of 5.0 NTU. Since 15 minutes retention time resulted to supernatant of acceptable turbidity level, it can be recommended to operate with as to increase daily production.

Summary Table

The recommended retention time and the corresponding turbidity levels obtained over the pH range under study are summarized in the table below:

Table 4.4 Recommended Retention Time and Turbidity at Varied pH Values

pH	Recommended Retention time (minutes)	Turbidity level (NTU)
6.0	15	4.00
6.5	15	3.98
7.0	15	4.04
7.5	15	3.72
8.0	15	3.49
8.5	15	3.11

4.3.4: Using Changes in Water Colour to Determine the Optimal Retention Times

The effect of retention time on turbidity removal was studied at varied pH values using the optimal mixing speed (150:25 rpm) and PAC dosage (15 ppm) identified in experiments 1. In this section, turbidity levels of flocculated water samples were determined at 5, 10, 15, 20, 25 and 30 minutes.

1. Colour Levels at pH 6.0

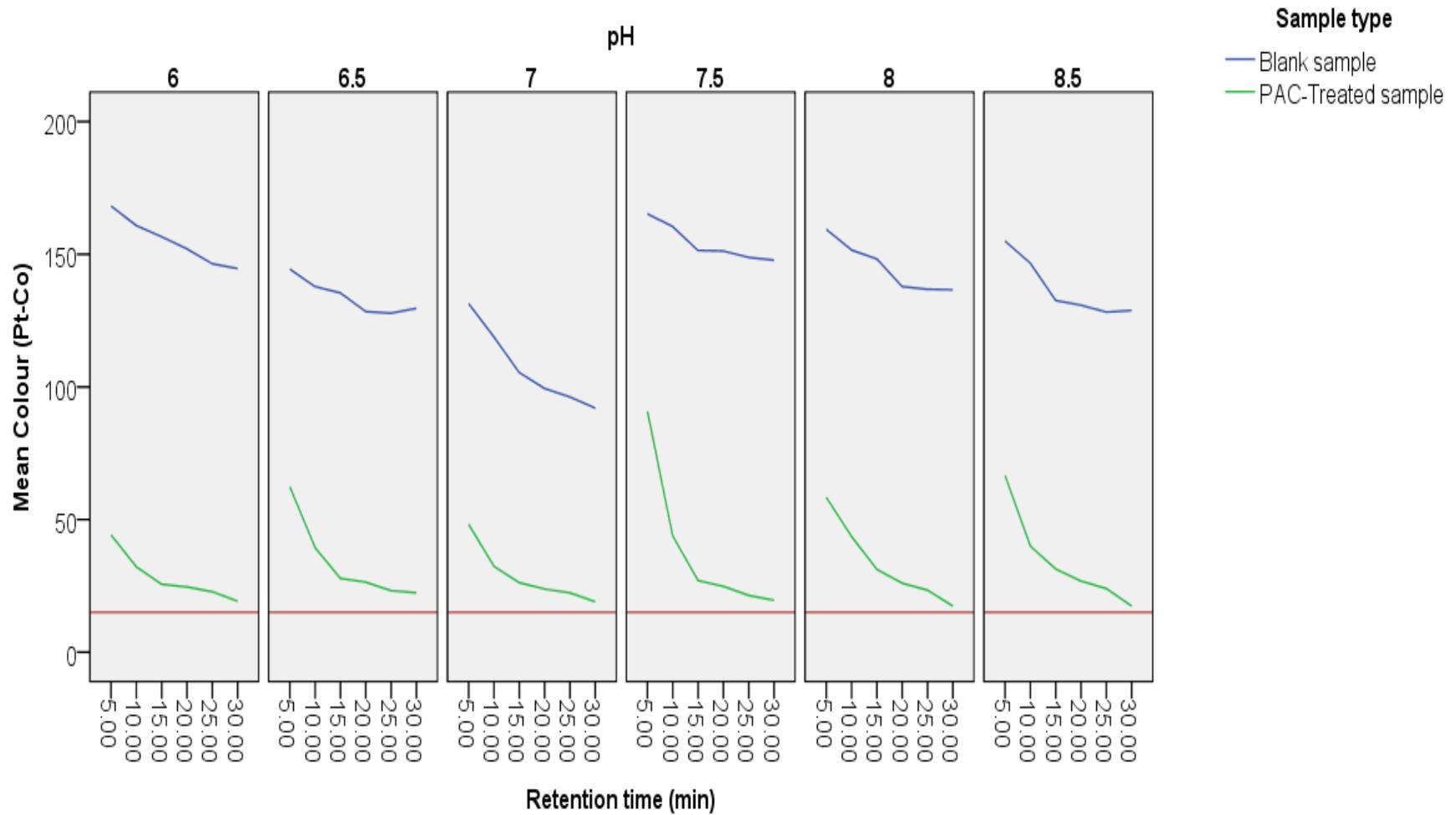
When the PAC-treated water samples were allowed longer times to remain in contact with the ions of the PAC, the better the water colour (see Figure 4.7). Similar observation was made by Aziz *et al.* 2009 when colour removal from water was monitored over time using PAC coagulant. Though allowing more settling time improved the colour satisfactorily, however, ANOVA showed no significant difference between the colour values recorded for the 15 minutes and the 20, 25 and 30 minutes. Therefore 15 minutes settling can be recommended for the production of safe water.

2. Colour Levels at pH 6.5

A sharp improvement in the colour of the treated water was observed over the first 15 minutes, but remained virtually steady up to the 30th minute. The small change in water colour after the 15 minutes settling suggests that much of the impurities contributing to water colour such as dissolved organics had settled. All colour values recorded were above the threshold set by WHO and GWCL for settled water limit of (15 Pt-Co units). Clearly, it can be seen that allowing 30 minutes time for settling produced relatively satisfactory colour. However, a one-way ANOVA showed that there is no significant difference between the recorded colour values for 15, 20, 25 and 30 minutes (p value > 0.05). Hence allowing 15 minutes retention time in the settling tanks can be considered as adequate for the production of safe water.

3. Colour Levels at pH 7.0

From Figure 4.7, it was observed that as the retention time increased, colour of treated water reduced. This could be explained that as more time is allowed, agglomeration increases, thus increasing particle sizes to facilitate settling. All colour values recorded were above the WHO and GWCL settled water limit of 15.0 Pt-Co units. Although these values failed to meet the standard requirement, however, ANOVA indicated that there is no significant difference between the recorded values for the 15, 20, 25 and 30 minutes (p value > 0.05). Therefore, 15 minutes retention time can be adopted to increase daily production.



*The horizontal red line represents the WHO and GWCL guideline value for settled water

Figure 4.7 Mean Colour of PAC-flocculated Water at Different pH and Retention Times

4. Colour Levels at pH 7.5

At pH 7.5, colour removal was found to be rapid over the first 15 minutes. However, colour reduction from the 15th minute up to the 30th minute remained almost stable. One-way ANOVA showed that the colour values recorded for 15, 20, 25 and 30 minutes are not significantly different (p value > 0.05), even though all values are above the allowable level for settled water (15.0 Pt-Co units). Therefore, 15 minutes settling time can be said to enhance production of safe water for the people.

5. Colour Levels at pH 8.0

From Figure 4.7, it was realized that increased retention times improved the colour of the treated water. All colour values recorded at this pH failed to meet the permissible level for settled water (15.0 Pt-Co units) established by WHO and GWCL. Statistically, the colour value recorded for 15 minutes is not significantly different (p value > 0.05) from that of the 20th and 25th minutes. Hence 15 minutes is enough for more contaminants to settle out of water.

6. Colour Levels at pH 8.5

A progressive reduction in water colour was observed when the PAC-treated samples were allowed to remain in contact with the coagulant. This could be explained that as more time is allowed, particle agglomeration increases, thus increasing precipitation with consequent decrease in colour. All colour values recorded were above the standard (15.0 Pt-Co units). Although these values failed to meet the standard set by GWCL for settled water, the value recorded for 15 minutes is not different from that of the 20 and 25 minutes (p value > 0.05). Hence 15 minutes retention time can be said to be good to provide safe water for the populace.

Summary Table

Generally, allowing 15 minutes settling improved the colour of the treated water over the pH range 6.0 to 8.5. The table below is the summary of the recommended retention time and the corresponding colour levels obtained over the pH range under study.

Table 4.5 Recommended Retention Time and Colour at Varied pH Values

pH	Recommended Retention time (minutes)	Colour (Pt-Co)
6.0	15	26
6.5	15	28
7.0	15	26
7.5	15	27
8.0	15	31
8.5	15	31

4.4 Results for Laboratory Experiment 3

The initial characteristics of the raw water sampled from the Barekese Headworks were examined. The sampled water was then subjected to the Jar Test at varied pH and the effects of mixing time on turbidity removal were investigated (see section 3.8.3). The mean turbidity, colour, iron values and residual Aluminium levels are presented in tables in appendix B.

4.4.1 Initial Raw Water Characteristics

Initial characteristics of the raw water sampled from the Barekese Headworks are as below:

pH = 6.85

Turbidity = 24.6 NTU

Colour = 318 Pt-Co

4.4.2 Using Turbidity as a Tool to Assess the Effects of Mixing time on Coagulation Efficiency

The effect of mixing time on turbidity removal was examined at varied pH values using the optimal mixing speeds (150:25 rpm) and PAC dosage (15 ppm) identified from experiment 1. In this section, the time for the fast mixing was reduced from 5 minutes to 2 minutes, and the slow mixing time from 10 minutes to 5 minutes.

1. Turbidity Levels at pH 6.0

It was observed from Figure 4.8 that allowing more settling time improved the turbidity of the treated water. This observation was found to be consistent with the findings made by

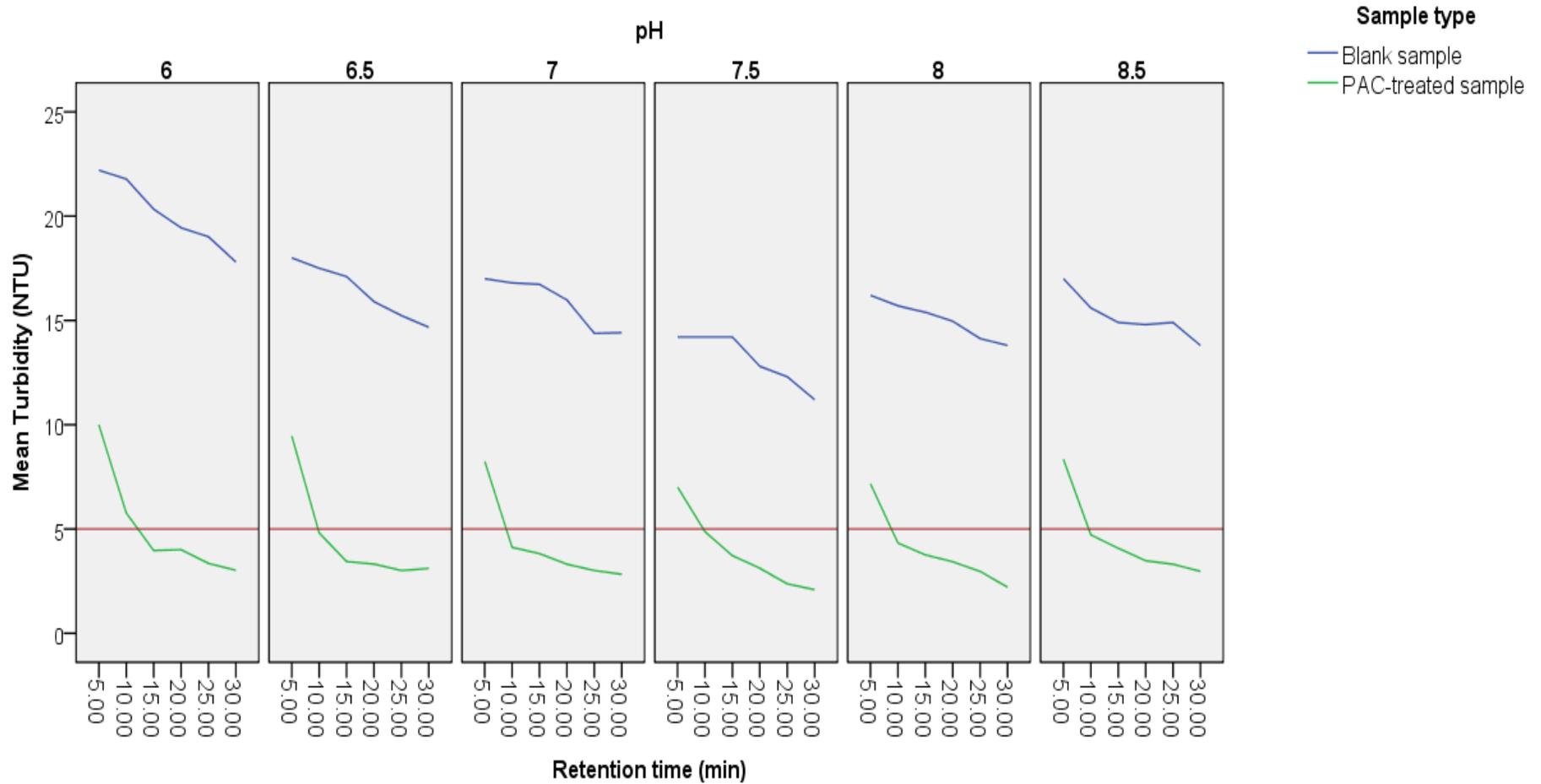
Mohammed and Shakir (2018) when coagulation efficiency was monitored over time using PAC as coagulant. It was also realized that the turbidity levels recorded for the first 10-minute settling failed to meet the guideline value (5.0 NTU). This is because at the early stages of settling, there is re-dissolution and re-deposition of microflocs onto relatively larger flocs, and hence much of the flocs are left in suspension. By the 15th minute time, much of the flocs had increased in size and density, and thus settled by gravity. Although 30 minutes settling time was found to produce supernatants of low turbidity value, however, the 15 minutes settling can be adopted to increase daily production.

2. Turbidity Levels at pH 6.5

The turbidity of the flocculated water samples was observed to decrease significantly when the samples were allowed adequate time to settle (see Figure 4.8). The sharp drop in turbidity during the first 15 minutes of settling informs that the bridging of smaller particles to form larger ones occurred rapidly, and hence attained high densities to settle by gravity. With the exception of the 5th minute, all turbidities determined at other times met the GWCL guideline of 5.0 NTU for settled water. One-way ANOVA showed that there was no significant difference between the turbidity value record for the 15th minute and the 20, 25 and 30 minutes retention times (p -value > 0.05). Therefore, 15 minutes retention can be said to be adequate to improve the turbidity of PAC-treated water.

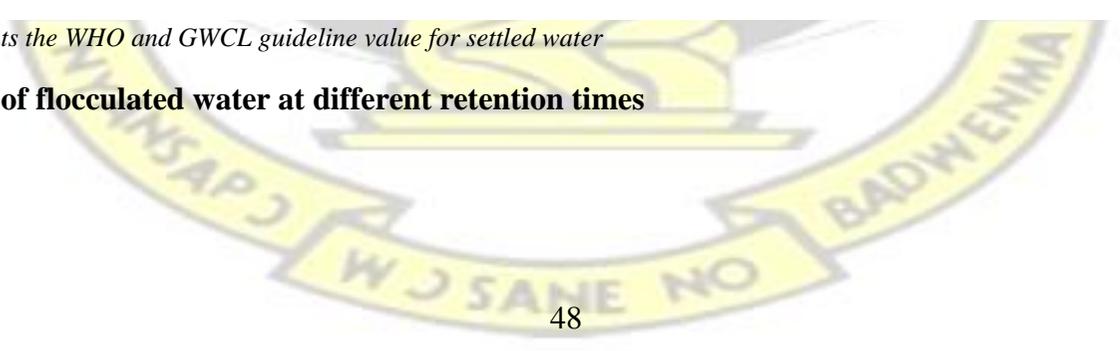
3. Turbidity Levels at pH 7.0

From Figure 4.8, it was realized that as the retention time increased, turbidity decreased. This suggests that as more time is allowed for the flocculated samples to settle, agglomeration increases, thus increasing particle sizes to facilitate settling. The high turbidities recorded for the 5 minutes retention suggests that the sizes and densities of the flocs formed were small and lighter. All turbidity values recorded, apart from the 5th minute, were within the GWCL settled water limit of 5.0 NTU. Although longer periods of contact with the coagulant improved the turbidity of the treated water, however, the values recorded for the 15 minutes and the longer residence times are comparable (p value > 0.05). Therefore, 15 minutes retention time can be adopted in order to increase daily production.



*The horizontal red line represents the WHO and GWCL guideline value for settled water

Figure 4.8 Turbidity level of flocculated water at different retention times



4. Turbidity Levels at pH 7.5

The longer the water samples were allowed to be in contact with the coagulants, the better the turbidity of the supernatants. All the turbidity readings, except that for the first 5 minutes, met the guideline value of 5.0 NTU established by WHO and GWCL for settled water. Although longer periods of contact with the coagulant improved the turbidity of the treated water considerably, however, the change in turbidity from the 15 minutes to the 30 minutes was not substantial (p value > 0.05). Therefore, 15 minutes retention time can be adopted in order to increase daily production.

5. Turbidity Levels at pH 8.0

Generally, increasing the retention time improved the turbidity of the supernatants obtained adequately (see Figure 4.8). A sharp drop in turbidity observed between the 5th and 10th minutes signifies that there was a rapid bridging of particles and that enhanced fast precipitation of the particles out of the water. All turbidity readings, except that for the first 5 minutes, were acceptable (≤ 5.0 NTU). Therefore, 15 minutes retention is recommended to improve the turbidity of treated water.

6. Turbidity Levels at pH 8.5

A significant improvement in the treated water turbidity was observed when the samples were allowed to remain in contact with the coagulant over longer times. All turbidity readings, except that for the 5th minute, were within the acceptable limit of 5.0 NTU established by WHO and GWCL for settled water. Hence the 15 minutes retention can be adopted to achieve the supply of safe water.

Summary table

The table below is the summary of the recommended retention time and the corresponding turbidity levels obtained over the pH range under study.

Table 4.6 Recommended Retention Time and the Corresponding Turbidity Levels

pH	Recommended Retention time (minutes)	Turbidity level (NTU)
6.0	15	3.97
6.5	15	3.44
7.0	15	3.82
7.5	15	3.72
8.0	15	3.76
8.5	15	4.08

4.4.3 Using Colour as a Tool to Assess the Effects of Mixing Time on Coagulation

Efficiency

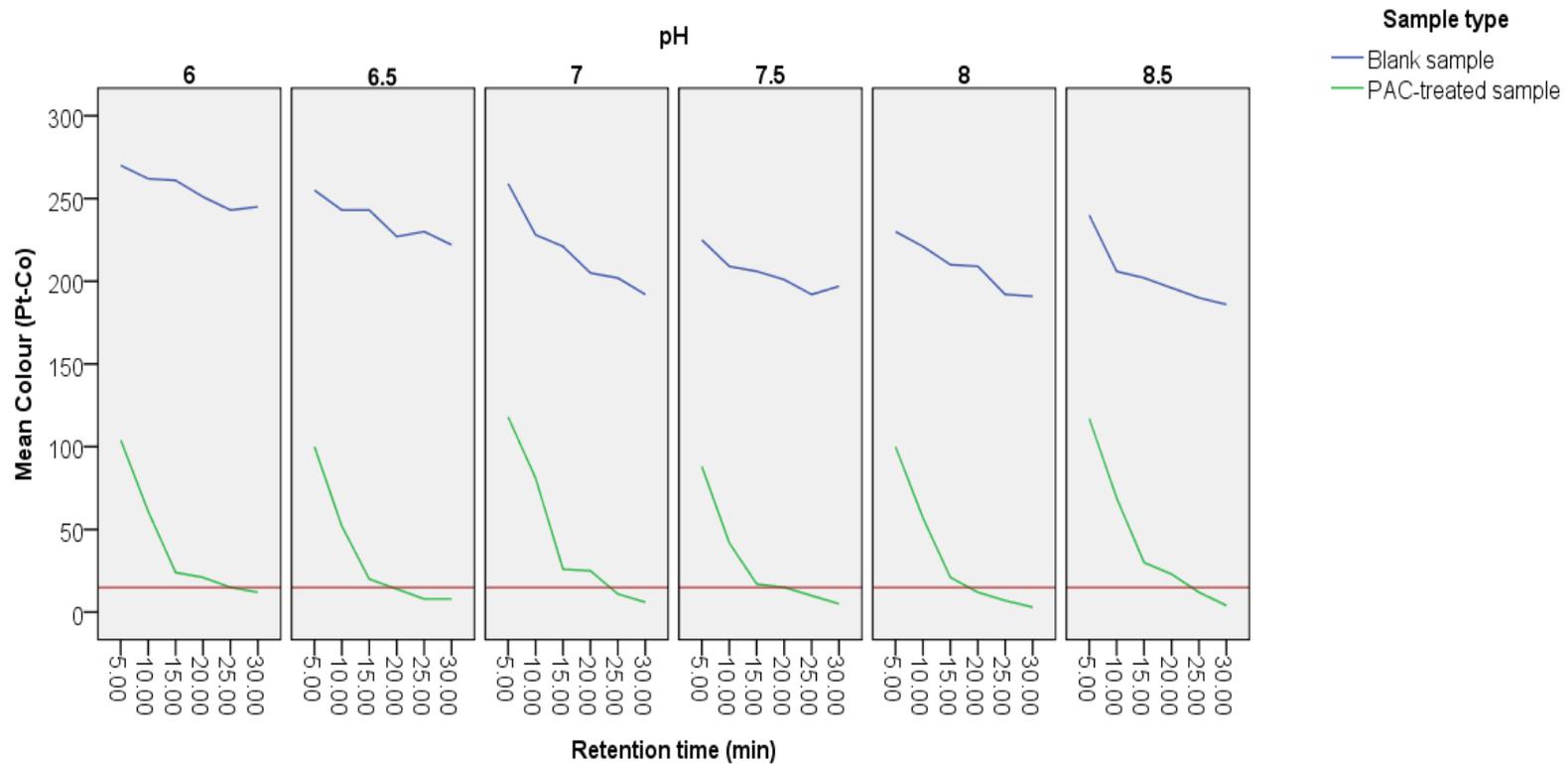
The effect of mixing time on colour removal was investigated at varied pH values using the optimal mixing speeds (150:25 rpm) and PAC dosage (15 ppm) identified from experiment 1. In this section, the time for the fast mixing was reduced from 5 minutes to 2 minutes, and the slow mixing time from 10 minutes to 5 minutes

1. Colour Levels at pH 6.0

From Figure 4.9, it was realized that increasing contact time significantly improved the colour of the treated water. Similar observation was made by Aziz *et al.* 2009 when the effect of settling time on the removal of colour from water was studied. It was found that only 25 and 30 minutes retention times resulted to supernatants of acceptable colour values. However, 15 minutes settling time can be considered since the difference between the recorded colour value (24 Pt-Co) and the guideline value (15 Pt-Co) is not appreciable.

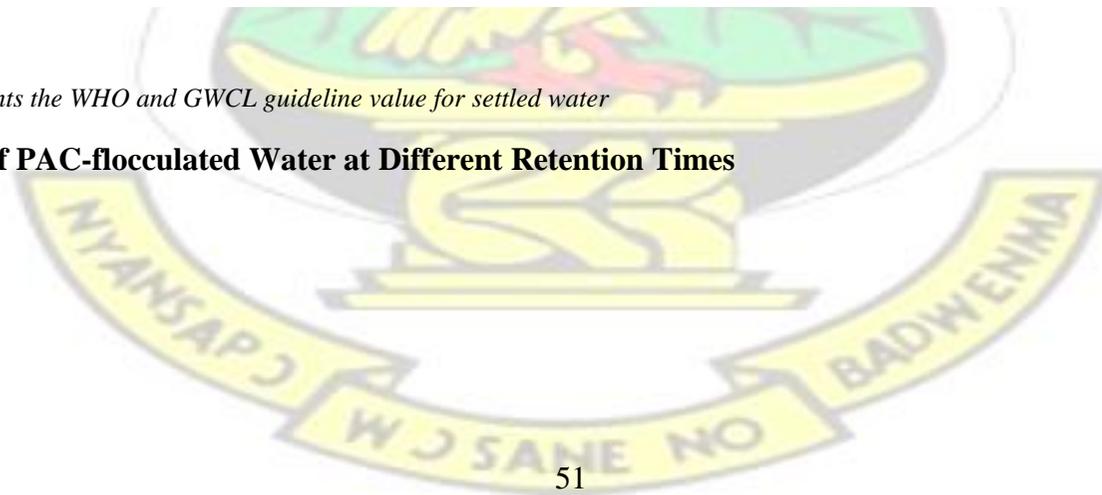
2. Colour Levels at pH 6.5

Allowing more settling time adequately increased the colour of the PAC-treated water. This is similar to the findings of Aziz *et al.* 2009, when the effect of settling time on the removal of colour from water was monitored using PAC as the coagulant (see Figure 4.9). A sharp improvement in the colour of the treated water was observed over the first 15 minutes, but remained virtually steady up to the 30th minute. The small change in water colour after the 15 minutes settling suggests that much of the impurities contributing to water colour such as dissolved organics, humic acids, etc had settled. All colour values recorded when the treated water sample was allowed to stay in contact with the coagulant beyond 10 minutes met the



*The horizontal red line represents the WHO and GWCL guideline value for settled water

Figure 4.9 Colour Level of PAC-flocculated Water at Different Retention Times



Guideline value (15 Pt-Co units). Hence, 15 minutes retention time in the settling tanks can be considered as adequate for the production of safe water.

3. Colour Levels at pH 7.0

From Figure 4.9, it was observed that as the retention time increased, colour of treated water reduced. This could be explained that as more time is allowed, agglomeration increases, thus increasing particle sizes to facilitate settling. All colour values recorded, apart from that for 25 and 30 minutes, were above the WHO and GWCL settled water limit of 15.0 Pt-Co units. Although these values failed to meet the standard requirement, however, 15 minutes retention time can be adopted to increase daily production.

4. Colour Levels at pH 7.5

Also, allowing more settling time adequately increased the colour removal efficiencies. This is similar to the findings of Aziz *et al.* 2009 and Zahra *et al.* 2017 when the effect of retention time on the removal of colour from water was studied. All colour values recorded for 20, 25 and 30 minutes retention met the GWCL guideline value (15 Pt-Co). However, the colour value recorded for the 15 minutes settling (17 Pt-Co) is statistically not different from the guideline value. Therefore, 15 minutes settling is adequate to effect sufficient colour removal from water.

5. Colour Levels at pH 8.0

A sharp drop in colour of the treated water was observed over the first 15 minutes. The rate of colour reduction decreased after 15 minutes settling. This suggests that much of the colour-contributing factors had been removed. Colour values recorded when the treated water sample was allowed to stay in contact with the coagulant beyond 15 minutes met the guideline value (15 Pt-Co units). The colour value recorded for the 15 minutes settling (21 Pt-Co) is comparable with the guideline value. Hence, 15 minutes retention time in the settling tanks can be considered as adequate for the production of safe water.

6. Colour Levels at pH 8.5

A progressive reduction in water colour was observed when the PAC-treated samples were allowed to remain in contact with the coagulant over time. This could be explained that as more time is allowed, particle agglomeration increases, thus increasing precipitation with consequent decrease in colour. Only colour values recorded after 25 minutes settling met the guideline value. However, 20 minutes can be considered so as to increase daily production.

Summary Table

Generally, allowing 15 minutes settling improved the colour of the treated water over the pH range 6.0 to 8.5. The table below is the summary of the recommended retention time and the corresponding colour levels obtained over the pH range under study.

Table 4.7 Recommended Retention Time and the Corresponding Colour Levels

pH	Recommended Retention time (minutes)	Colour (Pt-Co)
6.0	15	24
6.5	15	20
7.0	15	26
7.5	15	17
8.0	15	21
8.5	20	23

4.4.4 Comparison Between Turbidity and Colour Values for the Different Mixing Times.

In Table 4.8, it can be seen that when the time for fast mixing was reduced from 5 minutes to 2 minutes and the slow mixing time from 10 minutes to 5 minutes, the turbidity and colour of the PAC-flocculated water generally improved, except the turbidity values recorded at pH 8.0 and 8.5. Even though the turbidity values obtained at pH 8.0 and 8.5 were relatively high when the mixing time was reduced, however, all the recorded values met the standard guideline value of 5.0 NTU. Therefore, in order to increase daily production to meet the growing demand, the reduced mixing time is chosen over the prolonged mixing.

Table 4.8 Turbidity and Colour Values for the Different Mixing Times

pH	Turbidity		Colour	
	5:10 mixing time	2:5 mixing time	5:10 mixing time	2:5 mixing time
6.0	4.00	3.97	26	24
6.5	3.98	3.44	28	20
7.0	4.04	3.82	26	26
7.5	3.72	3.72	27	17
8.0	3.49	3.76	31	21
8.5	3.11	4.08	31	30

4.4.5 Using Changes in Iron Concentrations of PAC-Flocculated Water to Determine the Optimal Retention Times

1. Iron Levels at pH 6.0

The initial pH and iron concentration of the sampled water were 7.62 and 5.45 mg/l. However, when the pH of the water was adjusted to 6.0, the iron level decreased to 4.22 mg/l. The reduction in iron levels at pH 6.0 is as a result of the reduction of iron to the ferrous state (Fe^{2+}), which causes it to dissolve in the solution (Vasudevan *et al.*, 2009). From Figure 4.10, it was observed that allowing the flocculated water sample more time to settle significantly reduced the iron content of the supernatant obtained. A similar observation was made by Hossain *et al.* 2016 when iron removal efficiency from drinking water was assessed. It was realized that only the iron levels obtained after 25 and 30 minutes settling met the standard requirement (0.30 mg/l) established for settled water by WHO and GWCL. Therefore, 25 minutes settling is preferred.

2. Iron Levels at pH 6.5

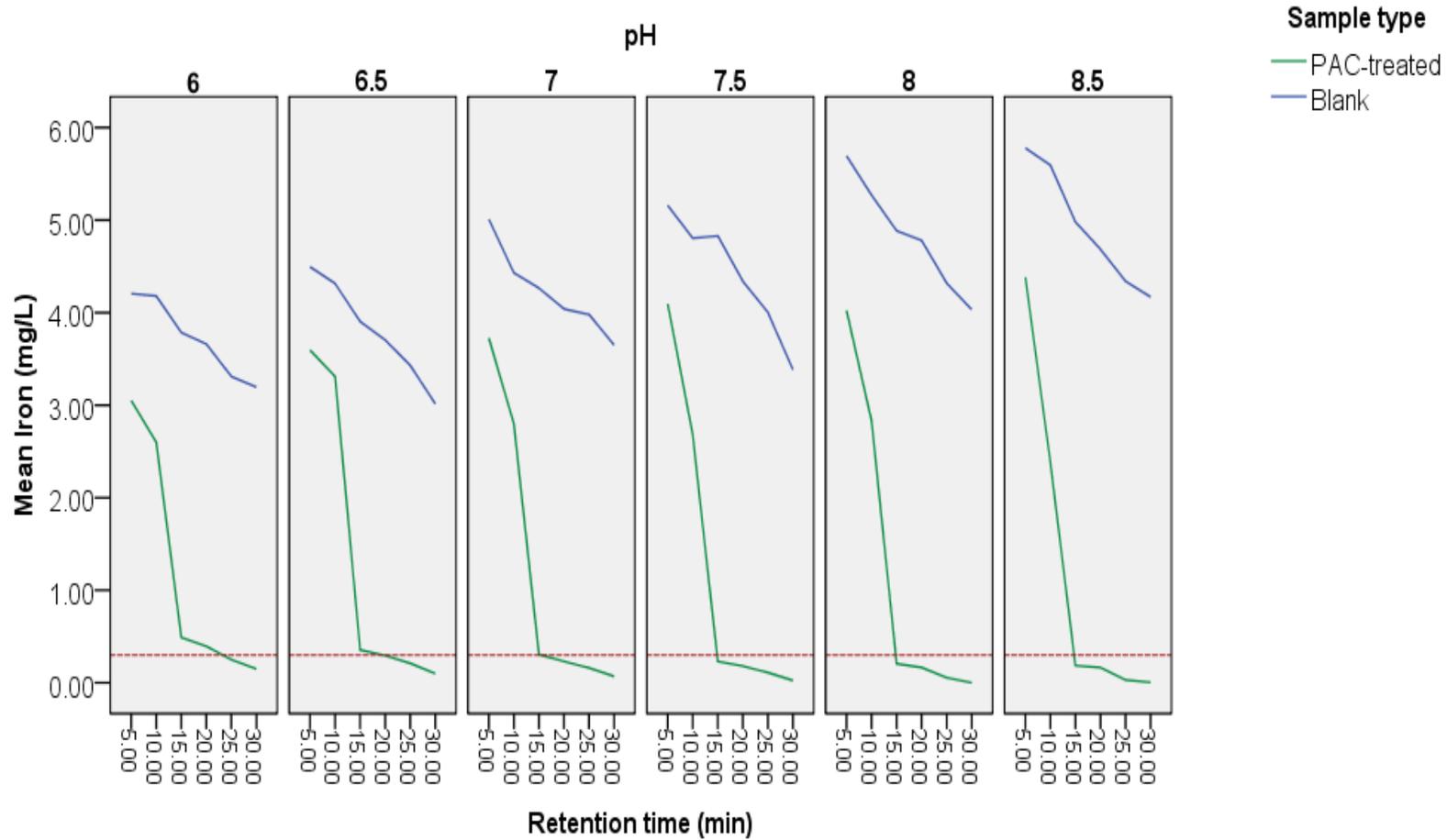
At pH 6.5, the iron concentration of the sampled water was recorded as 4.53 mg/l. After the jar experiment, the mean iron value was found to decrease with time. Similar finding was observed by Hossain *et al.* 2016 when the effect of settling time on iron removal was monitored. Analysis of variance showed that there are no significant differences between the iron values recorded for the 15, 20 and 25 minutes settling at 95% confidence. The iron level recorded at the 15th minute was also found not to be different from the guideline value. Therefore, 15 minutes settling can be said to be adequate for iron removal.

3. Iron Levels at pH 7.0

The pH and iron content of the sampled water were recorded as 7.62 and 5.45 mg/l. However, when the pH was adjusted to 7.0 using 0.1N HCl solution, the concentration of iron dropped to 5.11 mg/l. After the jar experiment, the mean iron level was found to reduce drastically within the first 15 minutes of settling.

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*The horizontal red line represents the WHO and GWCL guideline value for settled water

Figure 4.10 Iron levels of flocculated water at varied pH and retention times

The decrease in iron concentrations with respect to time was found to be consistent with the findings of Hossain *et al.* 2016. A one-way Analysis of Variance indicated that the iron level measured for the 15 minutes settling time is not different from the standard requirement (p value > 0.05). Therefore, the 15 minutes settling is preferred.

4. Iron Levels at pH 7.5

The raw water sampled from the Barekese Headworks has initial pH and iron concentration 7.62 and 5.45 mg/l. However, when the pH of the water was adjusted to 7.5 using 0.10N HCl solution, the iron level decreased to 4.22 mg/l. From Figure 4.10, it was observed that allowing more time for settling significantly reduced the iron content of the supernatants obtained. One-way ANOVA showed no significant difference (p value > 0.05) between the iron values obtained for the 15 and the guideline value. Hence, 15 minutes settling can be considered to increase daily production.

5. Iron Levels at pH 8.0

When the pH of the sampled water was adjusted to 8.0, the iron concentration increased to 5.84 mg/l. After the jar experiment, the mean iron values recorded when the flocculated water samples were allowed to settle for 5, 10, 15, 20, 25 and 30 minutes were 4.03, 2.83, 0.21, 0.17, 0.06 and 0.00 mg/l respectively. The corresponding iron removal efficiencies were estimated as 31.08%, 51.54%, 96.49%, 97.17%, 99.06% and 100%. Similar to the findings of Hossain *et al.* 2016, increasing the retention time increased the removal efficiencies. Analysis of variance (ANOVA) showed that there are no significant differences between the iron value recorded for the 15 minutes settling and the standard requirement. Therefore, the 15 minutes settling can be considered to increase daily production.

6. Iron Levels at pH 8.5

The pH and iron content of the sampled water were recorded as 7.62 and 5.45 mg/l. However, when the pH was adjusted to 7.0 using 0.1N HCl solution, the concentration of iron further increased to 5.85 mg/l. After the jar experiment, the mean iron levels recorded when the flocculated water samples were allowed to settle for 5, 10, 15, 20, 25 and 30 minutes were 4.39, 2.38, 0.19, 0.17, 0.03 and 0.01 mg/l respectively. The decrease in iron concentrations with respect to time was found to be consistent with the findings of Hossain *et al.* 2016. A one-way Analysis of Variance indicated that the iron value measured for the 15 minutes settling time and the guideline value are not different (p value > 0.05). Hence, 15 minutes settling time can be considered to be adequate for iron removal.

Summary

Contrary to the findings of Hossain *et al.* 2016, Albrektiene *et al.* 2011 and Pang *et al.* 2009, increasing the pH of the sampled water increased the iron concentration. However, the iron removal efficiency was found to increase with increase in pH. From the results discussed above, it was observed that increasing settling time led to a reduction in iron levels. It can therefore be deduced that 15 minutes settling enhances sufficient removal of iron from PAC-flocculated water.

Table 4.9 Recommended Retention Times and Iron levels at Different pH Values

pH	Recommended Retention time (minutes)	Iron levels (mg/l)
6.0	25	0.25
6.5	15	0.36
7.0	15	0.31
7.5	15	0.23
8.0	15	0.21
8.5	15	0.19

4.4.6 Using Changes in Residual Aluminium to Determine the Optimal Retention Times

The retention time required to sufficiently reduce residual Aluminium in water after treatment with PAC was investigated and the results are shown in Figure 4.11.

1. Residual Aluminium levels at pH 6.0

The initial pH and Aluminium concentration of the sampled water were 7.62 and 0.08 mg/l. However, when the pH of the water was adjusted to 6.0, the Aluminium level increased to 0.10 mg/l. After treatment with the PAC, it was observed that the Aluminium levels increased. This observation suggests that not all ions of the PAC were involved in the destabilization process. However, the residual Aluminium concentrations significantly decreased when the PAC-flocculated water samples were allowed to stand and settle. This is because, as the destabilized particles bridges together and settle out of solution, excess Aluminium ions were trapped in the agglomerated mesh, and hence settled as well. The standard guideline value of Aluminium established for settled water by WHO and GWCL is 0.20 mg/l (Milind *et al.*, 2012). ANOVA showed no significant difference between the

Aluminium value obtained for the 15 minutes and guideline value. Therefore, 15 minutes settling time can be considered for use so as to increase daily production.

2. Residual Aluminium levels at pH 6.5

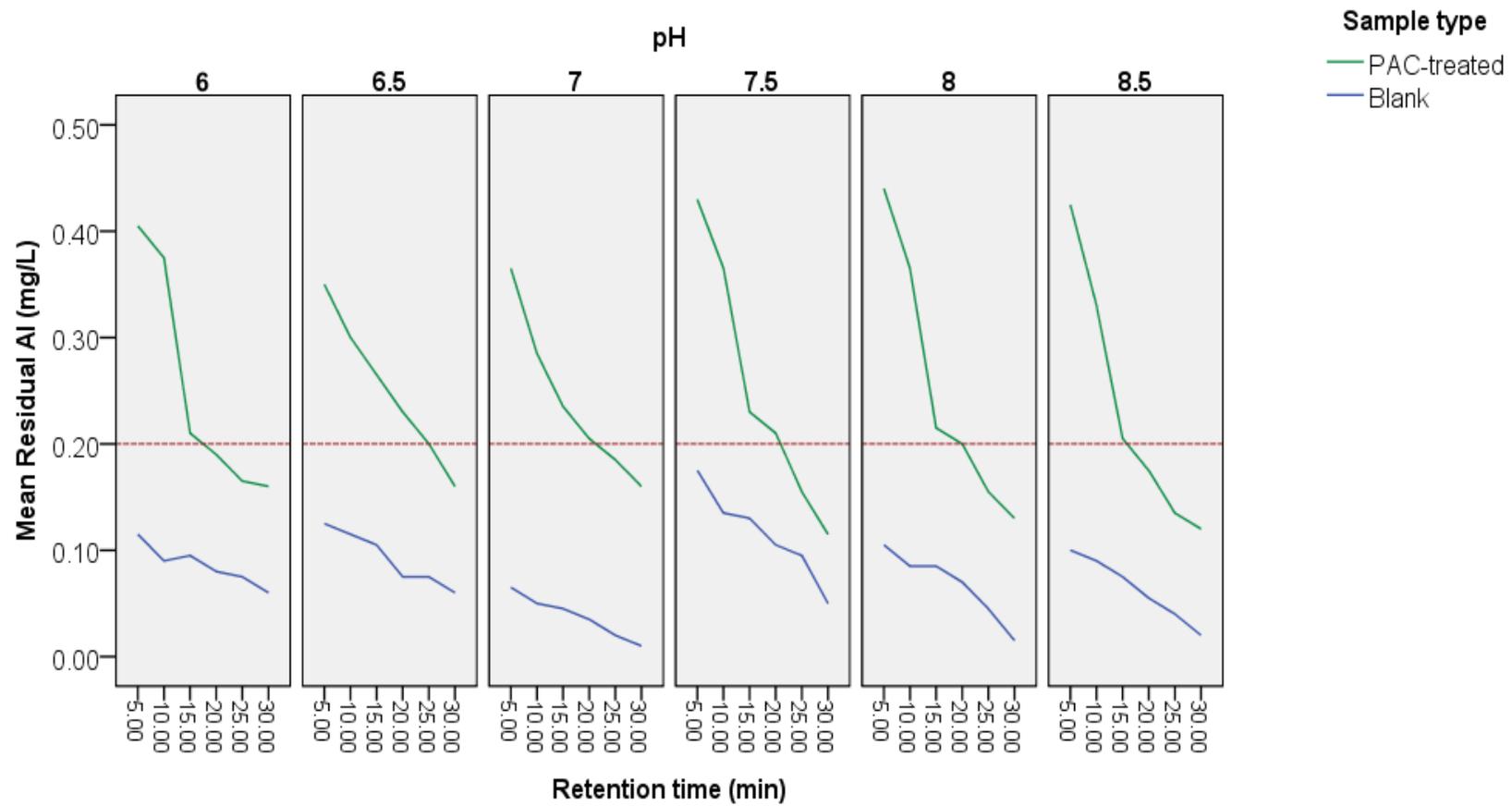
At pH 6.5, the Aluminium concentration of the sampled water was recorded as 0.12 mg/l. After the jar experiment, the Aluminium concentrations were found to be high initially, but started to decrease with time. ANOVA showed no significant difference between the Aluminium values obtained for the 15 minutes and the longer periods (p value > 0.05). Therefore, the 15 minutes settling can be employed to increase daily production.

3. Residual Aluminium levels at pH 7.0

The pH and Aluminium content of the sampled water were recorded as 7.62 and 0.08 mg/l. However, when the pH was adjusted to 7.0 using 0.1N HCl solution, the concentration of Aluminium dropped to 0.05 mg/l. After the jar experiment, the mean Aluminium levels recorded when the flocculated water samples were allowed to settle for 5, 10, 15, 20, 25 and 30 minutes were 0.37, 0.29, 0.24, 0.21, 0.19 and 0.16 mg/l respectively. The corresponding increase in Aluminium levels in the flocculated water were estimated as 86.30%, 82.46%, 78.72%, 75.61%, 72.97% and 68.75%. It was observed that increasing retention time led to a decrease in the residual Aluminium in the flocculated samples. Moreover, Aluminium values obtained after 15 minutes and beyond were not significantly different (p value > 0.05) from the permissible level of 0.2 mg/l. Therefore, the 15 minutes settling can be employed to increase daily production.

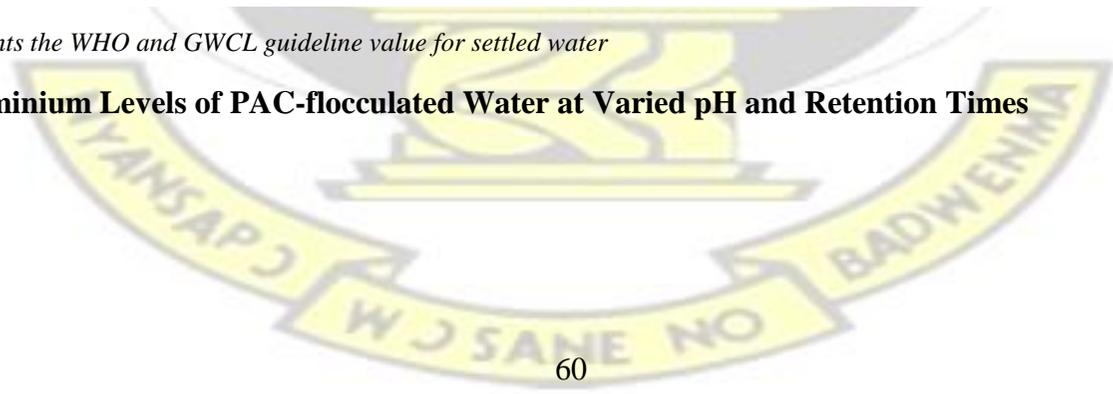
4. Residual Aluminium levels at pH 7.5

The raw water sampled from the Barekese Headworks has initial pH and Aluminium concentration 7.62 and 0.08 mg/l. However, when the pH of the water was adjusted to 7.5 using 0.10N HCl solution, the aluminium level increased to 0.20 mg/l. The observed negative percent increase could be explained that the stirring increased the surface area of the colloidal particles and this increased the number of effective neutralizations, with consequent increase in precipitation of impurities.



*The horizontal red line represents the WHO and GWCL guideline value for settled water

Figure 4.11 Residual Aluminium Levels of PAC-flocculated Water at Varied pH and Retention Times



One-way ANOVA showed that Aluminium values obtained after 15 minutes and beyond were not significantly different (p value > 0.05) from the permissible level of 0.2 mg/l. Therefore, the 15 minutes settling can be employed to increase daily production.

5. Residual Aluminium levels at pH 8.0

Increasing time for settling was found to decrease the residual Aluminium accordingly. One-way ANOVA showed that Aluminium values obtained after 15 minutes and beyond were not significantly different (p value > 0.05) from the permissible level of 0.2 mg/l. Therefore, the 15 minutes settling can be employed to increase daily production.

6. Residual Aluminium levels at pH 8.5

A progressive reduction in residual Aluminium was observed when the PAC-treated water samples were allowed to settle over 30 minutes time. Residual Aluminium concentrations recorded after 15 minutes up to the 30 minutes were comparable with the recommended guideline value. Therefore, 15 minutes settling can be said to be adequate for removal excess Aluminium from PAC-treated water.

Summary table

Table 4.10 Recommended Retention Times and Residual Aluminium Concentrations

pH	Recommended Retention time (minutes)	Iron levels (mg/l)
6.0	15	0.21
6.5	15	0.27
7.0	15	0.24
7.5	15	0.23
8.0	15	0.22
8.5	15	0.21

4.5 Cost Benefit Analysis

From the historic data collected, it was realized that the average volume of water treated per day is 3,339,400 litres and the average PAC dosage is 33.18 mg/l.

This implies that the mass of PAC required to treat 1.0 L of water = 33.18mg

Then, 3,339,400 litres will require 110,801,292 mg of PAC (i.e, 3,339,400 x 33.18)

Therefore, daily mass of PAC used at the plant = 110,801,292 mg \equiv 110.8 kg

Total weight of one drum of the PAC = 250kg

Current cost of one drum of the PAC = GH¢1917.12

Cost of existing operational conditions:

If 250 kg costs GHC 1917.12

Then 110.8 kg will cost GHC 849.67 (*that is,* $\frac{110.8 \times 1917.12}{250}$)

Therefore, considering the existing operational conditions, the cost of PAC used daily is GHC 849.67 or GHC 310,129.55 per year.

Cost of experimentally determined operational conditions:

Dose of PAC required is determined as 15 ppm \equiv 15 mg/l

This implies that the mass of PAC required to treat 1.0 L of water = 15 mg

Then, 3,339,400 litres will require 50,091,000 mg of PAC (i.e, 3,339,400 x 15)

Therefore, daily mass of PAC required = 50,091,000 mg \equiv 50.091 kg

If 250 kg costs GHC 1917.12

Then 50.091 kg will cost GHC 384.09 (*that is,* $\frac{50.091 \times 1917.12}{250}$)

Therefore, considering the experimentally determined conditions, the cost of PAC required daily is GHC 384.09 or GHC 140,192.85 per year

Difference

The difference between the two conditions = 849.67 – 384.09

Daily gains = GHC 465.58 per day

Annual gains \equiv GHC 169,936.70 per year

It can be deduced that adopting the experimentally determined operational conditions (mixing speed, mixing time and PAC dosage) will reduce the production cost by more than half the cost incurred for the existing operational conditions.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

From the results of the study, it could be concluded that:

- The quality (in terms of pH, turbidity and colour) of the Barekese raw water, over the last 6 years, is generally good.
- Of the three mixing speeds investigated, 150:25 rpm was found to provide favourable conditions for efficient coagulation using the PAC over the pH range of 6.0 to 8.5
- Turbidity and colour removal from PAC-flocculated water improved when mixing time was reduced from 5:10 (that is; 5 minutes fast mixing (at 150 rpm) and 10 minutes slow mixing (at 25 rpm)) to 2:5 (2 minutes fast mixing (at 150 rpm) and 5 minutes slow mixing (at 25 rpm)). Therefore, it could be deduced that prolonged mixing reduces the effectiveness of coagulation.
- The optimum dosage of the Polyaluminium Chloride required for sufficient coagulation is 15 ppm.
- The best pH range for efficient performance of the PAC between 6.5 and 8.0

5.2 Recommendations

Based on the findings above, it is recommended that the following be considered:

- Management of the Barekese Water Treatment Plant should consider operating with 150:25 rpm mixing speed, 2:5 mixing time and 15 ppm dose of the PAC.
- The effect of mixing time on the efficiency of the PAC in water purification be further investigated
- The performance of PAC dosages below 15 ppm in removing impurities from water should be examined.
- Before PAC is adopted at any plant, thorough performance assessment must be carried out.

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APPENDIX A
HISTORIC DATA FROM 2013 TO 2018

Table A1 Mean monthly raw water pH from 2013 to 2018

Months	Year					
	2013	2014	2015	2016	2017	2018
Jan	6.69	6.41	6.93	6.78	6.86	6.68
Feb	6.69	6.46	6.72	6.82	6.82	6.72
Mar	6.58	6.52	6.91	6.95	6.86	6.71
Apr	6.51	6.73	7.03	6.91	6.94	6.72
May	6.46	6.52	7.22	6.89	6.94	6.71
Jun	6.43	6.46	6.97	6.77	6.69	6.59
Jul	6.38	6.47	6.79	6.75	6.74	6.66
Aug	6.17	6.58	6.77	6.87	6.71	6.74
Sept	6.13	6.73	7.10	6.75	6.68	6.73
Oct	6.30	6.86	7.00	6.69	6.71	6.71
Nov	6.34	6.99	6.67	6.68	6.73	6.66
Dec	6.36	7.15	6.68	6.74	6.73	6.62

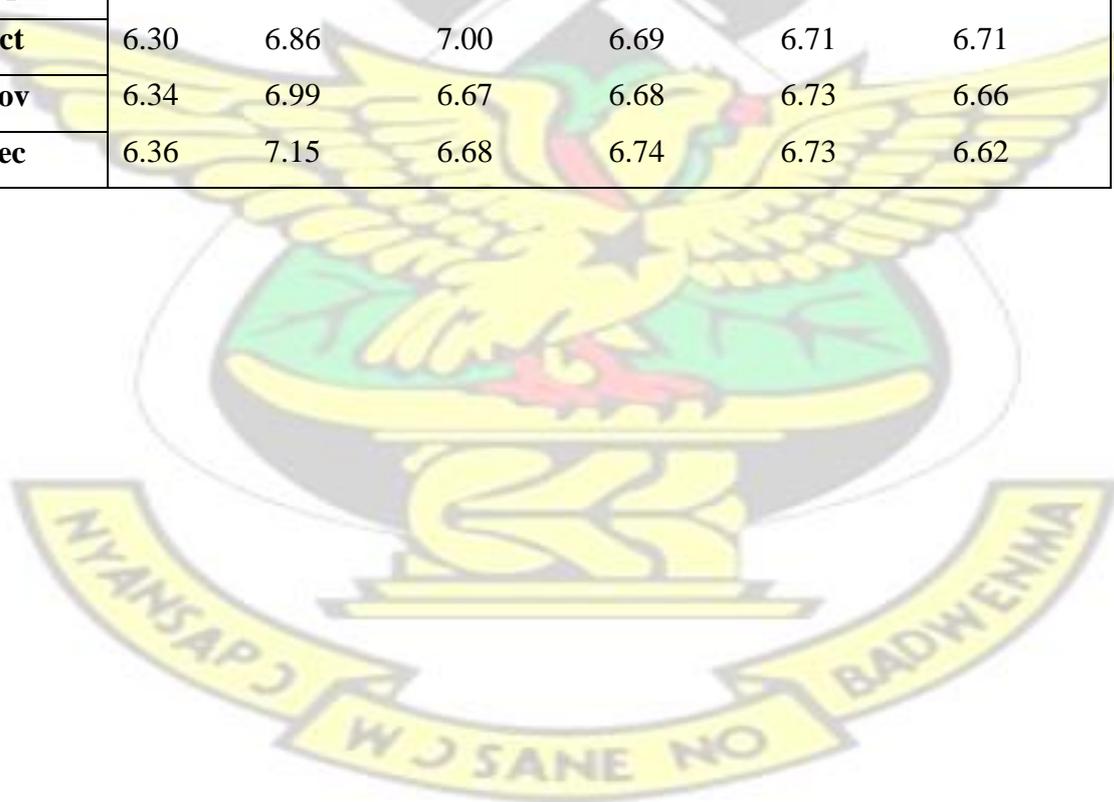


Table A2 Mean monthly coagulant consumption (ppm) and turbidity of raw and settled water (NTU) from 2013 to 2015

Month	2013			2014			2015		
	Raw water Turbidity	Alum dosage	settled water turbidity	Raw water Turbidity	Alum dosage	settled water turbidity	Raw water Turbidity	Alum dosage	settled water turbidity
Jan	12.89	71.13	2.86	17.75	69.63	4.70	9.29	60.42	2.45
Feb	50.20	63.65	4.01	13.16	66.67	4.42	9.33	56.73	2.26
Mar	13.46	62.09	4.69	16.29	65.34	3.03	11.37	58.18	2.04
Apr	15.86	68.79	3.42	12.81	62.07	3.39	21.93	65.43	3.05
May	16.88	70.88	3.73	16.69	66.52	4.21	21.37	72.97	4.01
Jun	20.48	70.74	4.54	31.70	70.17	6.23	25.08	73.44	4.95
Jul	13.63	67.93	4.23	22.67	69.67	4.00	36.24	74.47	5.44
Aug	8.04	72.50	3.87	10.78	64.50	3.27	15.10	67.22	2.95
Sept	9.47	73.87	3.32	10.24	60.34	2.39	9.65	65.24	2.20
Oct	16.54	78.24	5.41	17.48	61.35	3.19	15.53	72.99	3.16
Nov	14.82	67.17	5.78	20.28	62.96	3.71	15.80	70.27	3.41
Dec	15.98	69.56	6.41	18.23	64.67	3.15	12.12	69.95	2.91

Table A3 Mean monthly coagulant consumption (ppm) and turbidity of raw and settled water (NTU) from 2016 to 2018

Month	2016			2017			2018		
	Raw water Turbidity	Alum dosage	settled water turbidity	Raw water Turbidity	PAC dosage	settled water turbidity	Raw water Turbidity	PAC dosage	settled water turbidity
Jan	9.98	70.98	3.35	17.00	21.40	4.45	34.53	38.27	4.68
Feb	10.06	67.25	2.83	16.03	42.58	3.95	22.15	35.56	4.36
Mar	13.69	62.86	2.46	12.50	38.68	3.71	18.49	31.43	4.29
Apr	10.47	69.55	2.44	12.14	37.93	4.02	32.41	42.41	4.57
May	17.39	69.60	3.72	16.37	43.22	4.05	33.60	42.08	4.59
Jun	27.83	89.30	3.62	27.32	34.82	6.09	28.06	34.23	4.59
Jul	25.18	89.77	3.54	18.40	18.30	5.45	31.95	37.25	3.85
Aug	14.45	85.44	2.92	13.16	82.06 ϕ	3.97	13.54	19.47	3.54
Sept	24.60	77.47	5.99	43.35	72.05 ϕ	3.75	15.69	33.01	3.65
Oct	22.22	86.24	5.07	84.88	14.11	5.31	19.75	26.24	3.90
Nov	19.59	96.78	4.28	32.06	39.94	4.23	20.00	28.58	3.96
Dec	18.22	28.90*	4.22	33.45	43.15	4.09	22.06	30.05	4.01

The ϕ represents Alum and * represents PAC

Table A4 Mean monthly coagulant consumption (ppm) and colour of raw and settled water (Pt-Co) from 2013 to 2015

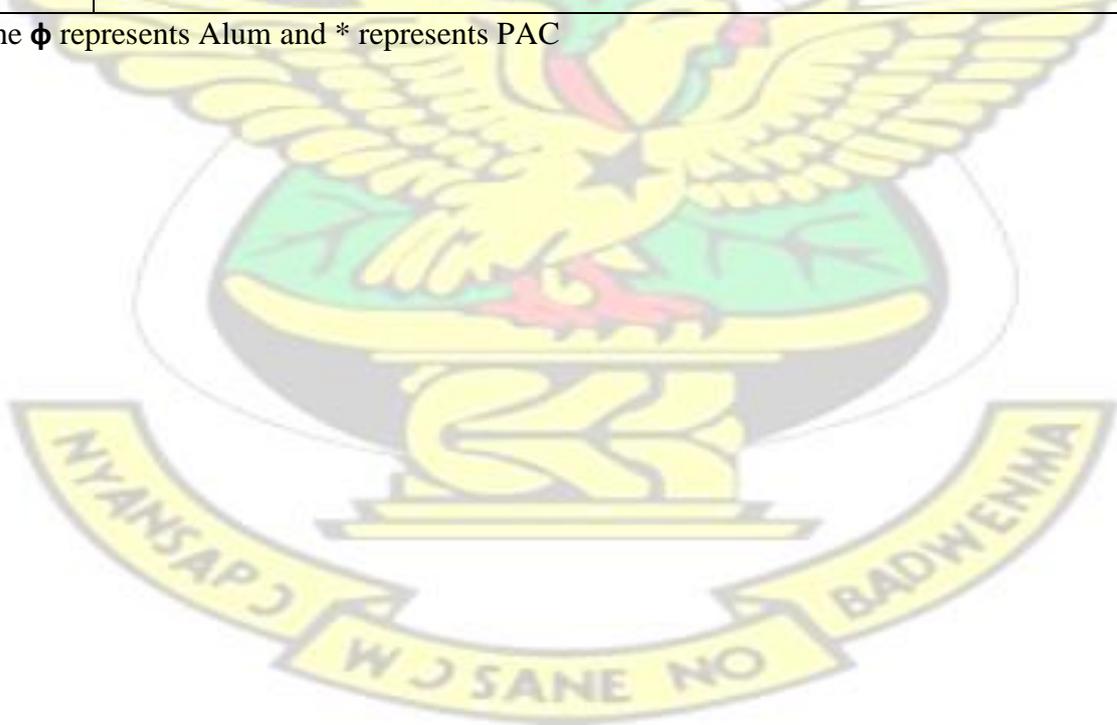
Month	2013			2014			2015		
	Raw water Colour	Alum dosage	settled water Colour	Raw water Colour	Alum dosage	settled water Colour	Raw water Colour	Alum dosage (ppm)	settled water Colour
Jan	179.39	71.13	13.23	187.11	69.63	28.89	143.26	60.42	22.49
Feb	185.43	63.65	16.53	170.63	66.67	24.90	143.10	56.73	22.77
Mar	182.28	62.09	21.35	176.45	65.34	21.77	131.84	58.18	18.83
Apr	207.01	68.79	21.00	146.72	62.07	20.32	209.89	65.43	26.16
May	204.10	70.88	23.15	178.93	66.52	27.28	225.92	72.97	32.38
Jun	163.09	70.74	19.80	202.13	70.17	26.87	201.42	73.44	30.57
Jul	172.62	67.93	18.12	189.75	69.67	22.49	203.25	74.47	30.23
Aug	147.23	72.50	19.20	159.43	64.50	23.23	170.28	67.22	19.09
Sept	145.87	73.87	21.16	155.44	60.34	18.45	162.29	65.24	17.74
Oct	166.56	78.24	23.48	181.37	61.35	21.90	177.25	72.99	20.03
Nov	178.76	67.17	26.96	197.01	62.96	25.96	177.89	70.27	21.67
Dec	422.53	69.56	32.55	195.72	64.67	22.30	172.05	69.95	20.14



Table A5 Mean monthly coagulant consumption (ppm) and colour of raw and settled water (Pt-Co) from 2016 to 2018

Month	2016			2017			2018		
	Raw water Colour	Alum dosage (ppm)	settled water Colour	Raw water Colour	PAC dosage	settled water Colour	Raw water Colour	PAC dosage (ppm)	settled water Colour
Jan	160.35	70.98	15.75	21.40	21.40	16.75	298.42	38.27	17.75
Feb	155.77	67.25	20.34	42.58	42.58	19.71	190.30	35.56	19.08
Mar	163.55	62.86	15.94	38.68	38.68	21.02	191.38	31.43	26.09
Apr	173.65	69.55	17.29	37.93	37.93	18.22	265.18	42.41	19.15
May	188.49	69.60	20.01	43.22	43.22	20.79	229.99	42.08	21.56
Jun	232.60	89.30	19.71	34.82	34.82	20.65	223.36	34.23	21.59
Jul	228.79	89.77	18.06	18.30	18.30	18.06	226.09	37.25	18.06
Aug	173.87	85.44	18.11	82.06 ϕ	82.06 ϕ	17.09	161.20	19.47	16.06
Sept	205.72	77.47	29.01	72.05 ϕ	72.05 ϕ	22.68	160.80	33.01	16.36
Oct	218.78	86.24	25.25	14.11	14.11	20.99	169.73	26.24	16.72
Nov	187.55	96.78	21.14	39.94	39.94	18.70	172.85	28.58	16.26
Dec	177.47	28.90*	20.45	43.15	43.15	18.58	174.52	30.05	16.71

The ϕ represents Alum and * represents PAC



APPENDIX B
LABORATORY EXPERIMENTAL RESULTS

Experiment 1

Table B1 Mean turbidity of flocculated water at different pH, mixing speed and PAC dosage

pH	Mixing speed	Turbidity of flocculated water (NTU)					
		Blank	15 ppm	20 ppm	25 ppm	30 ppm	35 ppm
6.0	180:40	14.30	5.22	7.00	6.25	11.63	13.33
	180:25	14.30	4.68	4.78	8.99	12.33	13.53
	150:25	14.04	4.61	4.84	5.70	11.26	12.89
6.5	180:40	9.23	4.95	4.17	5.59	4.88	3.76
	180:25	9.88	4.55	6.28	3.70	4.30	4.91
	150:25	9.77	3.94	4.19	3.75	3.73	3.82
7.0	180:40	8.77	5.20	5.53	4.62	3.73	5.33
	180:25	9.11	4.84	5.04	4.16	4.91	5.66
	150:25	9.48	4.05	5.30	4.72	4.38	5.82
7.5	180:40	9.00	5.86	5.11	3.92	5.61	7.74
	180:25	7.94	3.23	4.12	3.32	2.51	1.98
	150:25	8.25	3.98	4.82	3.42	3.94	3.70
8.0	180:40	6.30	3.70	3.98	3.78	3.42	2.86
	180:25	6.13	3.61	4.18	3.22	2.89	2.62
	150:25	7.02	3.26	3.70	3.02	3.03	2.68
8.5	180:40	7.56	5.38	4.60	4.22	3.95	3.90
	180:25	7.53	9.06	8.95	8.78	8.77	8.63
	150:25	8.03	4.02	4.27	4.73	4.13	3.66

Table B2 Mean colour of treated water at different pH, mixing speed and PAC dosage

pH	Mixing speed	Colour of flocculated water (Pt-Co units)					
		Blank	15 ppm	20 ppm	25 ppm	30 ppm	35 ppm
6.0	180:40	115	45	55	57	75	100
	180:25	122	55	55	95	100	105
	150:25	112	43	55	60	99	105
6.5	180:40	143	56	34	43	40	26
	180:25	145	43	40	37	41	61
	150:25	131	40	38	41	43	49
7.0	180:40	133	43	45	38	30	35
	180:25	165	65	54	43	59	47
	150:25	134	35	41	46	43	52
7.5	180:40	183	82	67	70	86	67
	180:25	174	50	42	40	37	35
	150:25	178	55	43	43	49	34
8.0	180:40	112	36	42	39	31	33
	180:25	119	45	53	42	41	36
	150:25	120	35	38	33	33	30
8.5	180:40	139	87	66	50	50	36
	180:25	111	74	53	42	38	29
	150:25	113	57	45	48	35	39

Experiment 2

Table B3 Mean turbidity of flocculated water at different pH and retention times

pH	Polymer dosage	Turbidity of flocculated water (NTU) at different retention times					
		5 min	10 min	15 min	20 min	25 min	30 min
6.0	Blank	13.40	13.48	12.85	12.76	12.41	12.14
	15 ppm	7.49	5.15	4.00	3.95	3.80	3.56
6.5	Blank	10.21	9.86	8.94	8.66	8.48	8.47
	15 ppm	5.37	4.93	3.98	3.90	3.83	3.56
7.0	Blank	10.18	9.64	8.98	8.63	8.41	8.21
	15 ppm	6.75	5.50	4.04	4.04	3.77	3.46
7.5	Blank	9.53	8.79	8.47	8.06	7.74	7.70
	15 ppm	6.60	4.50	3.72	3.67	3.34	3.11
8.0	Blank	8.13	7.74	7.27	6.85	6.84	6.34
	15 ppm	5.36	4.21	3.49	3.41	3.33	3.10
8.5	Blank	8.33	7.77	7.37	6.95	6.79	6.52
	15 ppm	5.48	3.85	3.11	3.04	2.84	2.60

Table B4 Mean colour of flocculated water at different pH and retention times

pH	PAC dosage	Colour of flocculated water (Pt-Co units) at different retention times					
		5 min	10 min	15 min	20 min	25 min	30 min
6.0	Blank	168	161	157	152	146	145
	15 ppm	44	32	26	25	23	19
6.5	Blank	144	138	135	128	128	130
	15 ppm	62	39	28	26	23	22
7.0	Blank	131	119	105	99	96	92
	15 ppm	48	32	26	24	22	19
7.5	Blank	165	160	151	151	149	148
	15 ppm	91	44	27	25	21	20
8.0	Blank	159	152	148	138	137	137
	15 ppm	58	44	31	26	23	17
8.5	Blank	155	147	133	131	128	129
	15 ppm	67	40	31	27	24	17

Experiment 3**Table B5 Turbidity of flocculated water at different pH and retention times**

pH	PAC dose (ppm)	Turbidity of flocculated water (NTU) at different retention times					
		5 min	10 min	15 min	20 min	25 min	30 min
6.0	Blank	29.9	20.10	19.30	18.00	18.20	17.80
	15 ppm	10.00	5.76	3.97	4.01	3.35	3.02
6.5	Blank	18.00	16.50	16.10	14.50	13.70	14.00
	15 ppm	9.46	4.81	3.44	3.32	3.01	3.11
7.0	Blank	17.00	15.80	15.00	13.50	13.20	12.30
	15 ppm	8.24	4.12	3.82	3.31	3.01	2.83
7.5	Blank	14.20	14.20	14.20	12.80	12.30	11.20
	15 ppm	7.01	4.87	3.72	3.12	3.01	3.09
8.0	Blank	16.20	15.70	15.00	14.40	13.40	13.80
	15 ppm	7.17	4.33	3.76	3.68	3.43	3.21
8.5	Blank	17.00	15.60	14.90	14.80	14.90	13.80
	15 ppm	8.35	4.72	4.08	3.48	3.31	2.97

Table B6 Mean colour of flocculated water at different pH and retention times

pH	PAC dosage	Colour of flocculated water (Pt-Co units) at different retention times					
		5 min	10 min	15 min	20 min	25 min	30 min
6.0	Blank	270	262	261	251	243	245
	15 ppm	104	61	24	21	15	12
6.5	Blank	255	243	243	227	230	222
	15 ppm	100	52	20	14	8	8
7.0	Blank	259	228	221	205	202	192
	15 ppm	118	81	26	25	11	6
7.5	Blank	225	209	206	201	192	197
	15 ppm	88	42	17	15	10	5
8.0	Blank	230	221	210	209	192	191
	15 ppm	100	57	21	12	7	3
8.5	Blank	240	206	202	196	190	186
	15 ppm	117	69	30	23	12	4

Table B7 Mean Iron concentration of flocculated water at different pH and retention times

pH	Polymer dosage	Iron concentration of flocculated water (mg/l) at different retention times					
		5 min	10 min	15 min	20 min	25 min	30 min
6.0	Blank	4.23	4.17	3.56	3.43	3.44	3.28
	15 ppm	3.05	2.60	0.49	0.40	0.25	0.15
6.5	Blank	4.18	4.19	4.01	3.89	3.18	3.11
	15 ppm	3.60	3.31	0.36	0.30	0.21	0.10
7.0	Blank	4.51	4.37	3.89	3.75	3.34	2.76
	15 ppm	3.73	2.80	0.31	0.23	0.16	0.07
7.5	Blank	4.48	4.26	3.92	3.66	3.52	3.27
	15 ppm	4.10	2.68	0.23	0.18	0.11	0.03
8.0	Blank	4.97	4.54	4.22	3.89	3.71	3.47
	15 ppm	4.03	2.83	0.21	0.17	0.06	0.00
8.5	Blank	5.05	4.32	4.31	4.19	4.25	3.83
	15 ppm	4.39	2.38	0.19	0.17	0.03	0.01

Table B8 Mean Residual Aluminium of flocculated water at different pH and retention times

pH	PAC dosage	Residual Aluminium of flocculated water (mg/l) at different retention times					
		5 min	10 min	15 min	20 min	25 min	30 min
6.0	Blank	0.11	0.09	0.1	0.08	0.08	0.06
	15 ppm	0.41	0.38	0.21	0.19	0.17	0.16
6.5	Blank	0.12	0.09	0.09	0.08	0.07	0.6
	15 ppm	0.35	0.30	0.27	0.23	0.20	0.16
7.0	Blank	0.13	0.12	0.12	0.09	0.1	0.07
	15 ppm	0.37	0.29	0.24	0.21	0.19	0.16
7.5	Blank	0.12	0.11	0.09	0.06	0.05	0.05
	15 ppm	0.43	0.37	0.23	0.21	0.16	0.12
8.0	Blank	0.07	0.05	0.05	0.03	0.01	0
	15 ppm	0.44	0.37	0.22	0.20	0.16	0.13
8.5	Blank	0.06	0.05	0.04	0.04	0.03	0.02
	15 ppm	0.43	0.33	0.21	0.18	0.14	0.12

