A Comparative Study of Metallic Coagulants

for

Rawal Lake Filtration Plant

By

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(2010-NUST-MS PhD-EnvE-15-03)

Master of Science
In
Environmental Engineering

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This is to certify that the thesis entitled

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APPROVAL SHEET

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Professor (Dr. Habib Nasir)

Dedicated to my beloved Father and Mother who had always been a source of inspiration. May ALLAH rest their souls in peace and tranquility. (Ameen)

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF ABBREVATIONS

ALUM **Aluminium Sulphate**

EC **Electrical Conductivity**

EPA **Environmental Protection Agency**

FCL **Ferric Chloride**

ICP-AES **Inductively Couple Plasma –Atomic Emission Spectrometry**

NSDWQ **National Standards for Drinking Water Quality**

NTU **Nephelometric Turbidity Unit**

PACl **Polyaluminium Chloride**

RLFP **Rawal Lake Filtration Plant**

TDS **Total Dissolved Solids**

WHO **World Health Organization**

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Rawal Lake Filtration Plant (RLFP) was commissioned in 1962 by JICA with Aluminum Sulphate [$Al_2(SO_4)_3.18H_2O$] as the sole coagulant. Since its commissioning the water quality of Rawal Lake has been affected by influx of polluted streams and waste disposal by visitors, yet the management never attempted to revisit the coagulation process or the coagulant. The total treatment capacity of the RLFP is 24 MGD out of which about 22.5 MGD is supplied to cantonment area and some other parts of Rawalpindi city and remaining to NIH and surrounding areas. In general, the quality of raw water to RLFP deteriorates after wet spells and improves in dry season except for off-flavor complaints in summer. Thus there was a serious need to check some other coagulants for Rawal Lake Filtration Plant to overcome these problems.

For this purpose three metallic coagulants: Aluminium Sulphate (Alum) [$Al_2(SO_4)_3.18H_2O$], Ferric chloride (FCL) [$FeCl_3$] and Polyaluminium Chloride (PACl) [$Al_n(OH)_mCl_{(3n-m)})_x$] were selected. An attempt was made to add secondary coagulants such as cationic polyelectrolytes but was discontinued due to enormous rise in cost of treatment. In addition to determining optimum individual dose of each selected coagulant, a combination was also tried. Keeping in view the wide variations in turbidity and pH of raw water over the year, the turbidity and pH of lake water samples was modified between 40 – 120 NTU and pH from 6 to 8. Raw water

samples for this study were taken from the inlet of Rawal Lake Filtration Plant. The main experimental variables were coagulant type and dose, turbidity and pH of raw water and the order with which the coagulants were dosed. Whilst turbidity reduction was used as base-line criteria, other variables such as changes in pH, residual coagulant concentration and alkalinity consumption by coagulant were also used for comparison. Residual pH, color, residual alkalinity, fecal coliform, residual coagulant concentration, Electrical Conductivity (EC) and Total Dissolved Solids (TDS) were also investigated. Finally a cost analysis was conducted to examine long term economic implications of the change in coagulant type/dose.

Results show that PACl exhibits the highest overall turbidity removal efficiency as compared to Alum and FCL at the lowest dose. PACl consumes less alkalinity when compared with other two coagulants. Residual coagulant concentration in case of PACl was also lower than the Alum and FCL. PACl also gives excellent removal efficiency for coliforms. PACl results at natural conditions (natural pH and turbidity) were far superior to the other two coagulants used, except that it was relatively expensive. Alum and PACl at the ratio of 90:10 & 95:5 with PACl as order 1st gives better results than Alum alone. At these combinations the cost of the coagulants is quite comparable with Alum alone.

INTRODUCTION

1.1   General

The quality of water for the purpose of human consumption has been of interest since its effects on health were first discovered. Considering the increase in demand and decrease in quality resources, water as essential fluid of life is a scarce commodity.Water supply and treatment are critical needs of the society. It was recognized earlier that water quality involves both aesthetic and health concerns depending on the purpose of consumption. The purpose of water treatment is to produce safe and aesthetically pleasing water. This requires that the water be free of harmful physical, chemical and biological pollutants, as well as have an acceptable taste and odor (Ray, 1993).

Coagulation/flocculation before filtration are still the major steps in conventional water treatment plants. Hydrolysis products from the coagulant remove suspended solids and organic matter either via charge neutralization or the incorporation of impurities into the hydroxide matrix (sweep flocculation). Multivalent salts such as aluminum sulphate (alum), ferric chloride, and ferric sulphate are commonly used coagulants in water treatment. However, their hydrolysis products vary significantly with changes in pH, temperature and nature of the water, and are therefore difficult to control. This in turn leads to under or over-dosing of the coagulant, resulting either in poorly treated water or greater environmental impact in the form of increased sludge volume. Polyaluminum chloride (PACl) is a type of inorganic polymer coagulant, developed to overcome the drawbacks of traditional

coagulants. As the hydrolysis products in PACl are preformed, it is less sensitive to pH and temperature variation. In addition, PACl contains highly positive charged polycations that are highly effective in neutralizing the negative charges of colloidal particles, thereby resulting in increased colloidal destabilization (Ng et al, 2013).

Many impurities in water and wastewater are present as colloidal solids, which do not readily settle. Finely dispersed suspended and colloidal particles that produce turbidity and color in the water cannot be removed sufficiently by mere sedimentation. Colloidal particles generally carry a negative electrical charge. Their diameter ranges from 10^{-4} to 10^{-6} mm. These particles are surrounded by an electrical double layer (diffuse layer and Stern layer) preventing contact between each other. Adding a coagulant (generally positively charged) and mixing the water causes compression of the double layer and thus neutralization of the electrostatic surface potential of the particles. The resulting destabilized particles stick together upon contact forming solids known as 'flocs' (Pritchard et al, 2010).

The potential for health problems associated with contaminated drinking water is great because many diseases are transmitted by water that is contaminated with bacteria or viruses (Mihelcic et al., 2001). Thus, throughout the world, the water quality standards have been developed based upon ultimate use of water. For example, in US primary drinking water standards relate directly to health, and secondary standards relate more to the appearance and non- consumptive uses of water. Primary standards are mandatory whereas secondary standards are suggested as upper limits for non-health related parameters (Ray, 1993).

Europe and USA are in agreement with respect to the required turbidity limits for both aesthetics and health purposes depending upon what purpose the water is going to be utilized. Depending on the source of water, these countries have the water turbidity limitation values as:

- Less than 1 Nephelometric Turbidity Unit (NTU) when the surface water is treated for human consumption.

- Less than 5 Nephelometric Turbidity Unit (NTU) for human consumptive purposes when source is ground water.

Most municipalities and industries obtain their water from surface sources (streams, rivers, lakes, reservoirs) or use groundwater. Since the world has experienced an increase in population and technological growth, the available fresh water is insufficient for future needs and is becoming increasingly scarce. Moreover, the distribution of the water sources throughout the world is not even. Therefore, some parts of the world (e.g., Middle East) constructed desalination plants using seawater as a source of drinking water (US EPA, 1999).

There are many sources of water, but limited amount can be used safely for drinking purposes. Table 1.1 lists those sources and also provides general comments regarding each of these sources (US EPA, 1999).

Table 1.1: Water Sources and typical Characteristics (US EPA, 1999)

Source of Water	Comments
Surface water	High flows, easy to contaminate, relatively high suspended solids (SS), turbidity, and pathogens. In some parts of the world, rivers and streams dry up during the dry season.
Groundwater	Usable as source for drinking water, low flows but has natural filtering capacity that removes suspended solids (SS) and turbidity. May be high in dissolved solids (TDS) including Fe, Mn, Ca, Mg (hardness). Difficult to clean up after contaminated.
Ocean	Energy intensive so costly compared to other sources. Desalination can occur by distillation, reverse osmosis, electrodialysis, freezing, and ion exchange.
Reclaimed water	Technically feasible. More likely to be unacceptable to the public

Generally, the surface waters are preferable sources due to their availability, attainability, treatability, etc. Many underground sources however, are free from visual contamination and it may therefore appear not to be necessary to treat the ground water. Groundwater may contain harmful chemical contaminants leached from the soil and rock formations through which the water moves during infiltration. Ground water may also be contaminated by infiltration of polluted water into the aquifer. The treatment required could only be determined from an analysis of the water. The raw water quality determines the treatment process required. The main aspects that must be taken into account are:

- The quality of the water source with time of the year;

- The quality of the treated water to be produced;

- The volume of water to be treated (capacity);

- The cost to consumers;

- The level of sophistication that is acceptable taking into account plant locality and level of expertise available to control and operate the plan;

- The support services available to assist with plant optimization, troubleshooting and maintenance and repair problems.

- The amount of suspended solids;

- The turbidity of the water;

- The nature of the suspended material;

- The chemical properties of the water (alkalinity and pH)

- The volume of water to be treated, and the availability of facilities, trained operators and supervisors.

Coagulation–flocculation has played, and will still play an important role, directly or indirectly, in the control of particulates, microorganisms, natural organic matter (NOM), synthetic organic carbon, precursors of disinfection byproducts (DBPs), and some inorganic ions and metals, and ultimately, in the control of drinking water quality. In this process, coagulants, such as alum or polyaluminum chloride (PACl), are added to water, and a metal ion such as Al^{3+} undergoes hydrolysis reactions to form other dissolved Al species and Al-hydroxide precipitates. These aluminum hydrolysis species help to aggregate various aquatic particles into larger flocs and then

these flocs are settled, filtered and removed from bulk water in subsequent processes. (Trinh & Kang, 2011)

Coagulation and flocculation processes are important parts of water and wastewater treatment regarding to the removal of suspended particles, and are used together to remove particles that can impart color to a water source, create turbidity, and retain bacterial and viral organisms. Also, some of these small particles may be pathogenic organisms themselves. The process of coagulation and flocculation is used to treat small particles in the size range of 0.001 to 1.0 micrometer. These colloidal particles typically have large surface areas and are usually negatively charged (AWWA, 1990).

In order to obtain an effective coagulation and flocculation, inorganic flocculants are used in large quantities, leave large amount of sludge, which needs further treatment procedures, which complicates handling and disposal procedures. This brings about the increase in the treatment costs. To minimize these drawbacks, synthetic polymers have gained popularity as water treatment chemicals. However, these materials also have limitations:

- They exhibit a significant degree of selectivity to certain types of colloids.
- They form large and strong floc, but usually do not produce a clear supernatant. Because, they are generally incapable of enmeshing all of the colloidal particles in raw water.
- Their unit costs are much higher than alum or ferric chloride
- Most of them are not readily biodegradable. (Kawamura, 1991)

During the period of study i.e. July 2013 to February 2014, turbidity of raw water varies in the range of 10 to 100 NTU and that of pH in the range of 7.36 to 8.21. The average turbidity of the raw water ranges 40 – 50 NTU and on the average, Alum dose of the RLFP ranges 60 – 70 mg/L.

1.2   Research Objectives

1. To compare metallic coagulants for Rawal Lake Filtration Plant (RLFP) and identifying the most effective individual and combined coagulant and most effective pH.

2. To examine the effect of these coagulants on the quality parameters such as Color, Alkalinity, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Fecal Coliform and residual coagulant concentration.

1.3   Hypothesis

Water quality of Rawal Lake has been changing since 1962. Alum may not be the best coagulant for Rawal Lake water, anymore.

Options: Alum, PACl, $FeCl_3$, Polyelectrolytes.

Test: Compare effectiveness of coagulants available in the national market.

Independent Variables

Coagulant Type, Dose, Raw water pH, Raw water turbidity.

Dependent Variables

Residual turbidity, Coagulated water, pH, Color, Alkalinity, Fecal Coliform, TDS, Residual Coagulant concentration.

LITERATURE REVIEW

The rapid development in industry and growth in population leads to the continued discharge of untreated wastewater into surface water and groundwater. Colloidal pollution is one of the main types, which not only produce esthetically unpleasing sight of water bodies, but also inhibit light penetration thereby disturbing the aquatic ecosystem. For removal of these particles, coagulation and flocculation are generally preferred owning to their relatively low cost, easy handling and high efficiency (Yang et al, 2014).

The efficiencies of treatment of fresh water sources for drinking water supply depend upon the treatment technology applied and potentially, on the quality of the raw water. There are a wide range of technologies available to deal with pollutants such as arsenic, manganese, natural organic matter (NOM) and turbidity. Common water contaminants that lower drinking water quality are both particulate and dissolved NOM and inorganic suspended particles. Dissolved organic matter (DOM) can be an important component in drinking water as it can react and lower residual chlorine levels and is a precursor in the formation of disinfection by products such as trihalomethanes, haloacetic acids and chlorophenols (Hussain et al, 2013).

2.1   Similar Studies

Vuppaladadiyam et al in 2013 made a comparative study to optimize the coagulation process for treatment of water sourced from the Palar River Basin and

supplied to the Vellore Municipality. The research was progressed to evaluate the water treatment efficacy of natural coagulant i.e. moringaoleiferaseed, available locally in abundance, as well as conventional coagulants viz. alum and ferric chloride. Primarily the basic operational parameters- pH and coagulant dosages were optimized. Further the treatment efficiency was evaluated on the basis of turbidity, total dissolved solids (TDS), organic content in terms of UV absorbance at 254 nm and microbial contamination (MPN for total coliform) for all three coagulants. Best removal efficiency was achieved near neutral pH with dosages of 45mg/L and 25mg/L for alum and ferric chloride, respectively. However, the Moringaoleifera were not found effective in removing targeted contaminants.

Malhotra in 1994 compared the performance of alum and PACl for water from Wainganga river, Narmada river and Kanhan river (India) having turbidities 150, 800 and 2200 NTU respectively. Turbidity reduction was the main controlling parameter. Along with this pH reduction, alkalinity consumption, sludge volume and residual aluminum concentration was also studied. The results of the study showed that PACl was an effective and useful substitute for solid alum which was conventionally used as a coagulant in most of the water treatment plants in India. PACl caused rapid coagulation of water at different turbidities, produc less sludge & left less amount of residual aluminium.

2.2   Coagulation and Flocculation Processes in Water Treatment

Impurities in water vary in size by about six orders of magnitude, from a few angstroms to a few hundred microns for suspended materials. The removal of a large

proportion of these impurities in water treatment is accomplished by sedimentation. However; some particles called colloids cannot be removed by sedimentation, since the size of colloids (about 0,01 to 1μm) is small and the repelling forces of the electrical charge are high. Under these stable conditions, Brownian motion keeps the particles in suspension. Brownian motion occurs by the constant thermal bombardment of the colloidal particles by the relatively small water molecules that surround them. The aggregation of these particles into large, more readily settleable mass is essential for successful separation by sedimentation. This process is called coagulation (Metcalf and Eddy, 2003).

Coagulation–flocculation has played, and will still play an important role, directly or indirectly, in the control of particulates, microorganisms, natural organic matter (NOM), synthetic organic carbon, precursors of disinfection byproducts (DBPs), and some inorganic ions and metals, and ultimately, in the control of drinking water quality. In this process, coagulants, such as alum or polyaluminum chloride (PACl), are added to water, and a metal ion such as Al^{3+} undergoes hydrolysis reactions to form other dissolved Al species and Al-hydroxide precipitates. These aluminum hydrolysis species help to aggregate various aquatic particles into larger flocs and then these flocs are settled, filtered and removed from bulk water in subsequent processes. The turbidity and NOM of water are the target substances to be removed during coagulation–flocculation treatment. Charge neutralization and sweep flocculation are two mechanisms for removal of turbidity and the concentration of colloids and coagulant dosages are critical factors that determine the predominant mechanism for removal (Trinh & Kang, 2011).

Coagulation and flocculation consist of adding a floc-forming chemical reagent to water to enmesh or to combine with nonsettleable colloidal solids and slow- settling suspended solids to produce rapid-settling flocs. Coagulation is the addition and rapid mixing of a coagulant, resulting in the destabilization of the colloidal fine suspended solids, and the initial aggregation of the destabilized particles. Flocculation is the slow stirring or gentle agitation to aggregate the destabilized particles and forming a rapid-settling floc (Reynolds, 2005).

In modern water treatment technology, coagulation/flocculation is a very important component of the overall suite of treatment processes. The understanding of design/optimization of coagulation/flocculation processes is more important today than in the past since the requirements for the removal of particulates have become increasingly stringent. It has two distinct conceptual components: The first refers to the floc scale physicochemical processes (floc scale hydrodynamics, flocculent adsorption dynamics, and collision rate). This scale can be studied experimentally using laboratory equipment with a well-defined flow field permitting the quantitative assessment of the involved processes. The second conceptual component refers to large scale tank hydrodynamics and its interaction with the local physicochemical processes. Both components are crucial and they must be taken into account in order to evaluate the overall large scale flocculation process (Samaras et al. 2010).

2.2.1 Response Surface Method (RSM) in Coagulation/Flocculation

Traditionally, 'one-factor-at-a-time' technique was used to optimize the treatment process, in which one parameter would be varied while the others were kept

at constant level. However, this technique not only fails to identify possible interactions between variables, but is also time-consuming and expensive because large number of experiments must be carried out. To overcome these drawbacks, response surface method (RSM) was used by Teh et al, for analyzing and modeling the effects of multiple variables and their interactions using a limited number of experiments. Recently, RSM is used widely in water and wastewater treatment and management (Teh et al, 2014).

2.2.2   Stability of Colloids

Many colloidal systems can remain unchanged for very long periods of time, even though they are thermodynamically unstable. A stable colloid is an irreversible (thermodynamically unstable) colloid that aggregates at a very slow rate.   In other words, stabilization of colloid refers to the chemical stability of particle, specifically with respect to the tendency to settle.

The stability of a suspension depends on the number, size, density and surface properties of solid particles of the dispersed phase and the density of the dispersion medium.   In an aqueous suspension; dispersed phase particles usually have negative charges. These negative charges are generated on the surface of solid particles in three ways. First is the isomorphic substitution in the solid lattice. Second is the ionization of surface groups (such as OH group in mineral oxides, carboxyl groups of latex particles, carboxyl or amino groups of proteins). The third method is the preferential adsorption of ions or ionizable species from the suspending medium. (AWWA, 1999). As the pH increases, the amount of negative the charge on the surface of the particles

increases. The particles having similar surface charge repel each other. This keeps the particles from aggregating into larger settable flocs. (Faust and Ally. 1998).

The aggregation of colloidal particles can be considered as involving two separate distinct steps:

(1) Particle transport to effect particle interparticle contact, and

(2) Particle destabilization to permit attachment when contact occurs.

Because of the negative surface charge, ions of opposite charge in the solution will be attracted towards the surface. The counter ions (e.g. Ca^{2+} or Mg^{2+}) are present in surrounding water. They accumulate on the surface of the suspended particles. There will be a higher concentration of the counter ions close to the surface than in the bulk of the liquid. Thus, there is a bound layer (Stern layer) of the counter ions at the particle surface and after this layer; a more diffused layer still exists. Only the bound layer moves with particles. There is a plane of shear between the bound layer and the diffuse layer. The potential difference between the plane of shear and bulk solution is called the zeta potential. As the zeta potential increases, the Columbian repulsion between the particles becomes stronger and the suspension becomes more stable. The double layer composed of the Stern and diffusive layers is shown in Figure 2.1 (Pritchard et al, 2010).
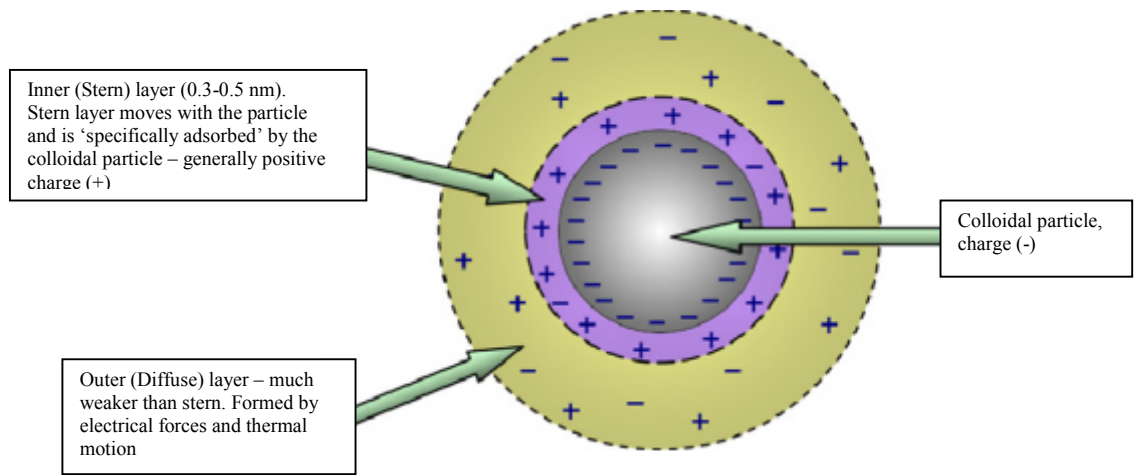
Figure 2.1: Electrical charge surrounding a colloidal particle: The Double Layer
(**Pritchard et al, 2010**)

Coagulation is concerned primarily with the aggregation of thermodynamically unstable (irreversible) colloids. By the help of the coagulation processes, the rate at which colloidal system aggregates increases.

As mentioned above colloids in natural water are predominantly negatively charged and they are stable by virtue of hydration or electrostatic charge on their surfaces. Depending upon the conditions, some coagulants can achieve colloidal destabilization by more than one method. The selection of the proper type and dosage of coagulant for a particular application requires an understanding of how these materials function. Following are the Destabilization mechanisms of the colloidal particles:

- Double layer compression

- Adsorption and charge neutralization

- Entrapment in precipitates (sweep flocculation)

- Interparticle bridging.

2.3 Commonly used Coagulants in Water Treatment

Different chemicals can be used as coagulants. The most common coagulants are:

- Aluminum sulfate (also referred to as alum),

- Ferric chloride,

- Polyaluminum chloride (PACl),

- Lime,

- Polyelectrolytes (synthetic or natural polymers).

Coagulant-aids are also sometimes used. These are substances added in very small quantities to improve the action of the primary coagulant. The characteristics of some example coagulants are stated below.

2.3.1 Aluminium Sulphate (Alum); $Al_2(SO_4)_3.18H_2O$

Aluminum sulfate, also known as alum, is one of the most common coagulants used today. It has been used in water treatment for many years. The United States has been using alum in water treatment systems since the late 1800s (AWWA, 1999). The chemical formula for alum is $Al_2(SO_4)_3$. It is a hydrolyzing metal salt coagulant. This means that the way in which alum destabilizes the particles in water is through hydrolysis. The alum is dissolved in water and the aluminum ions, Al^{3+} that form, have a high capacity to neutralize the negative charges which are carried by the colloidal particles and which contribute to their stability. The aluminum ions form strong bonds with the surrounding oxygen of the water molecules. This weakens the atomic structure of the water molecules and positive hydrogen ions are released into

the solution. The aluminum ions hydrolyze and in the process form aluminum hydroxide, $Al(OH)_3$ which precipitates as a solid. During flocculation when the water is slowly stirred the aluminum hydroxide flocs "catch" or enmesh the small colloidal particles. The flocs settle readily and most of them can be removed in a sedimentation tank (Jarvis et al, 2012).

The absorption of these hydrogen ions by the negatively charged particles results in destabilization of the particles as the charge is neutralized. An overdose of alum will produce what is called sweep floc. The alum that precipitates out of solution will settle to the bottom of a sedimentation basin, entrapping particles on its way down removing them from the effluent.

Every coagulant has an optimal pH range in which it works the best. Alum is most effective when working in a pH range between 5.5 and 6.5. Since aluminum may be harmful at high concentrations it must be allowed to precipitate completely as the hydroxide. Complete precipitation is a function of the pH of the water and the pH must therefore be closely controlled between 5.5 and 6.5 (Trinh & Kang, 2011).

2.3.2 Ferric Chloride; $FeCl_3$

Ferric chloride, $FeCl_3$, is another common coagulant. It has been used in high-rate filtration plants since the 1880s for its ability to reduce the turbidity of the water (AWWA, 1999). Working as a cationic coagulant, ferric chloride reacts with the water in a similar manner as alum causing a hydrolysis effect. The resulting products of that reaction neutralize the charge on the particles and destabilize the particles allowing

them to aggregate when slight motion is added to the solution. Ferric chloride can also be used as a sweep floc coagulant (AWWA, 1999).

Ferric chloride can be purchased in a liquid or dry form. The ferric salts have a wider optimal pH range than alum as ferric salts can be used between pH 4 and 9 (Davis and Cornwell, 1998). In the absence of alkalinity, the reaction between ferric chloride and water produces hydrochloric acid, which will lower the pH and present a need for a pH adjuster.

When added to water, the iron precipitates as ferric hydroxide, $Fe(OH)_3$ and the hydroxide flocs enmesh the colloidal particles in the same way as the aluminum hydroxide flocs do. The optimum pH for precipitation of iron is not as critical as with aluminum and pH values of between 5 and 8 give good precipitation. The reaction can be presented in a similar way as for aluminum sulfate (Zhao et al, 2012).

The coagulation of metallic salts releases hydrogen ions as well as coagulant species. These hydrogen ions neutralize alkalinity and if the initial alkalinity of water is low, the buffering capacity of the water will be destroyed and the initial pH of the water will decrease rapidly during the coagulation process (Ghawi, 2011).

2.3.3 Polyaluminum Chloride (PACl)

Polyaluminum chloride (PACl) is a type of inorganic polymer coagulant, developed to overcome the drawbacks of traditional coagulants. As the hydrolysis products in PACl are preformed, it is less sensitive to pH and temperature variation. In addition, PACl contains highly positive charged poly cations that are highly effective

in neutralising the negative charges of colloidal particles, thereby resulting in increased colloidal destabilization (Ng et al, 2013).

PACl compounds have the general formula $(Al_n(OH)_mCl_{(3n-m)})_x$ and have a polymeric structure, totally soluble in water. The length of the polymerised chain, molecular weight and number of ionic charges is determined by the degree of polymerisation. On hydrolysis, various mono- and polymeric species are formed, with $Al_{13}O_4(OH)_{24}{}^{7+}$ being a particularly important cation. A less predominant species is $Al_8(OH)_{20}{}^{4+}$ (Peter Gebbie, 2001).

These highly polymerised coagulants include the following:

- Polyaluminium chloride (PACl, n=2 and m=3),

- Aluminium chlorohydrate (ACH, n=2 and m=5), and

- Polyaluminium chlorohydrate (PACH): similar to ACH.

In practice, there is little difference between the performance of ACH and PACl in water treatment applications, even though ACH is more hydrated.

An important property of polyaluminium coagulants is their basicity. This is the ratio of hydroxyl to aluminium ions in the hydrated complex and in general the higher the basicity, the lower will be the consumption of alkalinity in the treatment process and hence impact on pH.

The polyaluminium coagulants in general consume considerably less alkalinity than alum. They are effective over a broader pH range compared to alum and experience shows that PACl works satisfactorily over a pH range of 5.0 to 8.0.

Another important advantage of using polyaluminium coagulants in water treatment processes is the reduced concentration of sulphate added to the treated water. This directly affects SO_4 levels in domestic wastewater (Trinh & Kang, 2011).

2.3.4 Lime; CaO

Lime is also used as coagulant, but its action is different than that of alum and ferric chloride. When lime is added to water the pH increases. These results in the formation of carbonate ions from the natural alkalinity in the water. The increase in carbonate concentration together with calcium added in the lime results in the precipitation of calcium carbonate, $CaCO_3$. The calcium carbonate crystals enmesh colloidal particles in the same way as alum or ferric flocs.

When lime is used as coagulant the pH has to be lowered in order to stabilize the water chemically. Carbon dioxide is normally used for this purpose.

2.3.5 Polyelectrolytes

Polyelectrolytes are mostly used to assist in the flocculation process and are often called flocculation aids. They are polymeric organic compounds consisting of long polymer chains that act to enmesh particles in the water.

A polymer is a chain of small subunits or monomers. Many polymers contain only one kind of monomer; nevertheless some contain two or three different types of subunits. The total number of subunits in synthetic polymer can be varied, producing material and different molecular weight. The polymer is called polyelectrolyte

depending on contained ionizable group. The classification is done according to ionizable group; the polyelectrolytes can be:

- Cationic, i.e. carry a positive charge,

- Anionic, i.e. carry a negative charge,

- Non-ionic, i.e. have no net charge (Nozaic et al., 2001.)

In comparison with inorganic coagulants, organic polymeric coagulants have inherent advantages of higher molecular weight, less pH dependence and increased aggregation capacity, while the high cost of organic coagulants limits their comprehensive application in water treatment. In order to utilize the advantages of both inorganic and organic coagulants, the composite inorganic– organic flocculants has recently become research hotpot. Sun et al developed a new composite inorganic– organic flocculant, polyferric aluminum chloride polydimethyldiallylammonium chloride (PFAC–PD), was developed to increase the aggregating ability of the coagulant (Sun et al 2011).

Another added benefit to polymeric coagulants is that they contain little or no aluminum. Researchers have established a link between aluminum and Alzheimers disease; however, it is unknown whether aluminum causes or is a result of the disease. Because the relationship is uncertain, the public is somewhat skeptical of aluminum being used in the treatment of water. Polymeric coagulants do not cause a problem in this regard.

Polymeric coagulants however, have some disadvantages. They cannot reduce the turbidity of the water to the degree that the inorganic metal salts can. They also could

not be used if the goal of the treatment included removing organics from the effluent. Sometimes polymeric coagulants do not work as well in the presence of chlorine. As already stated, they have a very small range of efficiency and if an over dose occurred re-stabilization could produce a major problem and clog the filters. The sludge polymeric coagulants produce is often stickier and is sometimes harder to remove from the hoppers especially if they were designed for the metal salt coagulants (Nozaic et al., 2001).
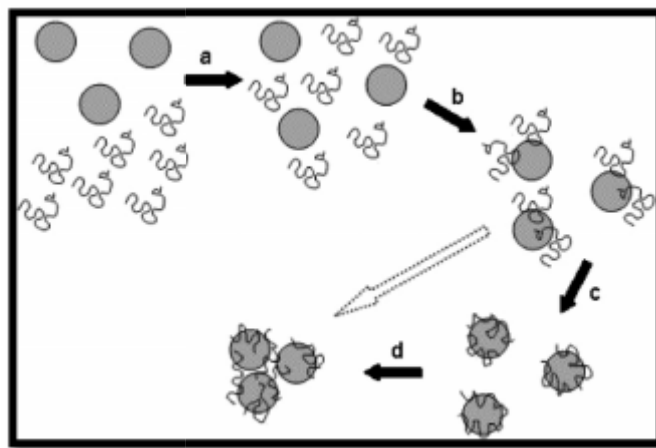
Figure 2.2: **Polymer Adsorption (Bolto et al, 2007)**
(a) Mixing, (b) Adsorption , (c) Rearrangement of adsorbed chains (d) Flocculation

Organic polymers or polyelectrolytes could be group into two groups depending on their origin:

- Synthetic polymers,
- Natural polymers

However the biodegradability of natural polymers reduces their shelf life and needs to be suitably controlled. Their required dosages are large and their solutions and flocs lose stability and strength because of biodegradability. It is evident that all polymers, whether natural or synthetic, have one or more disadvantages. In the past, several attempts have been made to combine the best properties of both by grafting synthetic polymers onto the backbone of natural polymers after purification. One of the greatest advantages gained is the consequent reduced biodegradability because of a drastic change in the original regular structure of the natural polymer as well as the increased synthetic polymer content within the product. It is also observed that the grafting of shear degradable polymers onto a rigid polysaccharide backbone provides fairly shear stable systems (Singh et al., 2003).

2.3.6 Natural Polymers

Synthetic organic polymers have been used as an effective coagulant aid in drinking water purification systems. However, organic polymers have potential limitations. Polymer formulations contain contaminants from the manufacturing process such as residual monomers, other reactants, and reaction by-products that could potentially negatively impact human health. Polymers and product contaminants can react with other chemicals added to the water treatment process to form undesirable secondary products.

Starch, one of the most abundant natural polymers in the world, is an interesting material to be used as a coagulant. Starch products have a special role in purification process for drinking water through flocculation. In its crude form, it

consists of a mixture of two polymers of anhydroglucose units, amylose and amylopectin. Due to its renewability, biodegradability and low cost, starch is often modified chemically or biochemically to produce coagulant. Currently, cationic starch is one of the most commonly investigated starch derivative coagulants to be used to effectively treat organic and inorganic matters in wastewater carrying negative charge. However, potentially hazardous chemicals such as formaldehyde, caustic soda and various solvents are often used for starch modifications (Teh et al, 2014).

Over the recent years, the use of natural polymeric materials has been tested in water treatment with the purpose of valorization of the available biological resources and the elimination of the possible negative impact of the synthetic polymers on human health due to the presence of residual monomers from manufacturing process and reaction by-products. Some natural polymers, such as polysaccharides, have been suggested to be moderately efficient due to their low molecular weights and high shear stability and they were noted to be cheap and easily available fromreproducible farmand forest resources. Additional advantages of these natural polyelectrolytes include safety for human health, biodegradability, and a wider effective dose range of flocculation for various colloidal suspensions. Hence, natural organic polymers have been studied for their flocculating ability to replace inorganic coagulants in recent years (Devrimci et al, 2012).

Polymeric flocculants, synthetic as well as natural, because of their inertness towards pH change, low dosage requirement have gained more interest in recent years. In comparison with synthetic organic/inorganic flocculants, modified natural polymer/ biopolymer based flocculants have drawn more attention because they are found to be efficient, less expensive, biodegradable and environmental friendly .Amongst various methods for modification of natural polymers/biopolymers, graft copolymerization of synthetic polymers (such as polyacrylamide and polyacrylic acid) onto natural polysaccharide backbone is one of the most useful method. By grafting polyacrylamide branches on rigid backbone of natural polysaccharides, the dangling grafted chains have easy approachability to the contaminants in effluents, and thus they are bestowed with highly efficient attributes. Several grafted polysaccharide based flocculants including amylopectin, carboxymethyl cellulose, chitosan, glycogen, guar gum, starch, and tamarind kernel polysaccharide have been reported as efficient flocculants for the treatment of industrial wastewater and synthetic effluents. Cellulose is one of the most abundant natural polysaccharide. It has been the subject of research in recent times, mainly with respect to modify its physical and chemical structure by improving its properties and broadening its industrial applications (Das et al, 2013).

In fact, various types of modified starch-based flocculants have been reported. Single cations or anions were usually introduced onto the starch resulting in improved water solubility and charge density. Moreover, long polymer branches such as polyacrylamide (PAM) were grafted onto the starch backbone, and thus increasing the molecular weight of flocculants so as to enhance bridging effect. Considering that surface charge of suspended particles in water can either be positive or negative,

cationic modified starch-based flocculants show good flocculation performance for negatively charged colloidal particles, but show deteriorated performance for positively charged ones and vice versa. Thus, amphoteric starch-based grafting copolymers with benefits of cations, anions and grafted branches are expected to be promising. In addition, real contaminated water is normally complicated. Even for the same contaminant, its surface charge in water bodies varies with different pH values. As a result, previously imprecise modification of flocculants can scarcely meet the increasing requirement of water treatment (Yang et al, 2014).

Water quality is considered the main factor controlling health and the state of disease in both man and animals. Surface water quality in a region is largely determined both by natural processes (weathering and soil erosion) and by anthropogenic inputs (municipal and industrial wastewater discharge).The anthropogenic discharges constitute a constant polluting source, whereas surface runoff is a seasonal phenomenon, largely affected by climate within the basin (Singh, 2004).

MATERIALS & METHODS

3.1 General

Series of laboratory experiments were conducted during this study. These included running jar tests, at different initial turbidities and pH with different doses (mg/L) of coagulants: Alum, Ferric Chloride and Polyaluminium Chloride (PACl). The coagulated/flocculated and settled water was tested for turbidity, pH, Color, Alkalinity, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Fecal Coliform and residual Aluminum concentration.

3.2 Study Methodology

The Rawal Lake constructed in 1960, east of Islamabad, is one of the main sources of water supply for Rawalpindi after conventional treatment. It supplies water to 1.7 million people. For the last few decades, Rawal Lake has been subjected to pollution by a number of sources including human settlement, poultry wastes, and recreational activities, agricultural activities, deforestation, erosion and sedimentation. The villages of Bhara Kahu, Malpur, Bani Gala and Noorpur Shahan are situated around Rawal Lake. Increased number of housing colonies and untreated sewage is adversely affecting the quality of water coming into the lake. Recreational activities are another source of pollution. Car washing is another activity which has been identified as a pollution risk. The excess irrigation water is drained out through

Nullahs that enters the lake. The use of pesticides and herbicides in agriculture is a source of toxic pollution.

This study was carried out in three phases. First: Extensive jar test experiments at natural turbidities and natural pH of raw water to determine the optimum coagulant dose of each coagulant. The natural turbidity of Rawal Lake Filtration Plant (RLFP) raw water varies between 10 NTU to 100 NTU with average around 40 – 50 NTU and that of pH varies between 7.36 to 8.21 for the months of July 2013 to February 2014. Optimum dose of Alum, PACl and $FeCl_3$ were determined based upon turbidity removal.

Second phase of the study was conducted on modified raw water of Rawal Lake Filtration plant w.r.t turbidity and pH. Turbidity was modified to 40, 80, & 120 NTU and pH's 6, 7, 8. Jar tests were carried out on these three turbidities and pH with wide and narrow ranges of coagulant dosages. Again optimum dose of Alum, PACl and $FeCl_3$ were determined based upon turbidity removal.

Third phase of the study was conducted by using a combination of optimum doses determined above to arrive at the most effective and most economical doses.

Table 3.1 shows the characteristics of raw water observed during the period of study.

Table 3.1 - Raw water Characteristics (During the period of study)

Sr. No.	Characteristics	Composition
1	Turbidity	10 – 100 NTU
2	pH	7.36 – 8.21
3	Alkalinity	190 – 200 mg/L as $CaCO_3$
4	Color	50 (Pt – Co Units)
5	Fecal Coliform	130 – 150 col./100 ml
6	EC	400 – 550 µS/cm
7	TDS	250 – 350 mg/L

Figure 3.1 shows the Experimental Steps.
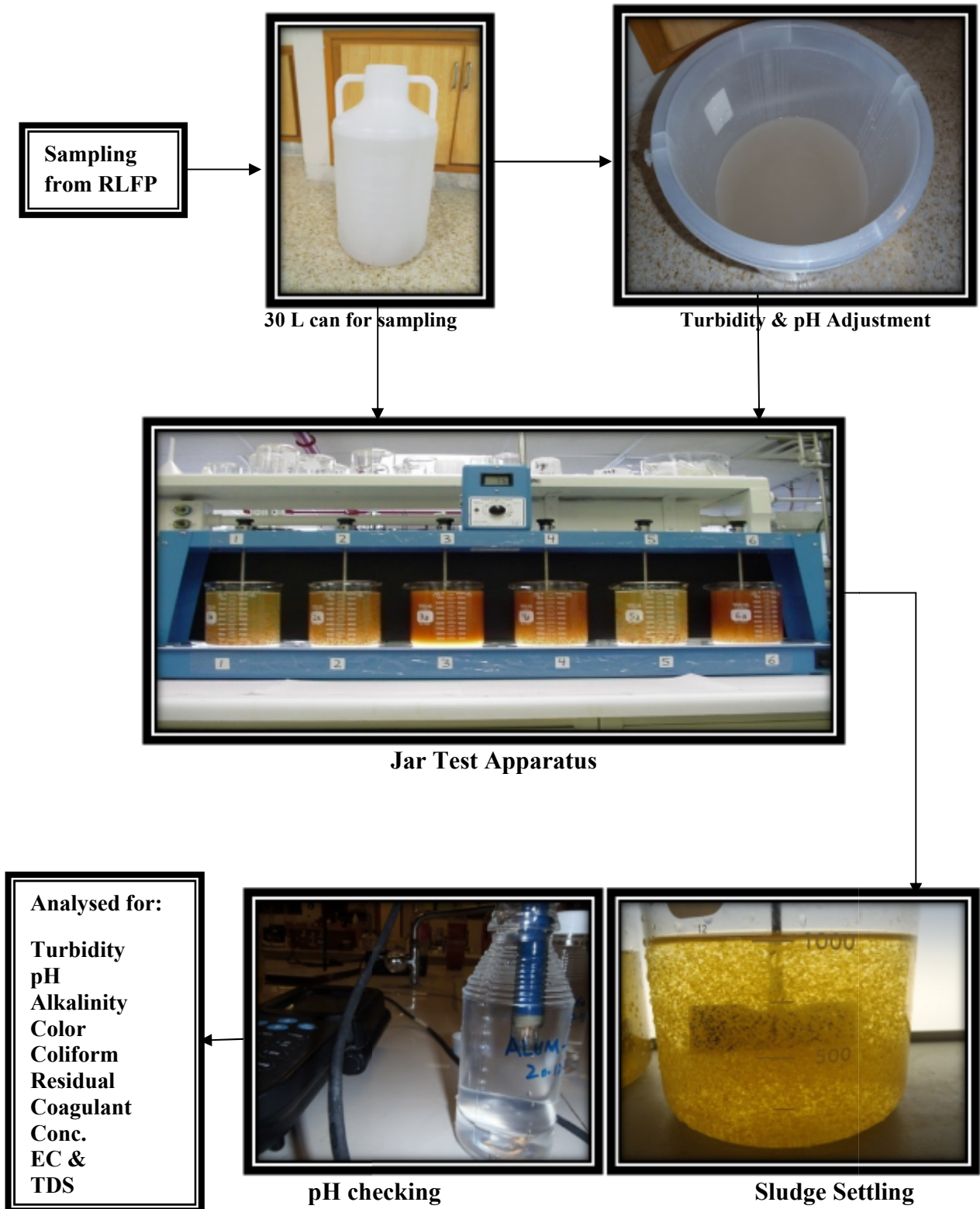
Sampling from RLFP → **30 L can for sampling** → **Turbidity & pH Adjustment**
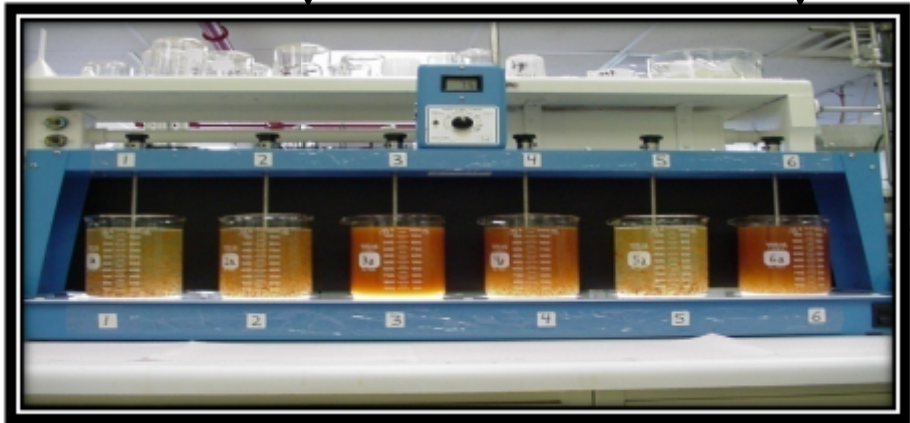
Jar Test Apparatus

Analysed for:

Turbidity
pH
Alkalinity
Color
Coliform
Residual
Coagulant
Conc.
EC &
TDS

pH checking
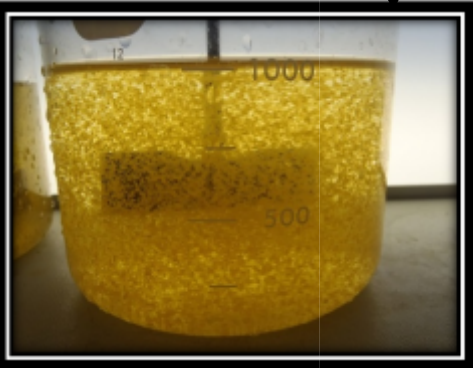
Sludge Settling

Fig 3.1: Experimental Steps

3.3   Materials

3.3.1   Raw Water

The water samples used for the coagulation experiments were taken from the inlet of Rawal Lake Filtration Plant (RLFP). Experiments were conducted on these samples immediately after the water was taken and brought to the laboratory.

3.3.2   Clay Suspension

In order to cover the wide variations in the Rawal Lake water turbidity and pH, its characteristics were modified in the second phase of the experiments. For this purpose Keoline clay was used. The stock solution was prepared in a way that 2.0 g of clay (Keoline) was allowed to dissolve in 1 liter of distilled water by mixing for 5 hours. The mixing is achieved by the use of a jar test apparatus. The turbidity of this sample was determined to be around 1900-2000 NTU. Lower turbidity samples were prepared by diluting this stock turbidity suspension with the raw water to yield turbidity values of 120, 80 and 40 NTU.

Table 3.2 shows the volume ratio of the stock solution vs raw water for three modified turbidities.

Table 3.2: Synthetic Turbidity Preparation

Stock Solution (ml)	Raw Water (L)	Turbidity (NTU)	Average Turbidity (NTU)
150	5	38 - 43	40
250	5	74 - 82	80
375	5	116 - 124	120

3.4 Coagulants and Chemicals

3.4.1 Aluminium Sulphate (Alum)

Aluminium Sulphate commonly called Alum was used from Panreac (already available in IESE lab).A stock solution of 10 g/L was prepared. To ensure the freshness of alum small volumes of a new solution was prepared all the times just before the experiment. A required amount of this stock solution was dosed into the jars during jar test experiments.

Table 3.3 shows the impurities present in the Alum (used in the experiments)

Table 3.3: Impurities in Alum

Formula	$Al_2(SO_4)_3.18H_2O$
Molecular Wt.	666.42
Solubility in water at 20 ^{0}C	600 g/l
Purity	51-59 %
Maximum Limit of Impurities	**Percentage**
Alkali and alkaline-earth salts	0.4
Chloride (Cl)	0.05
Ammonium (NH_4)	0.05
Heavy metals (as Pb)	0.004
As	0.0003
Cu	0.002
Fe	0.01
Ni	0.002
Pb	0.002

3.4.2 Ferric Chloride (FCL)

Anhydrous Iron chloride (already available in IESE lab) of Merck was used in this research work. A stock solution of 10 g/L was prepared. To ensure the freshness of Ferric chloride small volumes of a new solution is prepared all the times just before

the experiment. A required amount of this stock solution was dosed into the jars during jar test experiments.

Table 3.4 shows the impurities present in the Ferric chloride (used in the experiments).

Table 3.4: Impurities in Ferric Chloride

Formula	FeCl$_3$ (anhydrous)
Molecular Wt.	162.2 g/gmol
Solubility in water at 20 ^{0}C	920 g/l
purity	97 – 99 %
Maximum Limit of Impurities	**Percentage**
Phosporous compounds (as PO$_4$)	0.01
Nitrate (NO$_3$)	0.01
Sulphate (SO$_4$)	0.01
Cu	0.003
As	0.002
Ca	0.01
Fe (II)	0.002
K	0.02
Mg	0.01

3.4.3 Polyaluminium Chloride (PACl)

Commercial grade Polyaluminium Choloride (PACl) was used in this research. A stock solution of 10 g/L was prepared. To ensure the freshness of Polyaluminium Chloride (PAC) small volumes of a new solution is prepared all the times just before the experiment. A required amount of this stock solution was dosed into the jars during jar test experiments.

3.4.4 Hydrochloric Acid (HCl)

1 N Hydrochloric Acid was used to adjust the acidic pH of raw water. For this purpose 41.66 ml of 12 N HCl was dissolved in 500 ml of distilled water to make the

1 N stock solution of HCl. Required amount of this stock solution was dosed into the Raw water to adjust the pH.

3.4.5 Sodium Hydroxide (NaOH)

1 N Sodium Hydroxide was used to adjust the basic pH of raw water. For this purpose 4.0 g of sodium hydroxide was dissolved in 100 ml of distilled water to make the 1 N stock solution of NaOH. Required amount of this stock solution was dosed into the raw water to adjust the pH.

3.4.6 Sulfuric Acid (H_2SO_4)

0.02 N sulfuric acid was used for the determination of residual alkalinity of treated water. A stock solution of 0.02 N H_2SO_4 was prepared from 18 N H_2SO_4.

3.5 Methods

3.5.1 Coagulation Experiment

The jar test experiments were performed using a series of 6 place jar test apparatuses, namely VELP Scientifica JLT6 Jar Test. One liter of raw water sample was placed in each of the jars, and at each set a predetermined dose of any of the three coagulants Alum, Ferric Chloride and Polyaluminium Chloride (PACl) solutions were added as quickly as possible. Then, rapid mixing at 120 rpm for 1 minute was provided.

Then, the samples were slowly mixed @ 30 rpm for another 20 minutes for flocculation. The samples were then allowed to settle for 30 minutes for

sedimentation, and the supernatant samples were taken for the measurement of final Turbidity, pH, Color, Alkalinity, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Fecal Coliform and Residual Aluminium concentration. Maximum care was exercised in removing samples. All samples were collected from a fixed depth. The samples collected for Fecal Coliform were kept at 4ºC, if necessary until the measurement is conducted.

3.6 Variables of Interest

A series of independent variables including the initial turbidity, initial coagulant dose, initial pH and order of chemical addition were tested for their effects on the process.

The treated water was tested w.r.t residual turbidity, pH, Color, Alkalinity, EC, Total Dissolved Solids (TDS), Fecal Coliform and residual Aluminum concentration. Details of these variables and the tests conducted are explained below.

Table 3.5 shows the independent and dependent variables studied during the research.

Table 3.5: Independent and Dependent Variables investigated during the Study

Independent Variables	Dependent Variables
Raw water turbidity	Residual turbidity
Raw water pH	pH
Coagulant type	Color
Coagulant dose	Alkalinity
Order of coagulant addition	Fecal Coliform
	Residual Coagulant Conc.
	Electrical Conductivity (EC) & Total Dissolved Solids (TDS)
	Cost

3.6.1 Initial Turbidity

Since the turbidity is a very important variable of jar test and the natural waters may vary in terms of their turbidity, low, medium and high turbidity waters were prepared using the clay sample. Depending on the water source (river, lake or ground water) and the environmental events such as rainstorms or agricultural action, the turbidity of the water source may vary between low levels like 10 NTU and high levels around 1000 NTU.

Since most waters come from reservoirs to treatment plant, the high turbidity values are believed to be not very common and realistic. Therefore, much lower turbidity values were studied in this work. A high turbid water sample having 120 NTU was prepared using the keolin clay stock solution. Similarly, medium and low turbidity samples were prepared at 80 and 40 NTU, respectively. Also series of jar tests were performed on natural turbidities ranging from 10 – 100 NTU during the months of July 2013 to February 2014.

3.6.2 Alum Dose

For each set of initial turbidity, tests were done using initial Alum concentrations between 5 - 175 mg/L (Depending upon the initial turbidity of raw water).

3.6.3 Ferric Chloride Dose

For each set of initial turbidity, tests were done using initial Ferric chloride concentrations between 5 - 150 mg/L (Depending upon the initial turbidity of raw water).

3.6.4 Polyaluminium Chloride Dose

For each set of initial turbidity, tests were done using initial PACl concentrations varying from 5 - 150 mg/L (Depending upon the initial turbidity of raw water).

3.6.5 Order of Coagulant Addition

In order to check the performance of combined coagulants, Alum and PACl were tested in the percent ratios of 50:50, 75:25, 90:10, and 95:5 for their best doses. For this purpose two series of experiments were conducted; in the first series Alum was dosed as the first chemical and rapidly mixed for 1 minute, followed by PACl addition with 1 minute rapid mixing. In the second series PACl is dosed first and Alum is dosed next, following 1 minute rapid mixing of each. The purpose of this experiment was to economies the high cost of PACl.

3.6.6 pH

The natural pH of the raw water varies between 8.21 to 7.36 during the period of research. A series of experiments were carried out at this natural pH. To investigate the optimum initial pH three synthetic pH (6, 7, 8) were prepared and tested. 1 N HCl was used for maintaining acidic pH and 1 N NaOH was used for maintaining basic pH.

3.7   Analytical Techniques

3.7.1   Turbidity Measurement

Several methods are available to measure the turbidity of water. Turbidity in slow moving, deep water can be measured using a device called secchi disk. This method is no longer in use for turbidity measurement. The other methods used to measure turbidity are Nephelometric and Jackson methods with units NTU and JTU's respectively. This method can only be used in highly turbid waters.

In this study the turbidity measurements were performed using Nephelometric method according to the Standard Methods No. 2130 A (Standard Methods, 1995). Hach 2100 N model turbidimeter was used throughout the experiments. This method is based on a comparison of the intensity of light scattered under the defined conditions with the intensity of light scattered by a standard reference suspension under the same conditions. Hach 2100 N model turbidimeter measures the turbidity in either ratio or non-ratio mode. Light from a tungsten-filament lamp is focused and passed through the sample. The 90 degree scatter detector receives light scattered by particles and forward scatter detectors receive light that passes through the sample. The turbidmeter was calibrated by using the standards of 100 and 1000 NTU. The turbidmeter used in this study was shown in the Fig 3.2.

Fig 3.2: Turbidimeter HACH 2100 N

3.7.2 pH Measurement

The pH of water can be measured with a pH meter. It is an electric device with a probe. The probe contains an acidic aqueous solution enclosed by a glass membrane that allows migration of H^+ ions. The electrical potential of the glass electrode depends on the difference in H^+ ions between the reference solution and the solution into which the electrode is dipped. pH can also be measured with pH paper or by adding a regent (indicator solution) to the water sample and recording the color change.

The pH of all water samples in this study was measured using pH meter (Hach).The meter was calibrated using suitable buffer whose pH was known. The pH of water in the sample bottles was measured by dipping the pH glass electrode. Equilibrium between electrode and sample was established by stirring the sample to ensure homogeneity. Using the same temperature was also recorded in degree centigrade. The pH meter used in this study was shown in the Fig 3.3.

Figure 3.3: pH meter HACH

3.7.3 Color Measurement

Residual color of the water samples were measured with Spectrophotometer DR 2010, in co. pt. units. Stored program number of 120 for color was entered with corresponding wavelength of 455 nm. A blank sample of distilled water was prepared to zeroize the equipment prior to put the actual sample in the spectrophotometer. The water sample to measure the color was placed in the equipment and color was recorded as co. pt. units. The spectrophotometer used in this study was shown in the Fig 3.3.

Figure 3.4: Spectrophotometer HACH DR2010

3.7.4 Alkalinity Measurement

Alkalinity is measured by titration. An acid of known strength (the titrant) is added to a volume of sample water. The volume of acid required to bring the sample to a specific pH level reflects the alkalinity of the sample. The pH end point is indicated by a color change. Alkalinity is expressed in units of milligrams per liter (mg/L) of $CaCO_3$.

In this study, Alkalinity of the water samples was determined using titration method by taking 0.02N H_2SO_4 (Sulpheric Acid) in the burette and 50 ml sample water in the Erlenmeyer flask. Two drops of methyl orange added in the flask which changes the color of water sample to orange. While the sample stirred manually, it was titrated with H_2SO_4. Change of color from orange to pink indicates the end point. By using the formula stated below the Alkalinity of water sample was determined.

Alkalinity (mg/L) = $\dfrac{Volume\ of\ Acid\ X\ Normality\ of\ Acid\ X\ 50000}{Volume\ of\ Sample}$

3.7.5 Electrical Conductivity (EC) & Total Dissolved Solids (TDS) Measurement

To measure TDS using standard method, the water sample is filtered, and then the filtrate (the water that passes through the filter) is evaporated in a pre-weighed dish and dried in an oven at 180 ˚C, until the weight of the dish no longer changes. The increase in weight of the dish represents the total dissolved solids, and is reported in milligrams per liter (mg/L). Depending upon the chemistry of the water, TDS can also be estimated by multiplying specific conductance (in microohms/cm) by a factor between 0.55 to 0.75 (0.6 in this specific case). Moreover, TDS can be determined by measuring individual ions and adding them up. TDS meter is also used to measure the TDS level in the water.

In this study EC and TDS were measured by a portable meter. This meter measures pH, EC and TDS.

3.7.6 Fecal Coliform Measurement

As far as public health is concerned the most important aspect of drinking water quality is the bacteriological quality i.e. the presence of bacteria and viruses. It is not practical to test water for all organisms that it might possibly contain. Instead the water is examined for a specific type of bacteria that originates in large numbers in human and animal excreta and its presence is indicative of fecal contamination. Coliforms can be separated into fecal origin (fecal coliforms) and non-fecal coliforms

(originating from soils and vegetable matter).The predominant fecal coliform is Escherichia coli, which is commonly used as an indicator organism. Escherichia coli is about 1μm in diameter and 2-6 μm in length. It is a non-spor forming bacteria and can convert lactose into gas and acid. E.coli enters the aquatic environment from the discharge of fecal contamination introduced by some warm-blooded animal's source including humans. E.coli are above 90% of the total coliform bacteria present in stools. The existence of E.coli in water samples indicates the presence of fecal matter and possibility of the presence of pathogenic organisms of human origin .E.coli are generally non pathogenic (indicator organisms), but the bacteria of loe virulence may become pathogenic in the immune-compromised host. Also, certain types of E.coli frequently cause diarrhea, vomiting and nausea.

In this study membrane filtration (MF) method was used to detect the presence of fecal coliform in the water. In the initial step an appropriate sample volume (100 ml) was passed through a membrane filter with a pore size small enough (0.45 microns) to retain the bacteria present. The filter was placed in a petridish containing a culture medium (FC agar) that is selective for fecal coliform growth. The petridish was then incubated for 18 hours at 41.5 ˚C. Fecal coliform colonies are yellow in color (indicative of lactose fermentation). The colonies were counted using a magnifier or a low power microscope. Samples for fecal coliform test were taken in sterilized bottles.

3.7.7   Residual Aluminum concentration Measurement

In this study the residual aluminuim concentration was measured with ICP-AES = Inductively Couple Plasma –Atomic Emission Spectrometry shown the Fig 3.5.
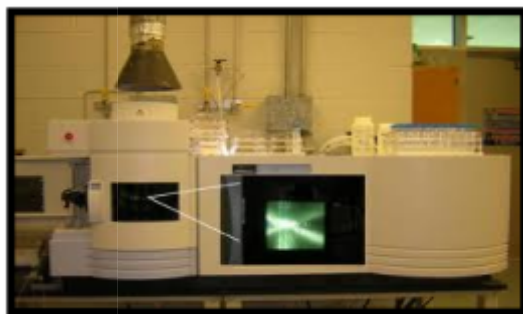
Figure 3.5: ICP-AES (Inductively Coupled Plasma Atomic Emission Spectrophotometer)

Figure 3.6 shows the schematic flow diagram of the study
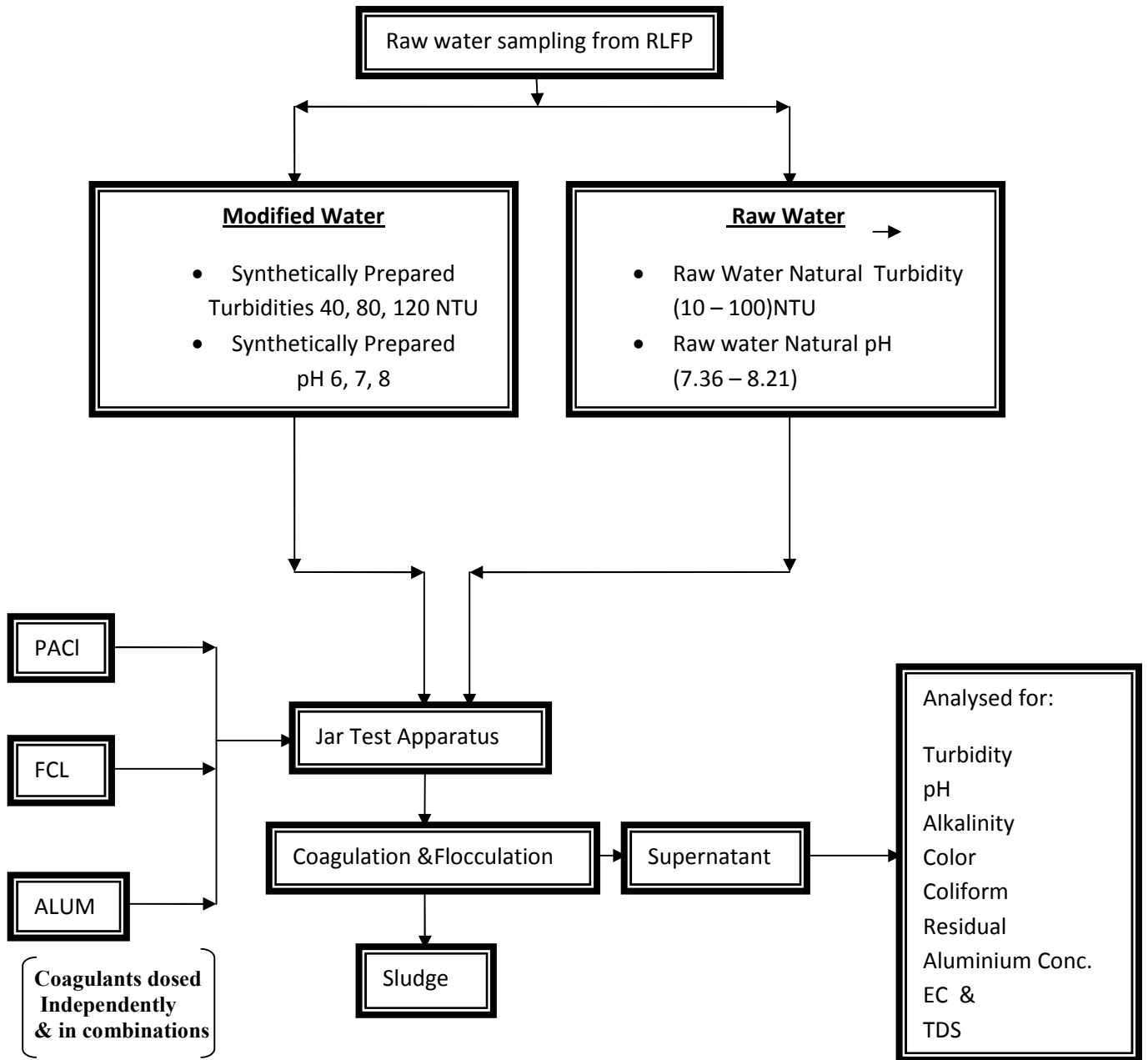
Figure 3.6: Flow diagram of the Study

RESULTS & DISCUSSION

4.1   General

This study was carried out to find the most effective coagulant type, dose and pH for Rawal Lake Filtration Plant (RLFP).   Jar test Experiments were carried out during the period of July 2013 to February 2014.   The total treatment capacity of the RLFP is 24 MGD out of which about 22.5 MGD is supplied to cantonment area and Rawalpindi city and remaining to NIH and plant surrounding areas.   Since commissioning in 1962, the Rawal Lake Filtration Plant (RLFP) has been using Aluminium Sulphate commonly called Alum as the sole coagulant.   The plant draws raw water from Rawal Lake.   The quality of raw water to RLFP is detoriating day by day because the nitrates, sulphates, phosphates, total suspended solids and turbidity rise in the wet season and fall in the dry season. Microbial load ranges between 130 – 150 Count/100ml.   Alkaline pH was observed most of the time.   In the treated water high turbidity, out of range pH, low alkalinity, objectionable taste and odor and out of range residual coagulant concentration was observed.   Thus there was a serious need to check some other coagulants for Rawal Lake Filtration Plant to overcome these problems.

Since the whole study was carried out in three stages, therefore the results were also illustrated in three parts.   Part-1 describes the results of baseline study i.e. the coagulation experimentation of the raw water having natural turbidity and pH (unmodified water).   A series of jar test were carried out in the 1st stage of research i.e.

the natural turbidity ranging (10 – 100 NTU) and natural pH ranges (7.36 – 8.21). For demonstration three raw water turbidities and pH were selected and that are 25, 65 and 100 NTU turbidity with pH's 8.05, 7.73, 7.95 respectively. Three coagulants were compared on these conditions on the basis of turbidity removal and results were represented graphically and tabulated form.

Part – 2 represents the results related to the modified raw water having turbidities 40, 80 and 120 NTU and pH 6, 7 & 8. Jar test experimentation for each turbidity and each pH was performed. Selected coagulants were compared on the basis of turbidity removal, residual pH, color, alkalinity, residual coagulant concentration, EC and TDS. Optimum dose in the both stages one and two were determined on the basis of turbidity removal. On the basis of these parameters the most effective coagulant was find out. Comparing the results of each coagulant at the three modified and natural pH the most effective raw water pH was determined. All the results were represented in the graphical and tabulated form.

Finally in the Part – 3 cost analyses was made on the basis of predetermined optimum doses and to economies the cost of coagulant combinations were applied. In this part results were represented in the tabulated form.

Part - I

4.2   Baseline Study

First part of the study was carried out by using raw water of the Rawal Lake i.e. the feed for RLFP. Most of the time during the study period raw water turbidity

remains below the 30 NTU. At this level of turbidity normally no coagulant was used by the RLFP and this turbidity was assumed to be removed at the filtration stage. High turbidities were observed during the month of July and August. Time series (Figure. 4.1) depicts the trend of three coagulants w.r.t turbidity removal and optimum doses respectively. The figures 4.1 illustrates clearly that PACl exhibits the least residual turbidity as well as the optimum dose as compared to Alum and $FeCl_3$. The plots also shows that the coagulant dose increases with the increase in the raw water turbidity and almost all the three coagulants exhibits fairly good removal efficiency of turbidity.

(a)

Residual Turbidity (NTU) vs *Time (days)*

Legend: PACl, Alum, FCL

(b)

Opt Coagulant Dose (mg/L) vs *Time (days)*

Legend: PACl, Alum, FCL
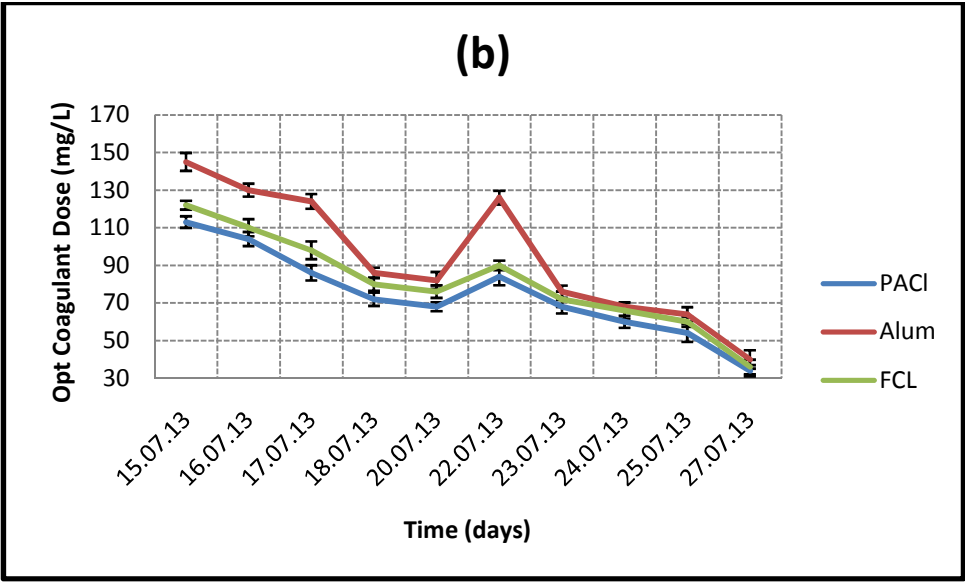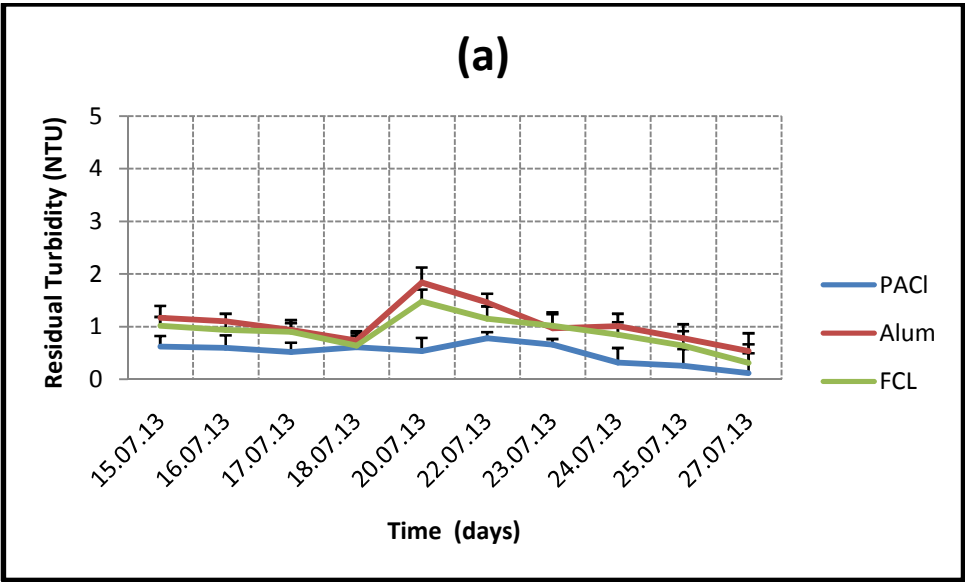
4.3   Determination of Most Effective Coagulant

The prime objective of this research work was to find out the most effective coagulant and its optimum dose and pH for Rawal Lake Filtration Plant (RLFP). For this purpose three coagulants Aluminum Sulphate (Alum), Ferric Chloride (FCL) and Polyaluminium chloride (PACl) were tested on raw water natural pH (7.36 - 8.21) and natural turbidity (10NTU – 100NTU). Also raw water from RLFP was modified w.r.t three synthetic turbidities 40, 80 and 120 NTU to check the performance of said coagulants. It is quite clear from the plots that during the whole band of natural pH and natural turbidities PACl gives low dose with high removal efficiency than other two coagulants. PACl also show same results with the synthetically prepared turbidities.

The chemistry of PACl is quite different from Alum. Alum is Aluminum Sulfate bonded to approximately 18 water molecules and has the formula $Al_2(SO_4)_3$.$18H_2O$. When Alum is added to water, hydrolysis occurs forming several monomeric Alumna species including Al^{3+}, $Al(OH)^{2+}$, $Al(OH)^{4-}$ before precipitating to the solid phase amorphous Aluminum hydroxide ($Al[OH]_{3(am)}$). The intermediate species formed are highly dependent on water pH, temperature, available alkalinity and the nature of the inorganic and organic particles in the water. The fact that Alum needs to go through the hydrolysis reaction makes it very dependent on water pH, temperature and available alkalinity. The colder the water the more viscous the solution and the slower the reaction path, making Alum less effective in the winter time.

PACl is pre-hydrolyzed meaning that Aluminum and chloride are combined with a solid or soluble base such as the (OH-) molecule thus improving the performance characteristics of the coagulant. The intermediate species formed include the monomeric species of Alum and polymeric high charge Alumna species including $Al_2(OH)_2{}^{4+}$ $Al_3(OH)_4{}^{5+}$ and $Al_{13}O_4(OH)_{24}{}^{7+}$

Since PACl is pre-hydrolyzed, the high charged polymeric Alumna species are immediately available for coagulation and charge neutralization rather than being formed in situ as with Alum. Charge destabilization and floc formation are faster and PACL is less pH and temperature dependent than Alum.

Unlike the Aluminum based coagulant $FeCl_3$ is not the effective coagulant at its pH of minimum solubility because it has the week positive charge of $Fe(OH)_2$ species. It shows relatively good performance at lower pH of about 5.5, where more positive charge is present and less negative charge on collides and NOMs. Like the other coagulants the surface charge on the ferric flocs is $Fe(OH)_{am}$ is pH dependent surface charge.

4.3.1   Performance of PACl

Polyaluminium chloride (PACl) proves itself the most effective coagulant for the RLFP with optimum coagulant doses (mg/L) of 60, 82 and 94 at 40, 80 and 120 NTU turbidities respectively. In most of the cases PACl shows the lower coagulant dose and higher removal efficiency as compared with Ferric Chloride and Alum. PACl not only exhibits excellent removal efficiency for turbidity but also gives very good results w.r.t Microorganisms, Color, pH, Alkalinity, Residual aluminum

concentration and Electrical Conductivity (EC) & Total Dissolved Solids (TDS). All these parameters were discussed in detail in the following sections.

4.3.2   Performance of Ferric Chloride

Ferric chloride also shows good results but not better than the Polyaluminuim chloride (PACl).   It is clear from the plots that the curve of Ferric chloride lies between the PACl and Alum which means that the Ferric chloride shows lower dose than Alum but higher than that of PACl.   The removal efficiency of Ferric chloride is comparable with PACl and slightly better in some cases but at the expense of higher doses than PACl.   The performance of Ferric chloride was also studied w.r.t Microorganisms, Color, residual pH, Alkalinity, Residual aluminium concentration and EC & TDS and is discussed later in this section.

4.3.3   Performance of Alum

Since one of the purpose of this research was to compare the performance of Alum with other coagulants.   The results of this research show that at the same turbidity and pH Alum requires higher doses than Ferric Chloride and PACl.   Alum requires coagulant doses (mg/L) of 72, 120 and 138 at 40, 80 and 120 NTU turbidities which is higher than both Ferric chloride and PACl.   As far as the removal efficiency is concerned Alum shows satisfactory results but lower than both PACl and Ferric chloride.

Figs 4.2 show the comparison of three coagulants at 40, 80 and 120 NTU turbidities respectively with natural pH.   In each case PACl shows the lowest dose

than FCL and Alum. As far as the % removal of turbidity is concerned PACl exhibts the maximum removal at 120 and 40 NTU turbidities while FCL shows the maximum removal at 80 NTU turbidity.

Figure 4.3 shows the comparison of three coagulants at 40, 80 and 120 NTU turbidities respectively with pH 6.   Figure 4.4 shows the comparison of three coagulants at 40, 80 and 120 NTU turbidities respectively with pH 7 and the Figure 4.5 shows the comparison of three coagulants at 40, 80 and 120 NTU turbidities respectively with pH 8.

(a)

(b)

(c)

(a)

(b)

(c)

(a)

(b)

(c)

(a)

(b)

(c)
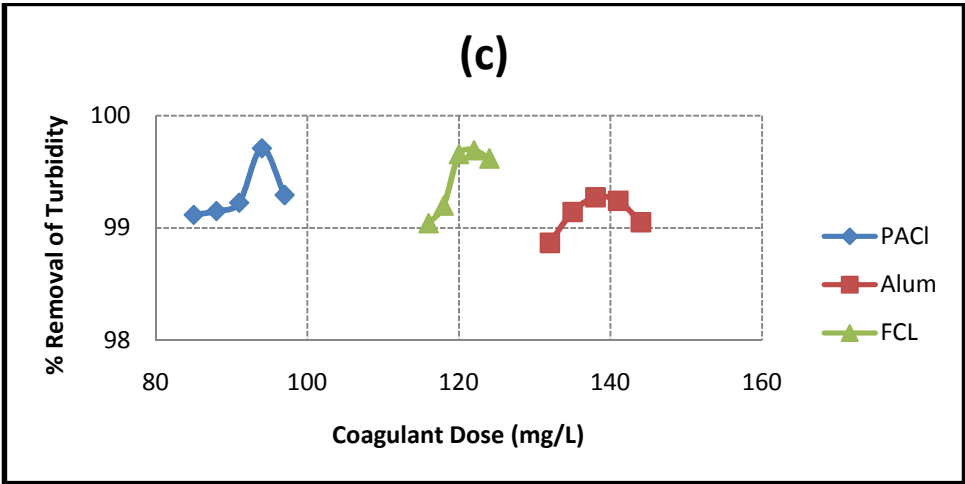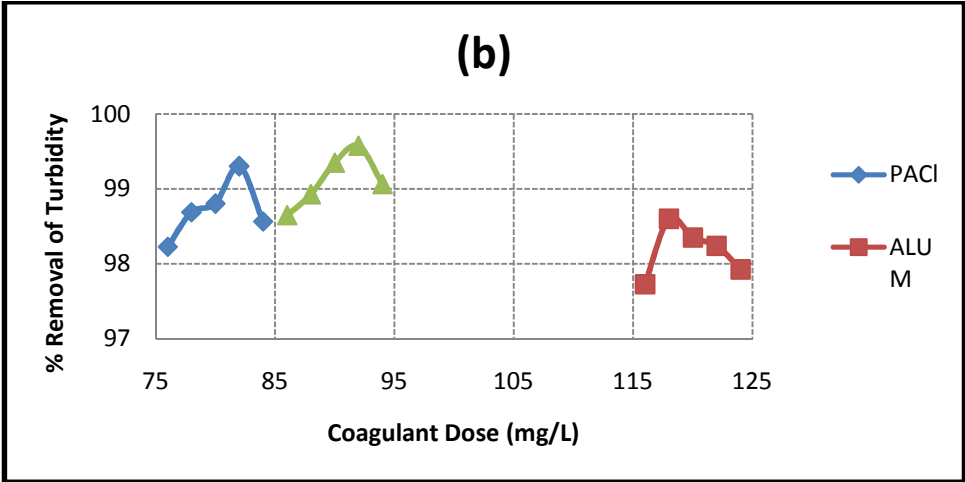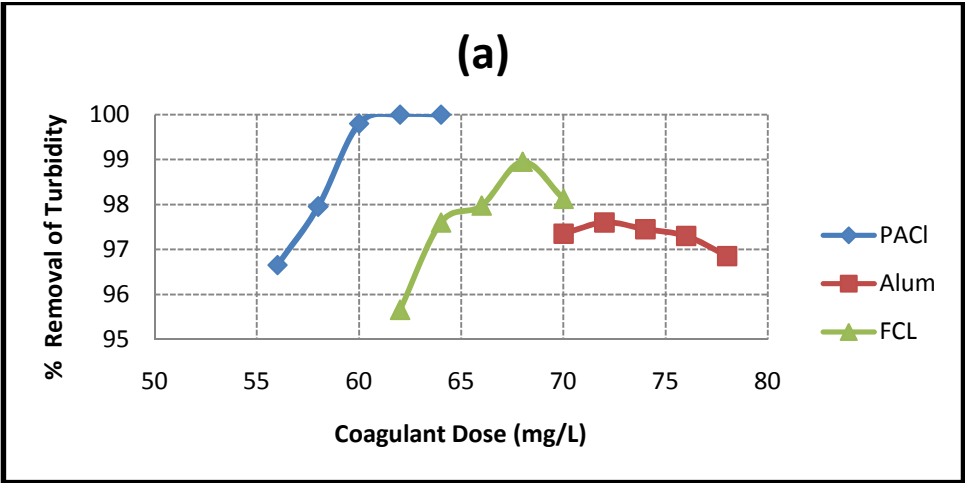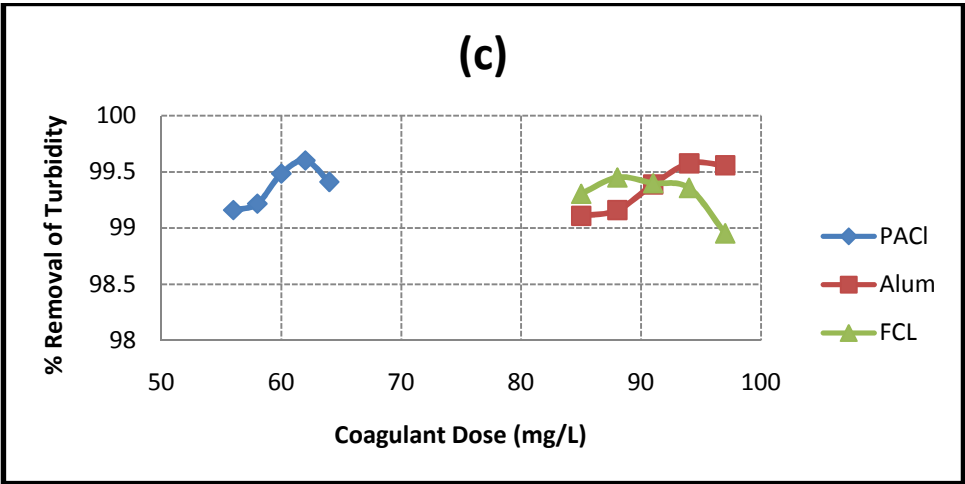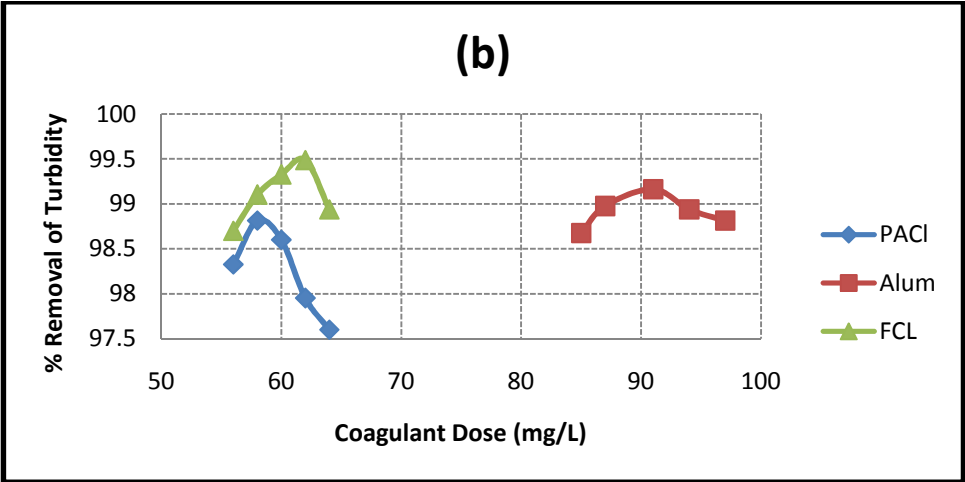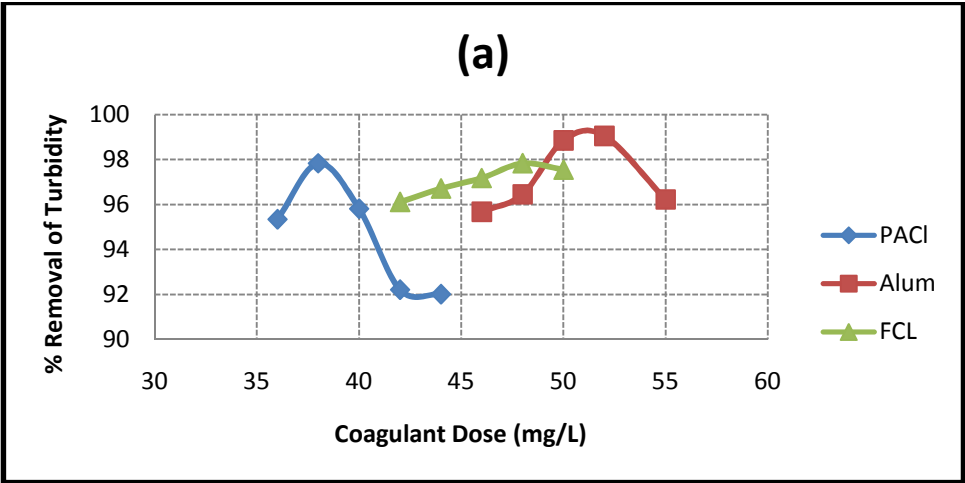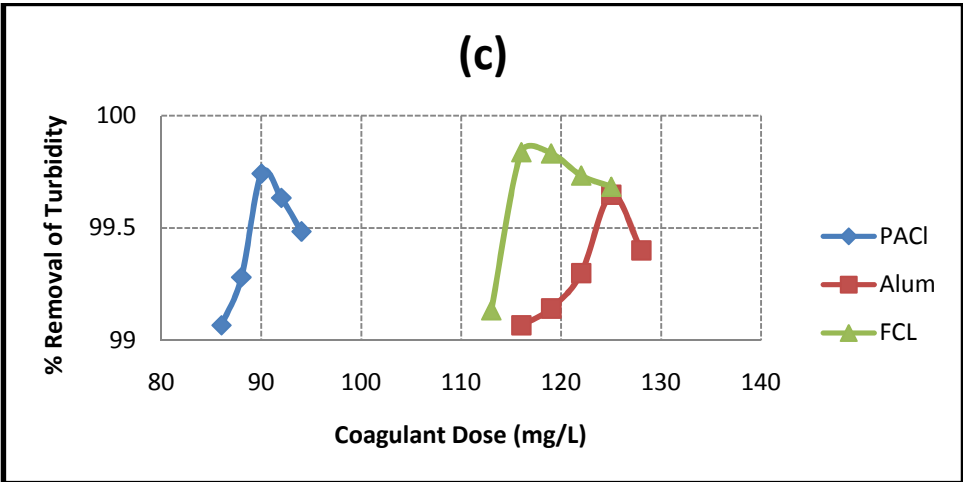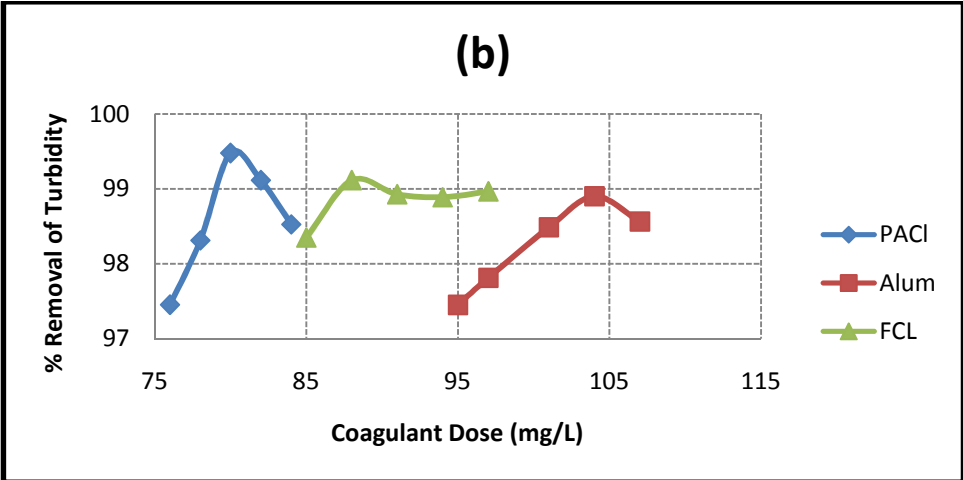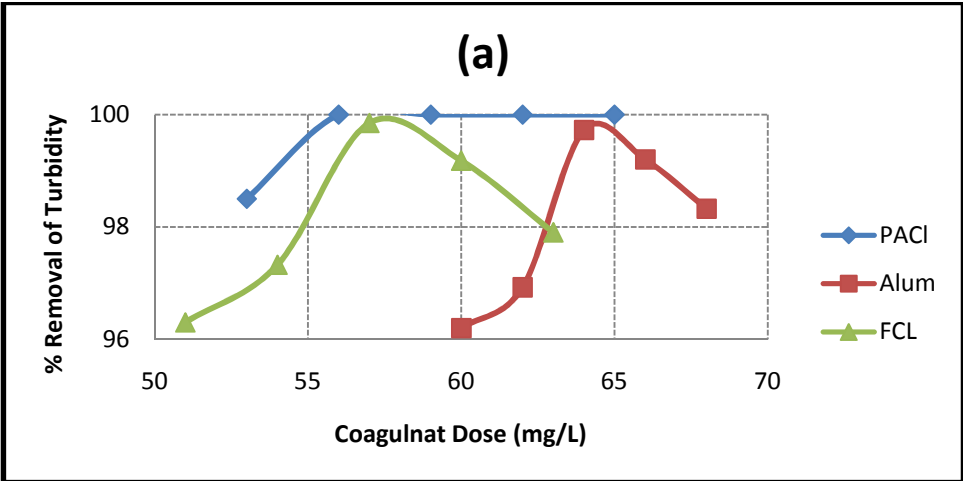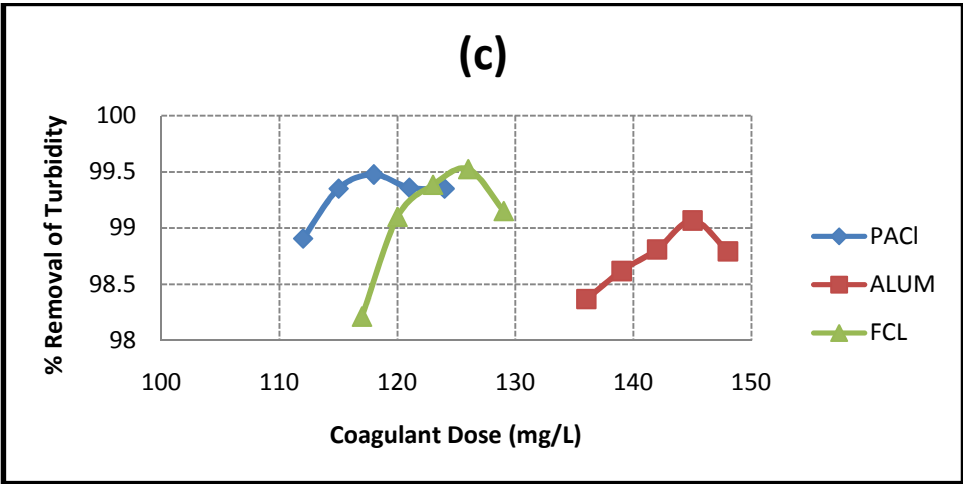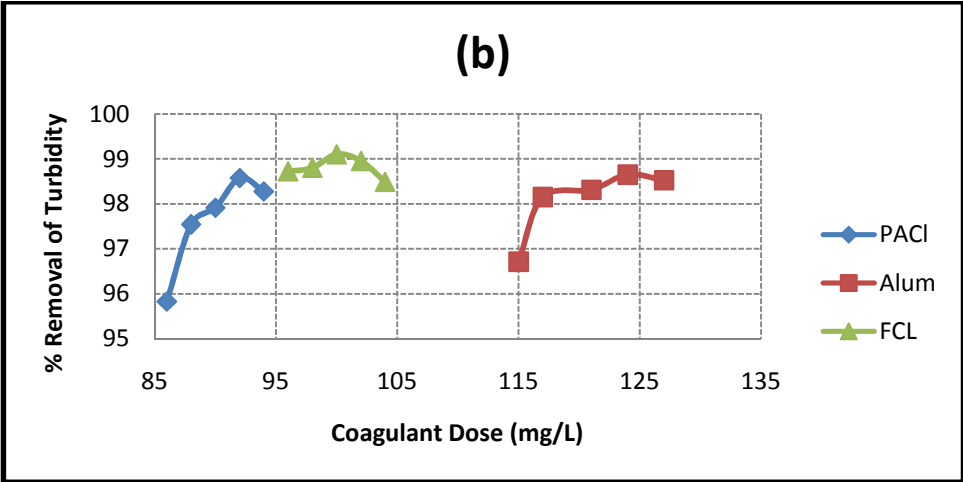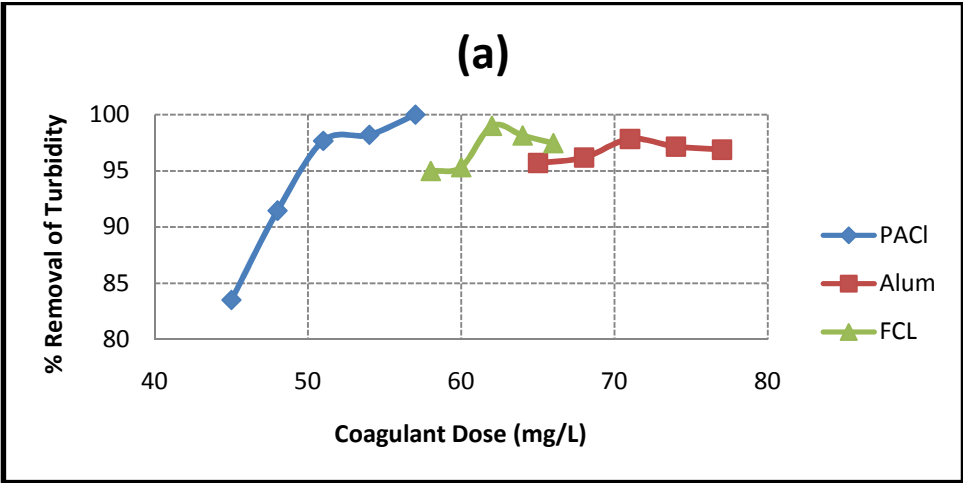
Optimum dose comparison with % removal of Turbidity of three coagulants at 40, 80 and 120 NTU at natural, 6, 7 and 8 pH is tabulated in Table 4.2.

Table 4.1: Optimum Coagulant Doses with % Removal of Turbidities

Coagulants	R.W Turbidity(NTU)	pH	Opt. Dose(mg/L)	% Removal
PACl	40	8.21	60	100
	80	7.27	82	99
	120	7.41	94	99
Ferric Chloride	40	8.21	68	98
	80	7.27	92	99
	120	7.41	122	99
Alum	40	8.21	72	97
	80	7.27	120	98
	120	7.41	138	99
At pH 6				
Coagulants	R.W Turbidity(NTU)	pH	Opt. Dose(mg/L)	% Removal
PACl	40	6	38	98
	80	6	58	98
	120	6	62	99
Ferric Chloride	40	6	48	97
	80	6	62	99
	120	6	88	99
Alum	40	6	52	99
	80	6	91	99
	120	6	94	99
At pH 7				
Coagulants	R.W Turbidity(NTU)	pH	Opt. Dose(mg/L)	% Removal
PACl	40	7	56	100
	80	7	80	99
	120	7	90	99
Ferric Chloride	40	7	57	99
	80	7	88	99
	120	7	116	99
Alum	40	7	64	99
	80	7	104	98
	120	7	125	99

At pH 8				
Coagulants	R.W Turbidity(NTU)	pH	Opt. Dose(mg/L)	% Removal
PACl	40	8	57	100
	80	8	92	98
	120	8	118	99
Ferric Chloride	40	8	62	99
	80	8	100	99
	120	8	126	99
Alum	40	8	71	97
	80	8	124	98
	120	8	145	98

(a)

(b)

(c)

(d)
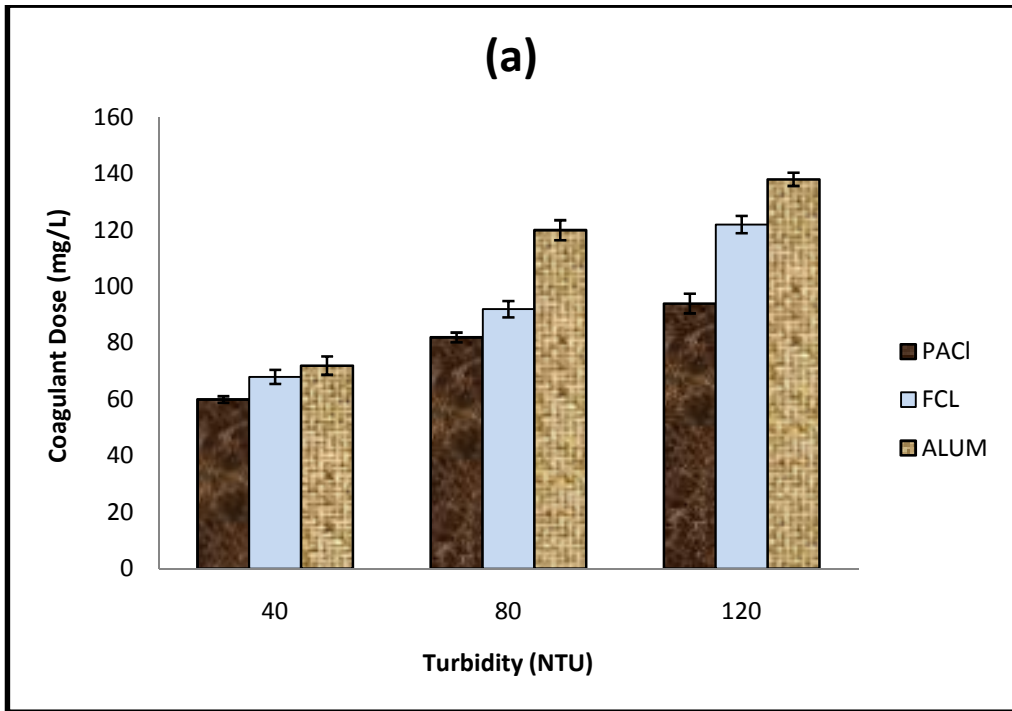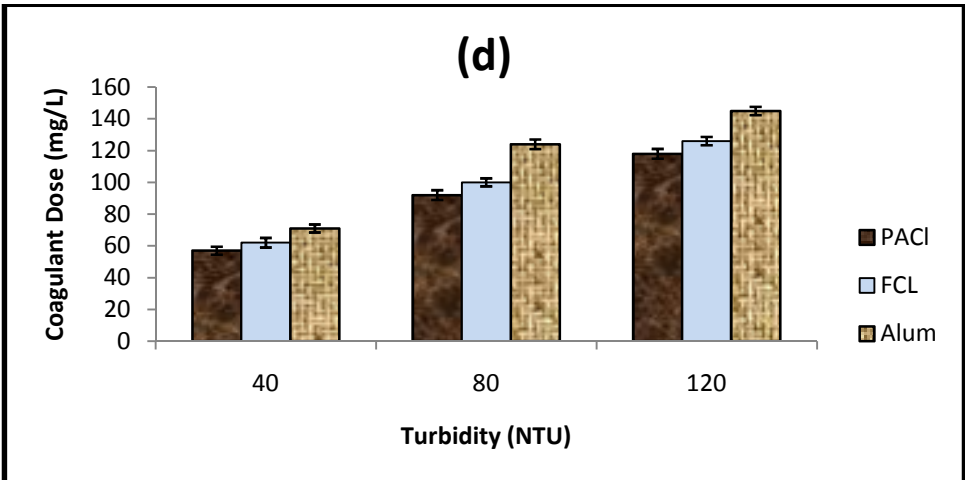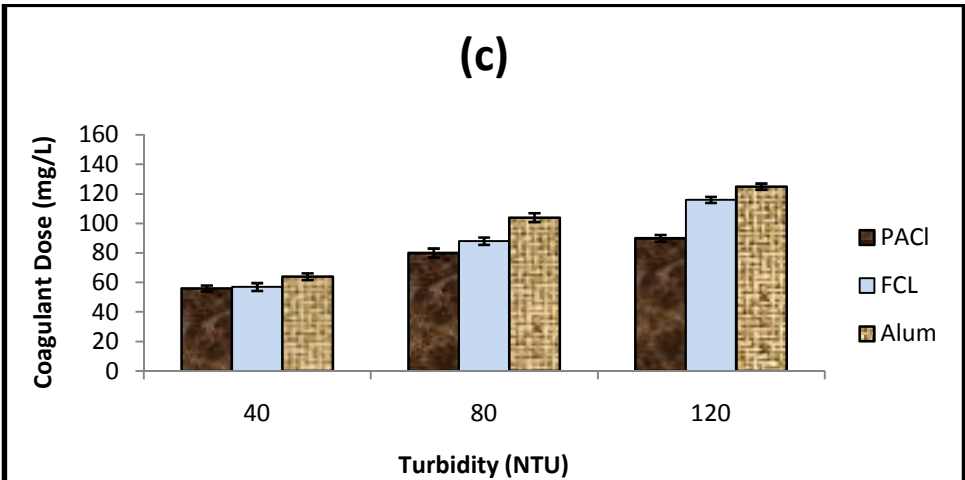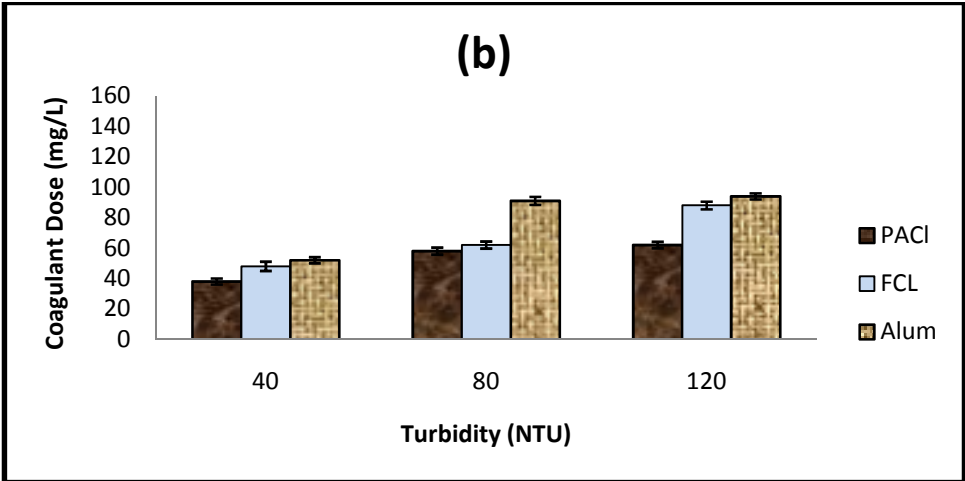
4.4 Determination of Optimum pH of Raw Water

Since the initial pH of the raw water affects the coagulation & flocculation process and the dose of coagulant varies with the change in the initial pH. Therefore the performance of all three coagulants is studied with varying initial pH values (6, 7, and 8) for both natural and synthetic turbidities. The performance of all three coagulants at these initial pH values were compared with that of natural pH. It is quite clear from the plots that all the three coagulants give minimum dose at pH 6 and maximum dose at pH 8. This means that as the initial pH of raw water raises coagulant dose also increases. As far as the % removal is concerned PACl shows the highest removal efficiency at pH 7 and above. Ferric Chloride gives the highest removal efficiency only at neutral pH of 7. Alum gives the highest removal efficiency at acidic pH of 6. Maintaining the initial pH upto 6 adds extra cost of Hydrochloric Acid (HCl) and manpower. Also it is quite troublesome to maintain the homogenized initial pH value at the bulk stage of about 24 MGD of raw water in RLFP.

As the pH of raw water increases (i.e., [H+] decreases), the surface charge on the collides becomes increasingly negative and the suspension becomes more stable. To neutralize this increased negative charge higher coagulant doses are required at high pH of raw water.

When any coagulant was added to and diluted in the water to be treated, the hydrolysis reaction occrs and produces hydrogen ions that react with alkalinity species in the solution. As a result of this alkalinity of the water to be treated was reduced. Since alkalinity is the buffering capacity of the water body, therefore the pH of water

was depressed. If some of this acid produced during the alkalinity consumption process is neutralized with base when the coagulant is manufactured, the resulting product is a prehydrolyzed metal salt coagulant solution. The degree to which the hydrogen ions produced by hydrolysis are preneutralized is called the *basicity.*

PACl is a preneutralized coagulant and is characterized by it degree of neutralization r.

$$r = [OH^-] / [M]$$

$$Basicity = (r / 3) \times 100\%$$

Commercial PACl generally have the basicity ranging from (15 – 85) %. In general higher the basicity higher the Al_{13}^{+7} fraction thus resulting high charge neutralization (low coagulant dose), low alkalinity consumption and pH depression at a lesser extent. The basicities of the Alum and $FeCl_3$ were quite lower than PACl.

The strong acid content or acidity of commercial coagulant solutions depends on the basicity of prehydrolyzed products and the acid content of acid supplemented products. The effective acidity of a coagulant product can be used to determine the relationship between the coagulant dosage and the pH after flocculation and floc separation. The effective acidities follow the order $FeCl_3$ > Alum > PACl. The coagulant having the high acidity will depress the pH of water at a high extent.

The solubility diagram of the Al $(OH)_3$ shows that the maximum amount of alum is converted to solid phase flocs at pH 6. By increasing or lowering the pH from this pH of minimum solubility the dissolved Al ions in the treated water will increase. Literature shows that the pH of minimum solubility for PACl and $FeCl_3$ are quite

higher than Alum and is about 8. As the basicity of a coagulant is raised its pH of minimum solubility is also increased.

4.4.1 Performance of PACl

Comparing the performance of PACl at different turbidities and initial pH's it is quite clear that PACl shows excellent results in all conditions. At natural pH of 7.41 and 120 NTU turbidity PACl exhibts 94mg/L of dose which is very much lower than Ferric chloride (122mg/L) and ALUM (138mg/L) at these conditions. At this pH and turbidity PACl also shows comparably high removal efficiency of turbidity than Ferric chloride and Alum. At the worst conditions of initial pH of 8 and 120 NTU turbidity PACl proves itself the best coagulant with lower dose and higher removal efficiency than Ferric Chloride and Alum.

Figure 4.7 shows the trend of PACl with varying pH at 120, 80 and 40 NTU, where 6, 7, 8 are the synthetic pH's of the modified raw water. Plot shows that as the initial pH of raw water reduces, the optimum coagulant dose was also decreased. This means that the optimum coagulant dose is maximum at pH 8 and minimum at pH 6. As far as the % removal is concerned maximum % removal was observed at pH 7 and above. In most of the cases PACl shows fairly good % removal at pH 7 and above.

(a)

PACl pH 7.41
PACl pH 6
PACl pH 7
PACl pH 8

(b)

PACl pH 7.25
PACl pH 6
PACl pH 7
PACl pH 8

(c)

PACl pH 8.21
PACl pH 6
PACl pH 7
PACl pH 8
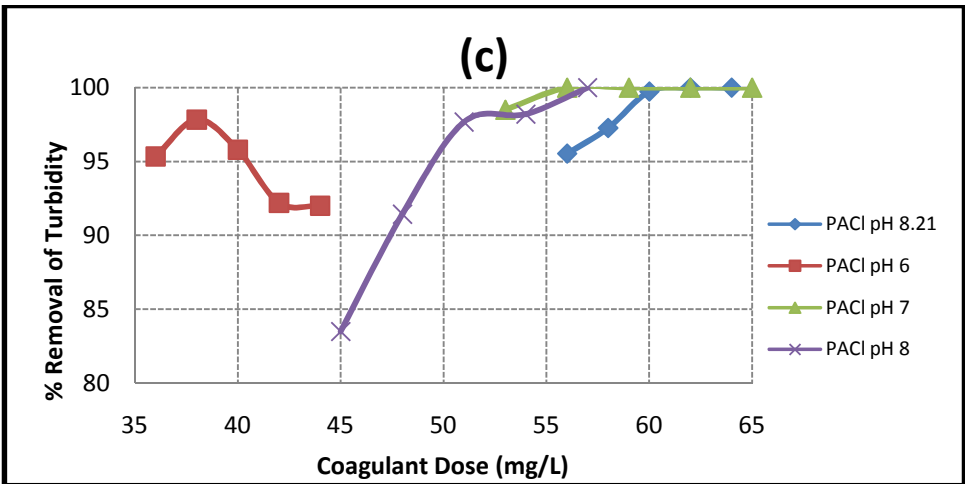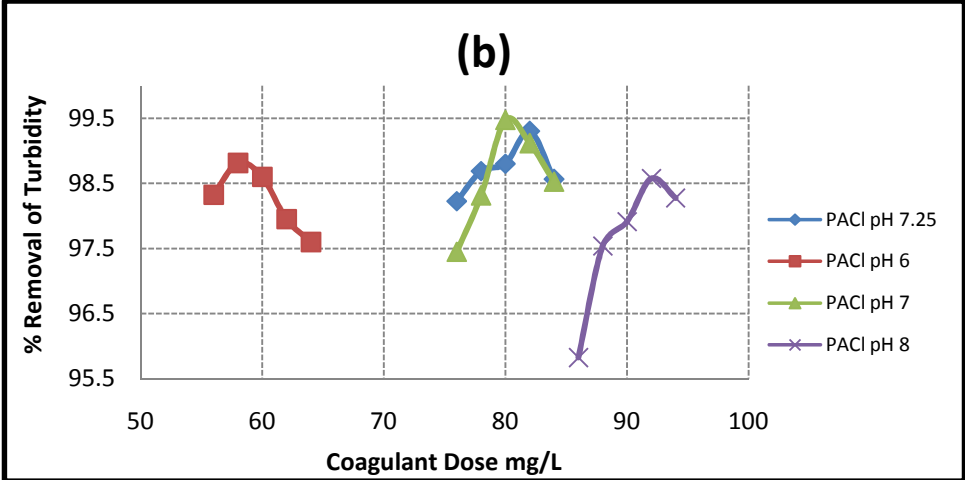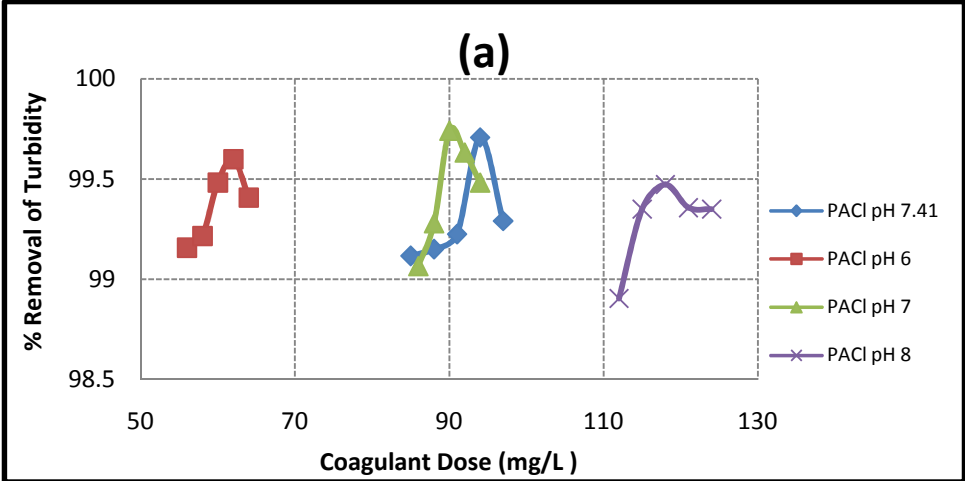
4.4.2 Performance of Ferric Chloride

Comparison of results shows that Ferric chloride makes its space between the PACl and Alum. At natural pH of 7.27 and 80 NTU turbidity Ferric chloride shows 92mg/L of dose which is higher than the PACl (82mg/L) and lower than the ALUM (120mg/L) at these conditions. At this pH and turbidity the removal efficiency of turbidity is also higher than Alum. Same pattern of results was also observed in other pH and turbidities. At lower pH i.e. 6 Ferric chloride shows lower removal efficieny of turbidity w.r.t both PACl and Alum.

Figure 4.8 shows the trend of Ferric chloride (FCL) with varying pH at 120, 80 and 40 NTU turbidities, where 6, 7, 8 are the synthetic pH's of the modified raw water. Plot shows that as the initial pH of raw water reduces, the optimum coagulant dose was also decreased. This means that the optimum coagulant dose is maximum at pH 8 and minimum at pH 6. As far as the % removal is concerned maximum % removal was observed at neutral pH of 7 and minimum % removal was observed at basic pH of 8.
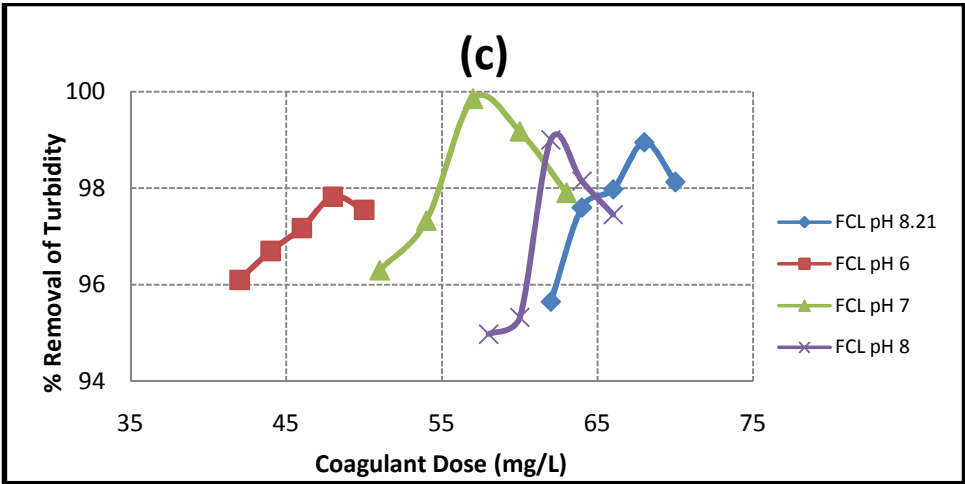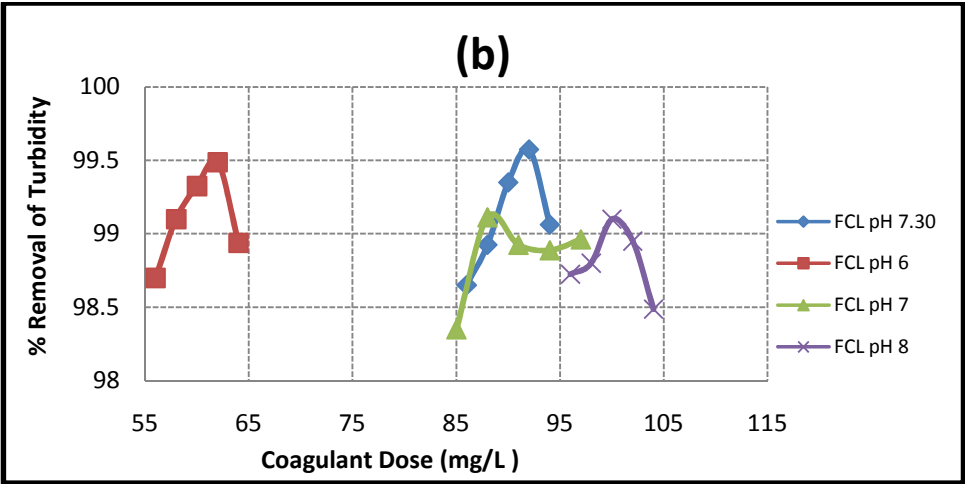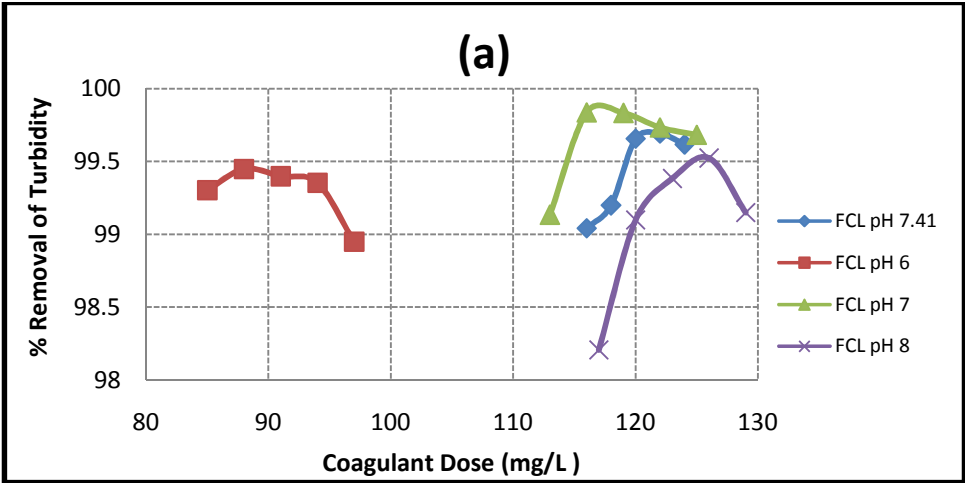
4.4.3 Performance of Alum

Figure.4.9 shows the trend of Alum with varying pH at 120, 80 and 40 NTU, where 6, 7, 8 are the synthetic pH's of the modified raw water. Plot shows that as the initial pH of raw water reduces, the optimum coagulant dose was also decreased. This means that the optimum coagulant dose is maximum at pH 8 and minimum at pH 6. As far as the % removal is concerned maximum % removal was observed at acidic pH of 6 and minimum % removal was observed at basic pH of 8.21.Alum gives maximum % removal at pH 6 while PACl gives maximum % removal at pH 7 and above.

It is clear from the plots (figure 4.9) that at all pH values Alum gives comparably higher optimum doses than Ferric chloride and PACl. The removal efficiency of turbidity for Alum is lower in some cases but satisfactory.

(a)

(b)

(c)
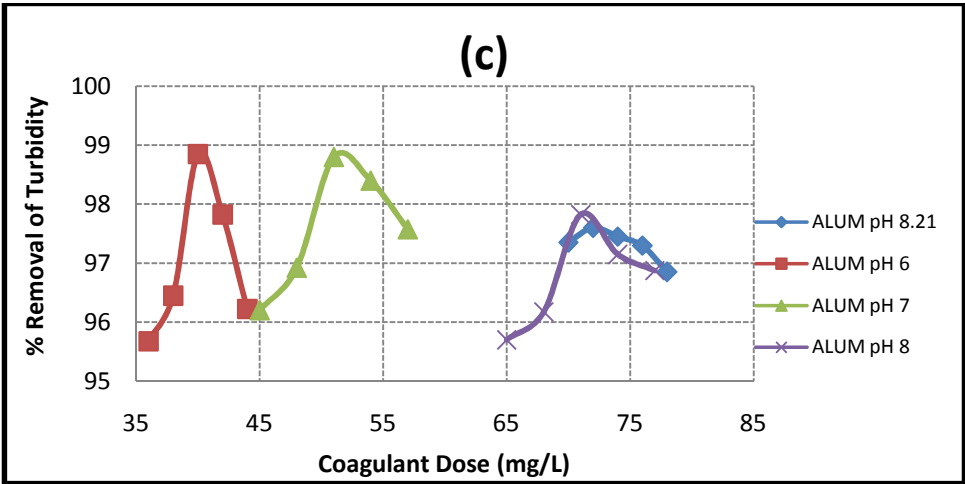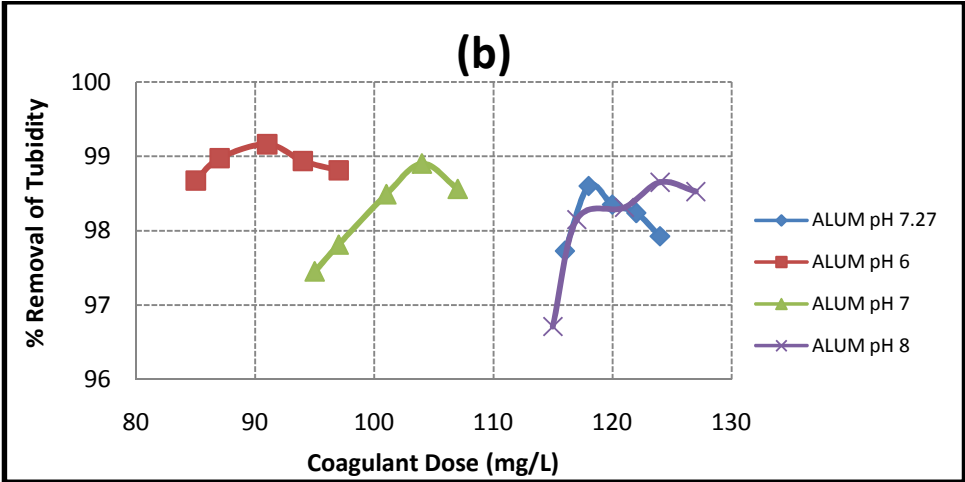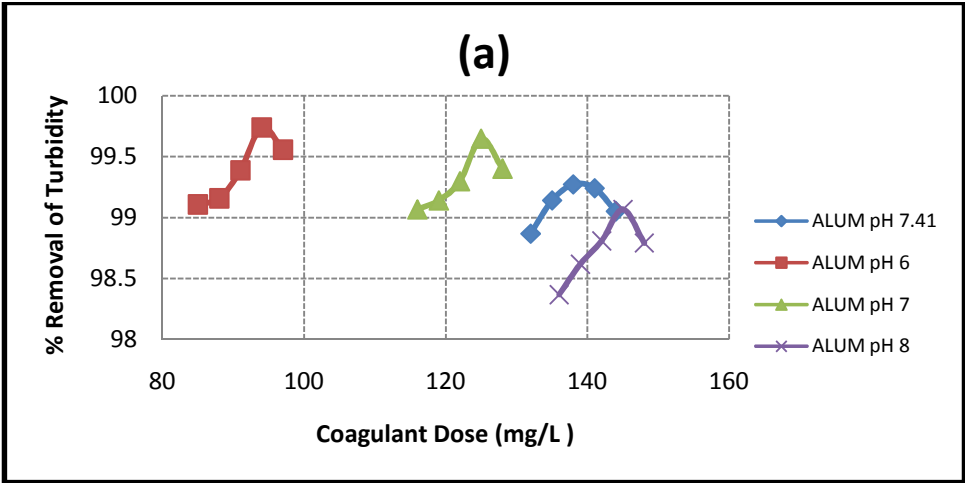
Figure 4.10 shows the comparison of optimum doses of three coagulants at 120, 80 and 40 NTU turbidity.
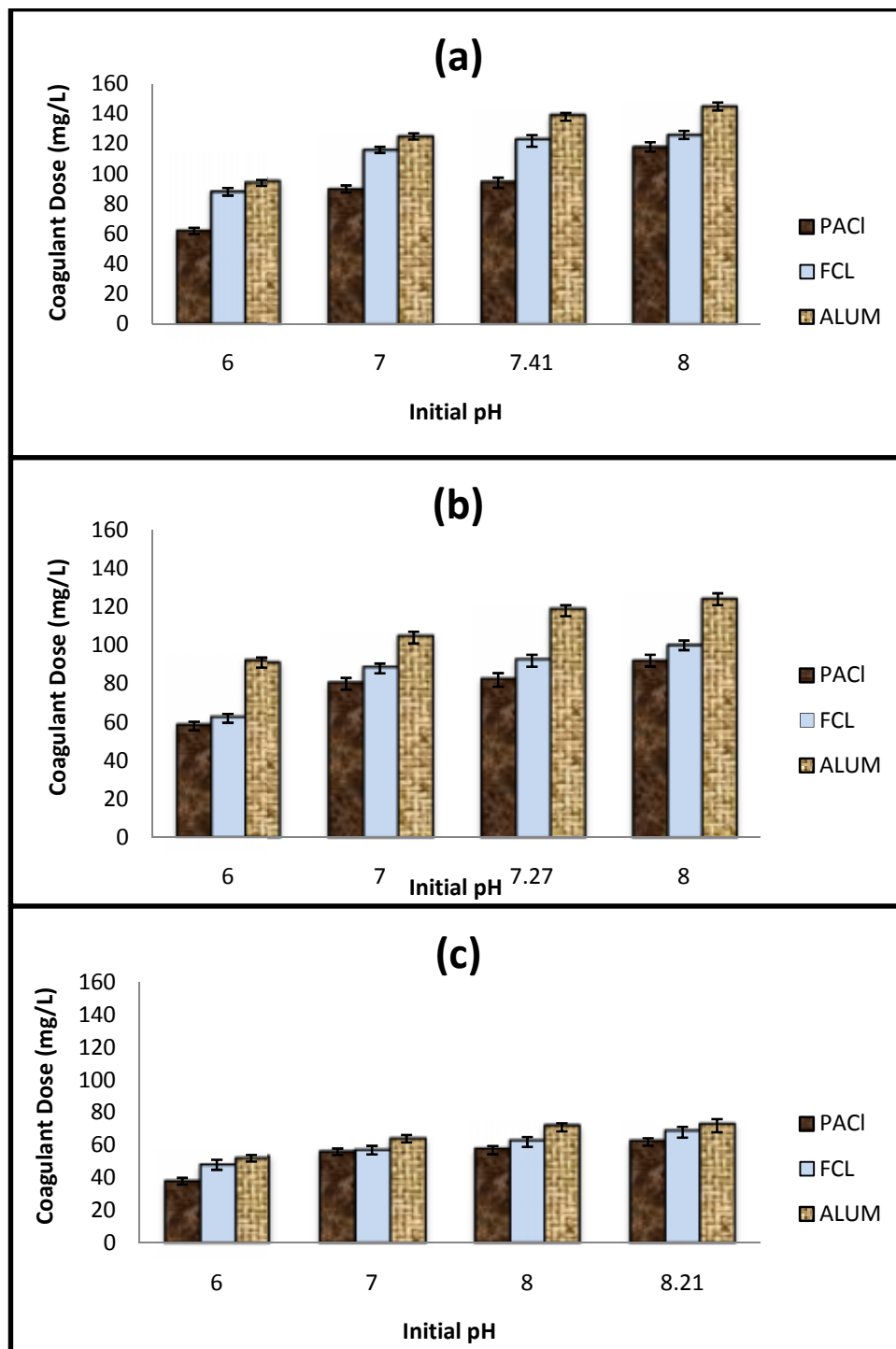
Figure 4.10: Optimum Coagulant Dose variation with pH
(a). 120 NTU (b). 80 NTU (c). 40 NTU

WHO & NSDWQ < 5 NTU

Residual Turbidity vs Coagulant Dose (mg/L) — PACl, ALUM, FCL
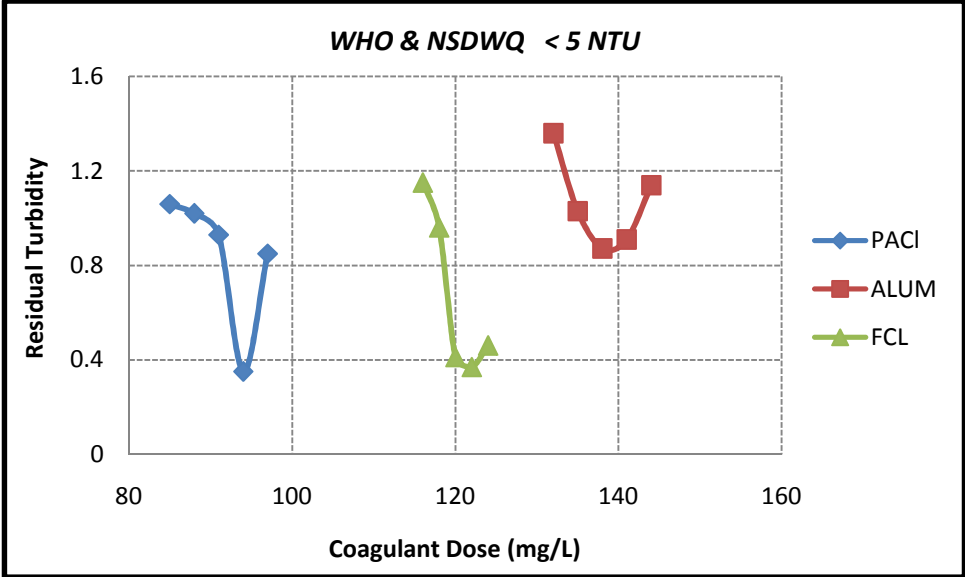
4.6   Effect of Coagulant Dose on pH of Coagulated Water

All the three coagulants shows same descending trend of residual pH of treated water. As the plots show that the slope of the Ferric chloride line is steeper than the other two (PACl & Alum). This means that Ferric chloride alters the pH of treated water more than the PACl and Alum. It is clear from the plots that the lines of PACl and Alum are quite close to each other with much lower slope values than Ferric chloride. This means that the PACl and Alum alters the pH of treated water at about same level but much lower than the Ferric Chloride. As far as the PACl and Alum is concerned PACl alters the pH lower than the Alum.   Table 4.3 shows the pH depression of raw water pH at optimum coagulant doses.

Table 4.2 - Comparison of Optimum pH for Three Coagulants at Natural Initial pH

Coagulants	Turbidity (NTU)	Initial pH	Optimum Dose (mg/L)	Final pH	% drop in pH
PACl	120	7.41	94	6.67	10
	80	7.27	82	6.92	4
	40	8.21	62	7.78	5
FCL	120	7.41	122	5.90	20
	80	7.27	92	6.76	7
	40	8.21	68	7.02	14
Alum	120	7.41	138	6.35	14
	80	7.27	118	6.80	6
	40	8.21	72	7.30	11

All the minimum values of treated water pH were observed at the initial pH of 6. Keeping in view of WHO limit of drinking water i.e. 6.5 – 8.5 in most of the cases the pH of treated water at optimum dose remains within the limits. Particularly at the initial pH of 6 with higher initial turbidities the residual pH of treated water lowers the lowest pH value of 6.5 at optimum dose. This requires the adjustment of pH of treated

(a)

(b)
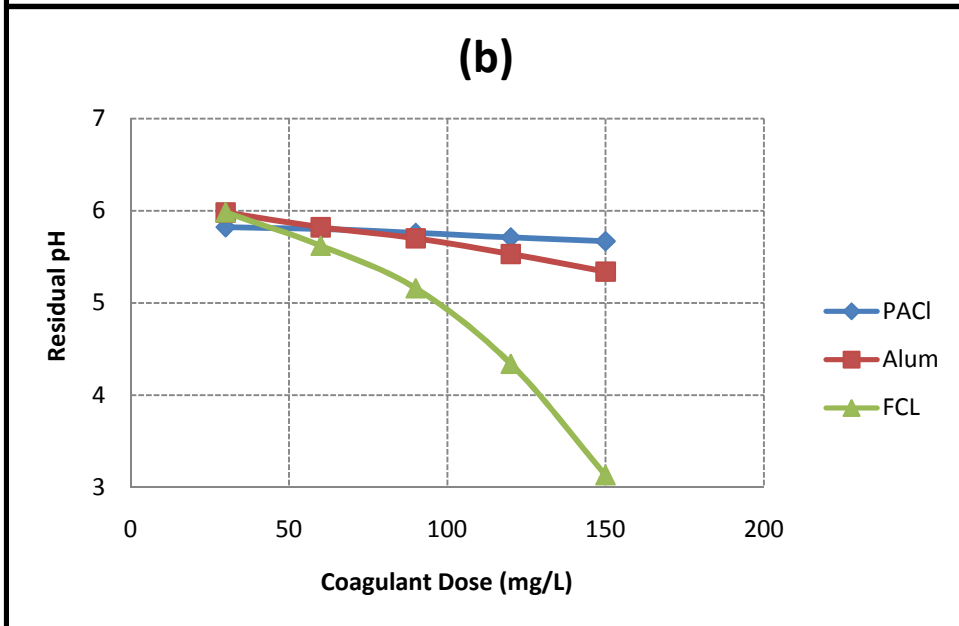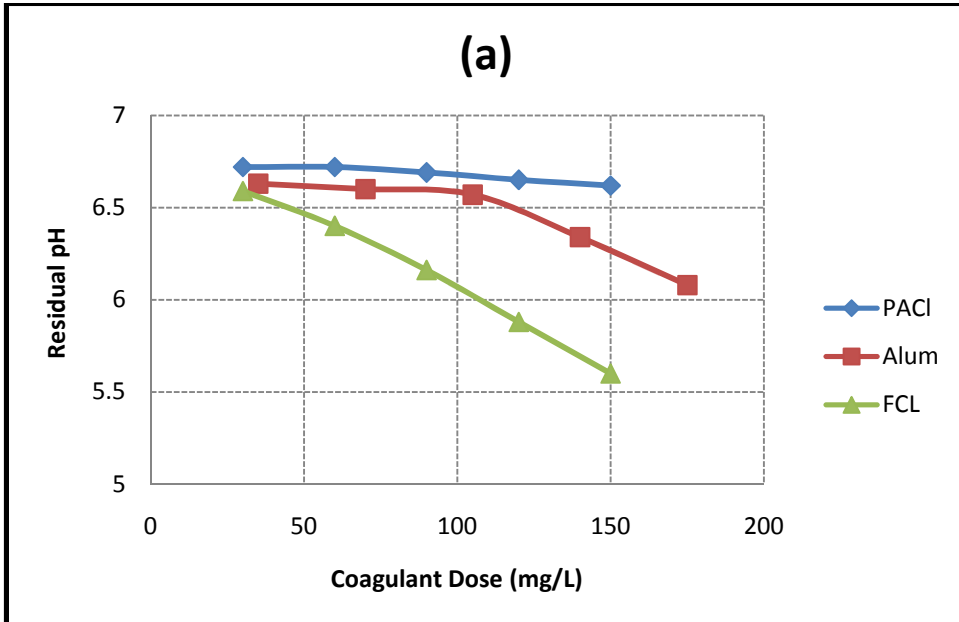
4.7   Effect of Coagulant Dose on Residual Alkalinity

Alkalinity is the buffering capacity of a water body. It measures the ability of water bodies to neutralize acids and bases thereby maintaining a fairly stable pH. Water that is a good buffer contains compounds, such as bicarbonates, carbonates, and hydroxides, which combine with H+ ions from the water thereby raising the pH (more basic) of the water. Without this buffering capacity, any acid added to a lake would immediately change its pH. Aquatic organisms benefit from a stable pH value in their optimal range. To maintain a fairly constant pH in a water body, a higher alkalinity is preferable. High alkalinity means that the water body has the ability to neutralize acidic pollution from rainfall or basic inputs from wastewater. A well buffered lake also means that daily fluctuations of CO_2 concentrations result in only minor changes in pH throughout the course of a day. Raw water of Rawal Lake Filtrtaion Plant has alkalinity in the range of 190 – 200 mg/L as $CaCO_3$ which is quite favorable.

Like pH residual Alkalinity of Treated Water shows the same descending trend. Plots (figure 4.13 and 4.14) show that with the increase in coagulant dose the alkalinity of treated water decreases gradually. Comparing the three coagulants PACl consumes less alkalinity of raw water than other two coagulants.

Alkalinity at optimum Doses		
Coagulant	Opt. dose (mg/L)	Alkalinity (mg/L as $CaCO_3$)
PACl	58	76
Alum	91	30
FCL	62	30

Alkalinity at optimum Doses		
Coagulant	Opt. dose (mg/L)	Alkalinity (mg/L as $CaCO_3$)
PACl	94	130
Alum	138	120
FCL	122	75
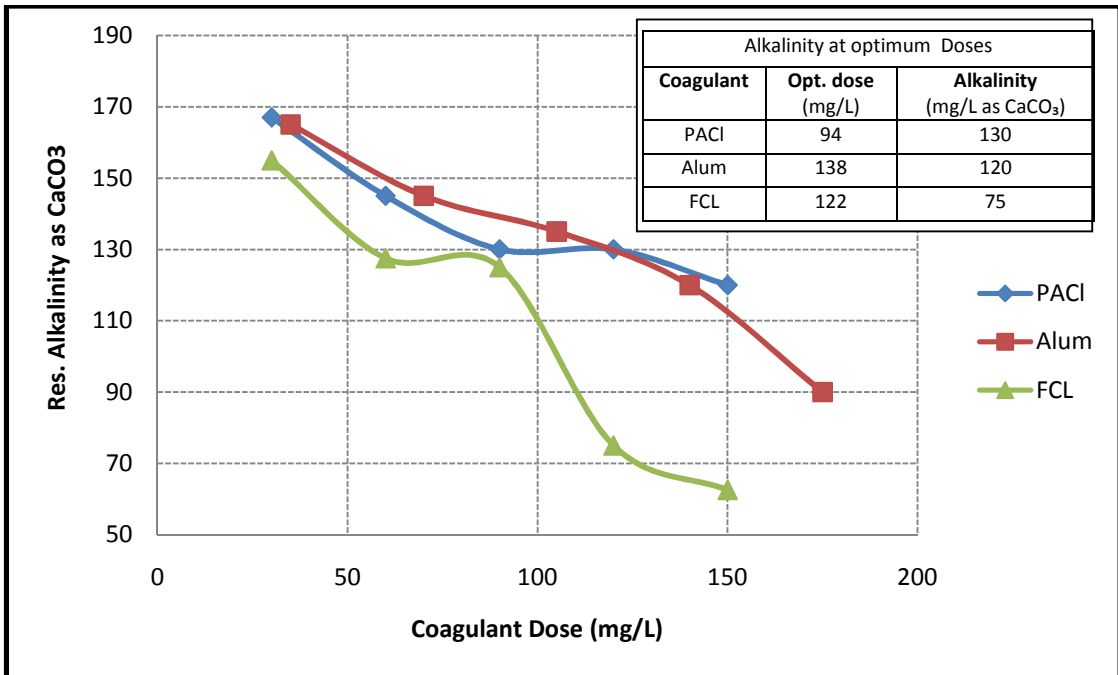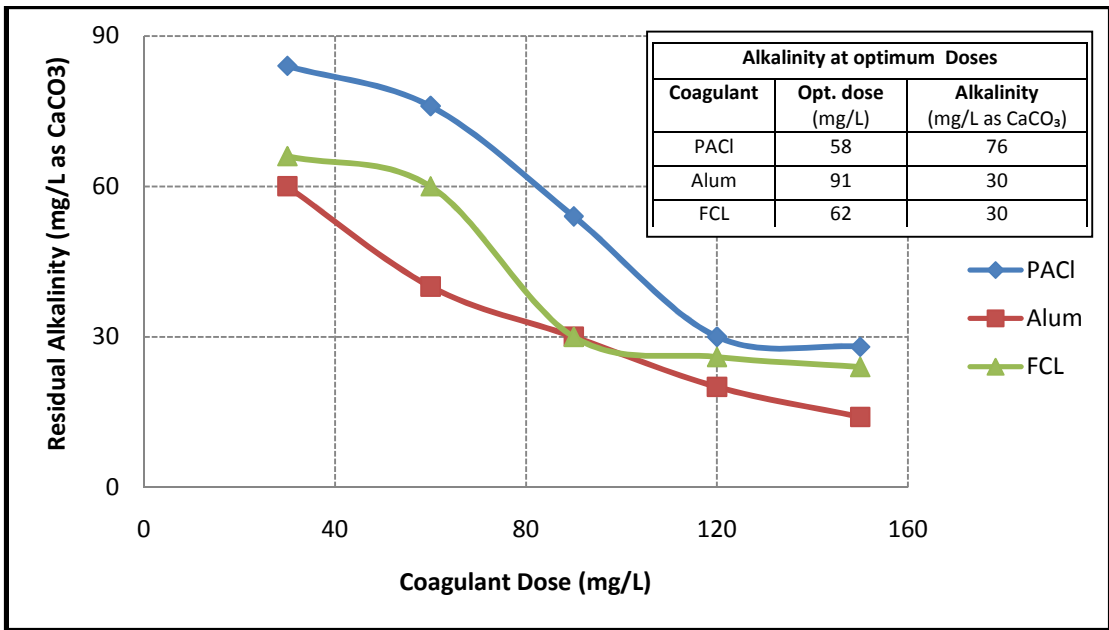
4.8   Color Removal

Ideally, drinking water should be clear and colorless. A change in the color of drinking water may be the first indication of a water quality problem. Color is normally more prevalent in surface water sources. The color of water is an indication of the organic content, including humic and fulvic acids, the presence of natural metallic ions such as iron and manganese, and turbidity. The characteristics of iron, iron bacteria, and humic substances can be very similar in drinking water. It is important to determine which of these is causing water problems, because the treatment options are very different. Chlorine can be used to treat iron and iron bacteria, but chlorine added to water containing humic substances may contribute to the formation of trihalomethanes (THMs). The humic and fulvic acids adsorb on the surface of aluminum and iron precipitates and also high Fe coagulant demand is required for the same level of color removal. Hence the $FeCl_3$ curve behavior is not good as compared to PACl and Alum in Fig. 4.37.

Figure 4.15 shows comparison of three coagulants for color removal. As the plots show that the PACl gives best removal efficiency than Alum and Ferric chloride. This means that PACl has good removal effect on the color producing constituents of Rawal Lake water.
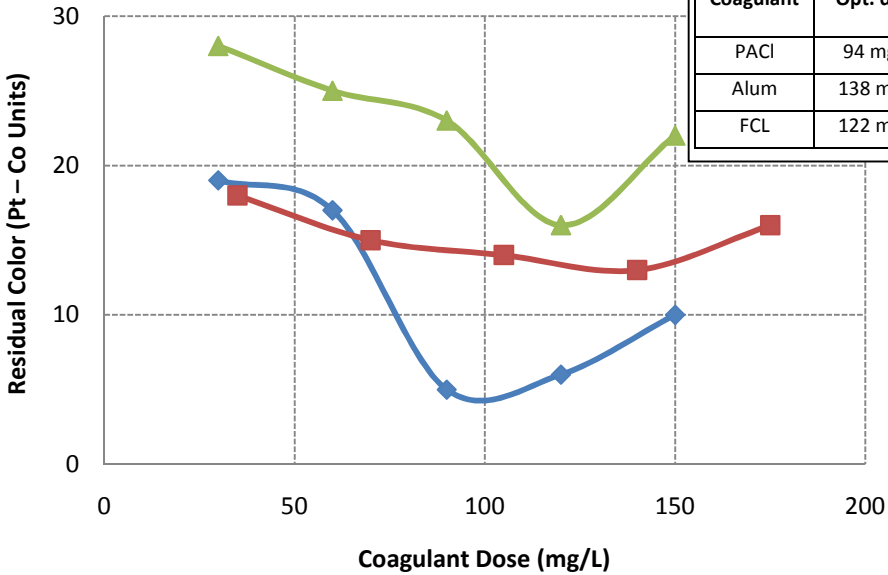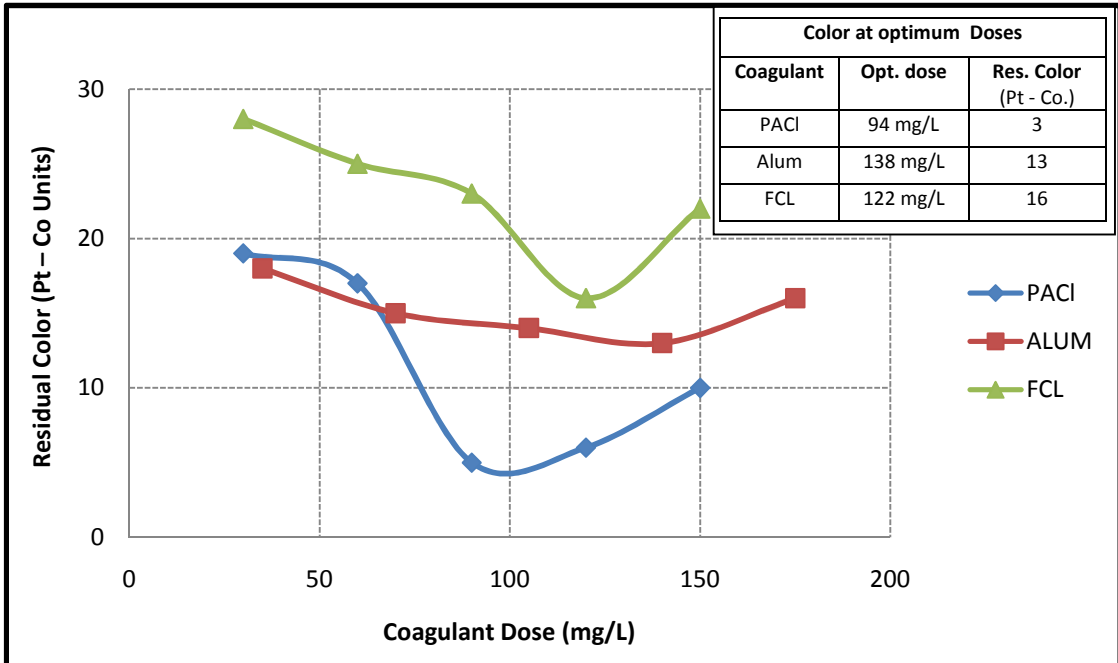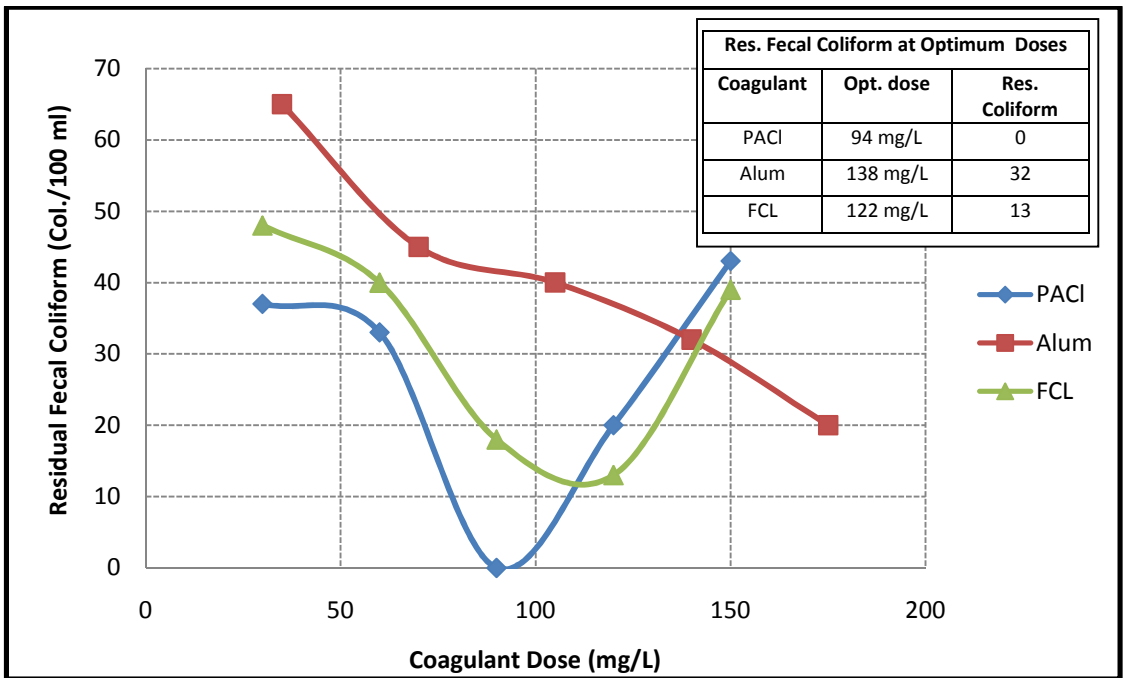
Color at optimum Doses		
Coagulant	Opt. dose	Res. Color (Pt - Co.)
PACl	94 mg/L	3
Alum	138 mg/L	13
FCL	122 mg/L	16

Res. Fecal Coliform at Optimum Doses		
Coagulant	Opt. dose	Res. Coliform
PACl	94 mg/L	0
Alum	138 mg/L	32
FCL	122 mg/L	13

Res. Aluminum at Optimum Doses		
Coagulant	Opt. dose	Res. Al. Conc.
PACl	94 mg/L	0.12
Alum	138 mg/L	0.44
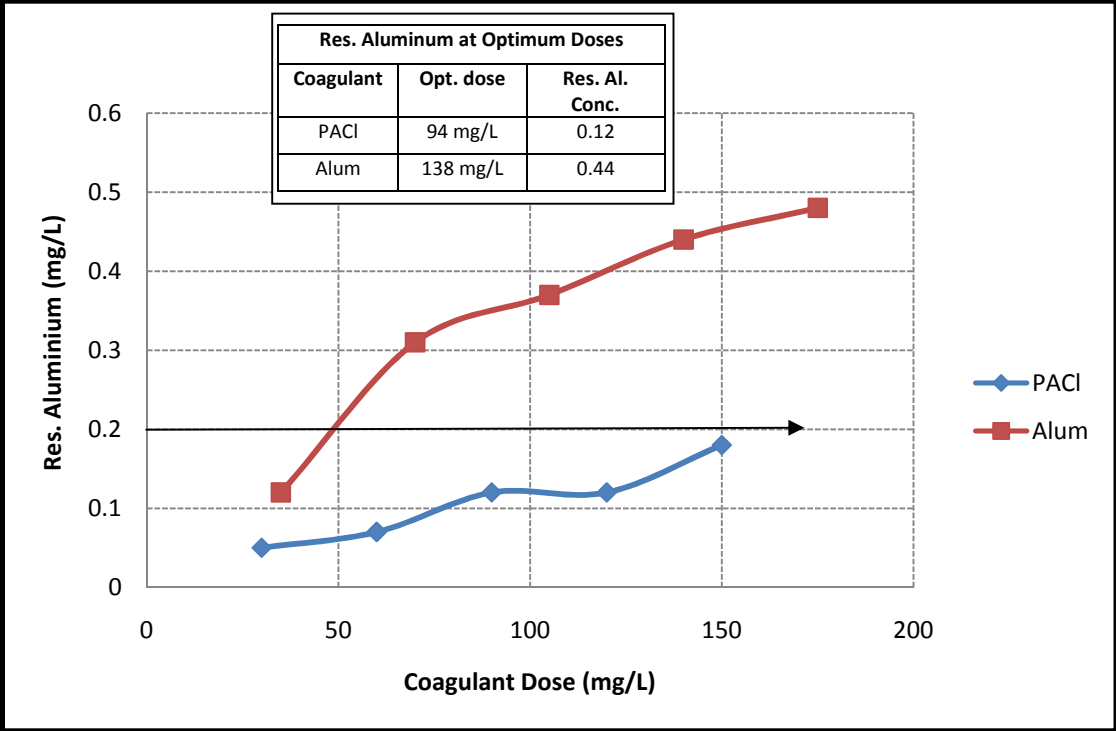
4.11 Effect of Coagulant Dose on Total Dissolved Solids (TDS) & Electrical Conductivity (EC)

Conductivity is a measure of the ability of water to conduct an electrical current. It is related to the amount of dissolved substances (or ions) in water, but does not give an indication of which minerals are present. Conductivity is about twice the total hardness value (mg/L as $CaCO_3$) in most uncontaminated waters. Changes in conductivity over time may indicate changes in your overall water quality. There is no health standard associated with conductivity. The electrical conductivity (EC) values of raw water range between $400 - 550$ µS/cm and that of hardness of raw water ranges between $150 - 300$ mg/L as $CaCO_3$.The Total Dissolved solids (TDS) of raw water ranges between $250 - 350$ mg/L.A slight rise in the both EC and TDS values were observed after coagulation.

The plots show in figures 4.18 and 4.19 that both EC and TDS show the same trends. With the increase in coagulant dose both EC and TDS are increasing for all three coagulants. Ferric chloride gives higher values of both EC and TDS than ALUM and PACl. The values of both EC and TDS remain within WHO and pak EPA limits for all three coagulants.
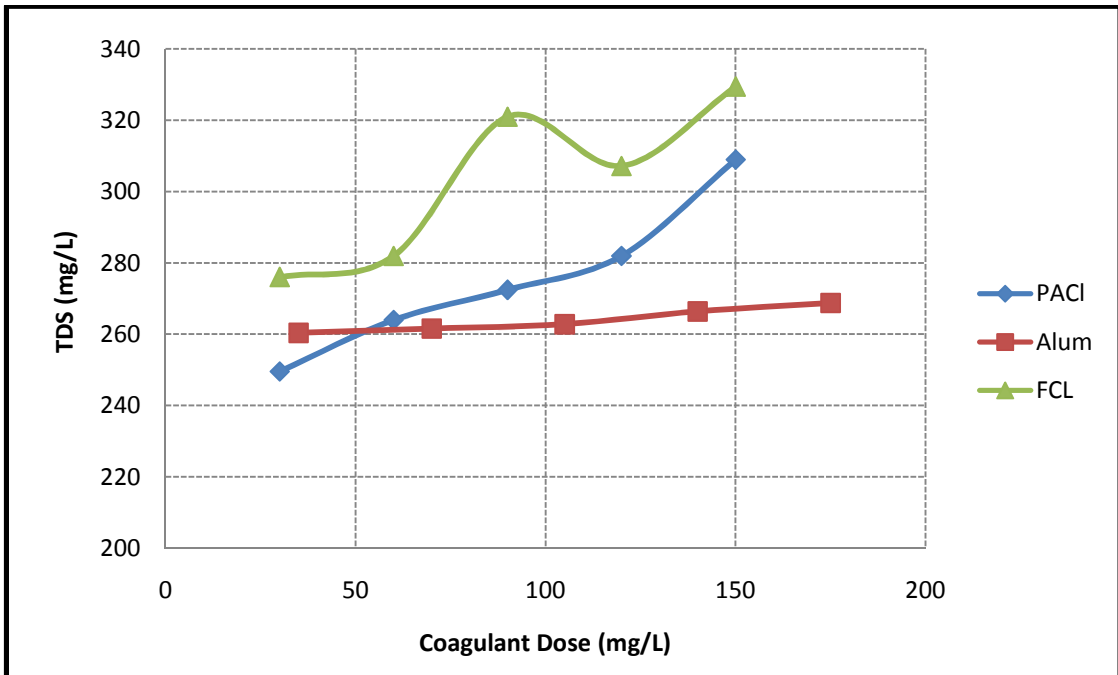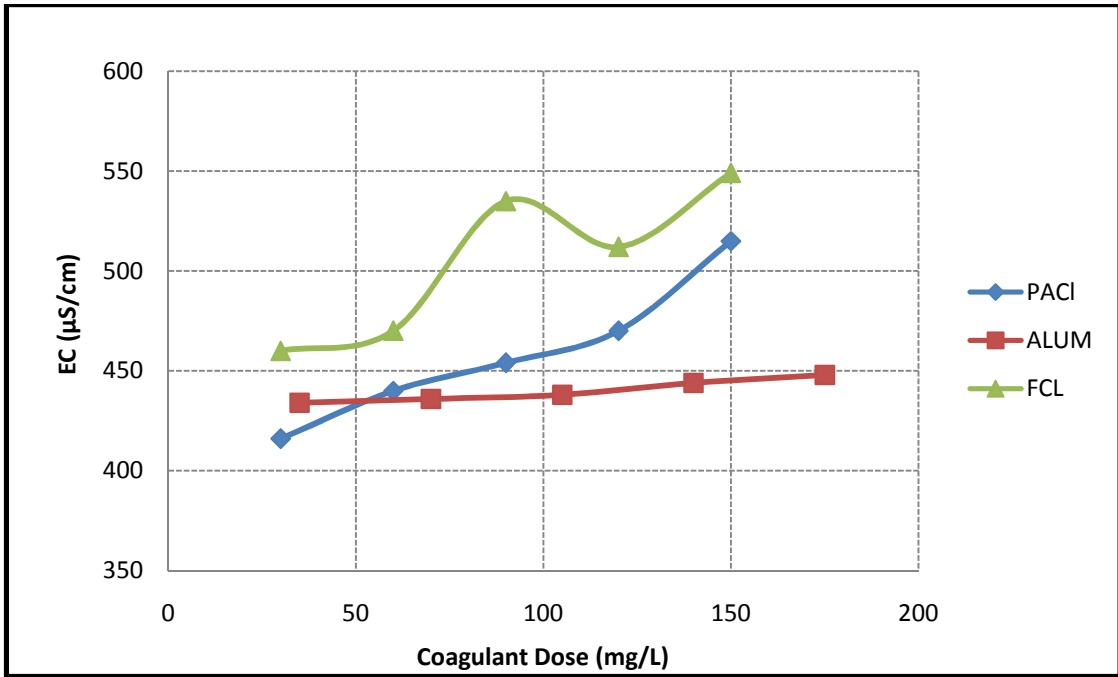
4.12   Cost Analysis

Cost is an important parameter when choosing the processes and the substances to be used in them for environmental engineering. Where decisions are to be done among different processes a cost benefit analysis should be done. These analyses reveal which process and what substances are more feasible for that particular system. For this reason, a brief cost analysis based on chemical costs is done between alum, which is used in Rawal Lake Filtration Plant (RLFP), and Polyaluminium Chloride (PACl).

In order to compare the cost of coagulants two conditions were selected.Condition-1 is the Initial Turbidity of 120 NTU and natural pH of 7.41 and Condition-2 is the Initial Turbidity of 40 NTU and natural pH of 8.21.Optimum doses at these conditions were used to calculate the cost of coagulants. In both conditions operative capacity of RLFP i.e. 24 MGD was used for calculations and price of commercial grade chemicals was used. (Quoted by Akbari Chemicals Ltd, Lahore). Table 4.4 shows the cost comparison of three coagulants.

Table 4.3 – Cost Comparison of Coagulants

	Coagulants	Unit Price (Rs./Kg)	Coagulant Dose (mg/L)	Amount Required (Kg/day)	*Total Price (Rs./day)
Codition-1 120 NTU, pH 7.41	Alum	40	138	12519	0.500
	PACl	115	94	8528	0.980
	FCL	135	122	11068	1.494
Codition-2 40 NTU, pH 8.21	Alum	40	72	6532	0.261
	PACl	115	62	5625	0.647
	FCL	135	68	6169	0.833

*cost is in Millions

Table 4.4 shows that in each condition Alum gives the lowest cost than Polyaluminium chloride and Ferric chloride. Also the cost of Ferric chloride is quite higher than both Alum and Polyaluminium chloride. Since PACl gives the best results in all conditions therefore to optimize the cost of whole system, combined doses of Polyaluminium chloride and Alum were investigated. For this purpose eight jar test runs were made with varying order of addition of coagulants. These tests were run at the condition-1. Four ratios were selected for this purpose i.e. Alum: PACl 50: 50, 75: 25, 90: 10, and 95: 5. Results of these combined doses with cost comparison are tabulated below in Table 4.5.

Table 4.4 – Optimization of overall cost of the system

Sr. No.	Coagulant	Order	Ratio	Dose (mg/L)	Res. Turbidity	pH	*Cost/day
1	Alum	1	50	69	1	6.74	0.740
	PACl	2	50	47			
2	PACl	1	50	47	0.47	6.82	
	Alum	2	50	69			
3	Alum	1	75	103	1.16	6.80	0.620
	PACl	2	25	23			
4	PACl	1	25	23	0.58	6.79	
	Alum	2	75	103			
5	Alum	1	90	124	2.90	6.67	0.548
	PACl	2	10	9			
6	PACl	1	10	9	0.76	6.76	
	Alum	2	90	124			
7	Alum	1	95	131	2	6.76	0.524
	PACl	2	5	5			
8	PACl	1	5	5	0.82	6.83	
	Alum	2	95	131			

*cost is in Millions

The table 4.5 shows that in all cases PACl with order 1st gives the better results (sr no.2, 4, 6, 8) than Alum with order 1st (sr. no.1, 3, 5, 7). At the condition-1 Alum alone gives the residual turbidity 0.872. This residual turbidity is higher than the results of PACl with order 1st. This means that PACl in combined doses also gives better result than alone Alum.

Since Alum alone at the condition-1 costs 0.500 Million and if it was assumed that at the expense of 20% extra cost i.e 0.600 Million better results can be achieved. Combination of ALUM and PACl with ratio of 90:10 and 95:5 with PACl order 1st (Sr. no. 6 & 7) costs 0.548 M and 0.524 M respectively both these costs are lower than 0.600. Hence both these conditions can be selected to optimize the cost of the whole system.
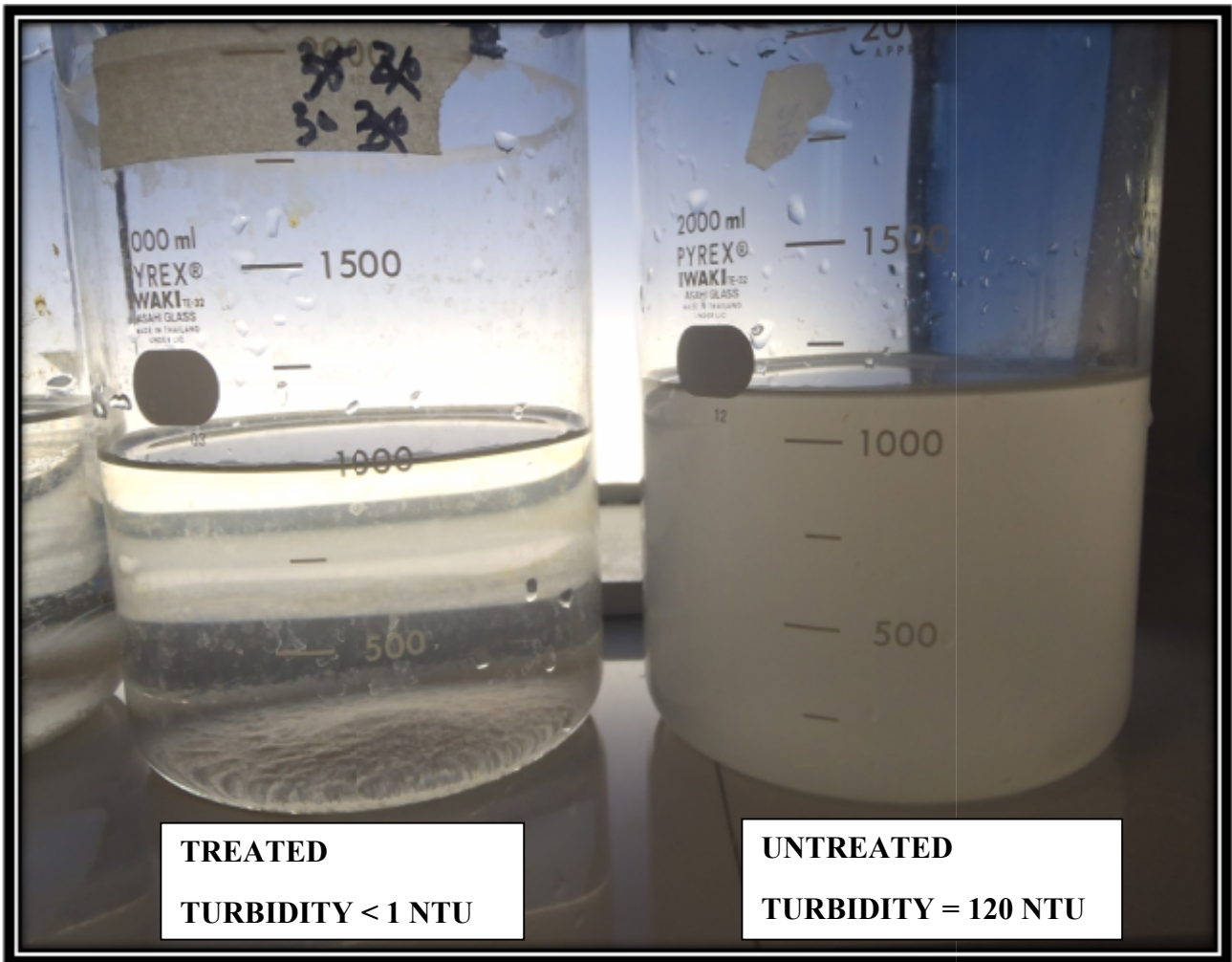
Fig 4.20 Comparison of Treated and Untreated Water

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The availability of a clean and safe water supply is essential for life sustenance and public health. Surface water is the cheapest and easily accessible source for water supply in the countries like Pakistan. Surface water with conventional treatment processes like coagulation and flocculation need to be focused rather complex and expensive processes like reverse osmoses etc. Water for domestic use needs to be safe and free from pathogens and other harmful substances. Keeping in view the fact that the water of Rawal Lake Filtration Plant is being consumed by a large population of Rawalpindi and Cantonment area, the study concluded that:

- Coagulant dose increases with the increase in the pH of raw water.

- All the three coagulants exhibit minimum optimum dose at pH 6 and maximum optimum dose at pH 8.

- PACl shows the highest removal efficiency at initial pH 7 and above, Ferric Chloride shows the highest removal efficiency at initial pH 7 while Alum shows the highest removal efficiency at acidic pH of 6. Since most of the coagulants are acidic in nature therefore coagulation process further reduces the pH of water. Thus the resultant pH is further reduced after coagulation. Reduction in pH by Alum would produce aggressive water of low pH.

- Although all the three coagulants exhibts minimum dose at initial pH of 6 but even then pH 6 was not feasible due to two reasons: Firstly maintaining the pH of raw water at 6 not only adds extra cost of HCl (Hydrochloric Acid) but also

maintaining a homogenized pH at bulk stage is quite difficult. Secondly After coagulation the pH of coagulated water was further reduced and falls into the corrosive range and need to be adjusted. Adjustment of this corrosive pH with lime solution also adds cost to the total bill.

▪ The depression in the pH of treated water was observed in the order of FCL < Alum < PACl. PACl least affects the treated water pH.

▪ PACl exhibits fairly high overall removal efficiency with lower optimum doses. Alum shows the lower removal efficiency with high optimum dose.

▪ PACl performance is fairly good w.r.t Turbidity, Color, Fecal Coliform, Residual Aluminium concentrations, Alkalinity, EC & TDS etc. Most of these parameters are within the WHO and PakEpa range. Ferric chloride consumes more alkalinity than both PACl and Alum but in case of coliform removal ferric chloride shows better result than Alum.

▪ Alum shows higher concentration of residual aluminium than PACl which is the serious drawback of Alum as the coagulant because this higher concentration of residual aluminium in drinking water may cause Alzheimer's disease.

▪ PACl shows higher cost than Alum. It can be optimized by combined coagulant doses of PACl and Alum.

▪ Alum and PACl at the ratio of 90:10 & 95:5 with PACl as order 1st gives better results than Alum alone. At these combinations the cost of the coagulants is quite comparable with Alum alone.(Just 5 – 10 % high)

- Since PACl exhibits higher removal efficiency w.r.t coliform than other two coagulants therefore low chlorine dosage at disinfection stage is required in case the PACl was used as coagulant. Hence, overall treatment cost can be further optimized.

- Keeping in view the above discussion PACl is the best coagulant at all pH and Turbidities therefore technically the Most Effective Coagulant for RLFP is Polyaluminium Chloride.

5.2   Recommendations

On the basis of this study following recommendations were made:

- In the conventional water treatment plant like Rawal Lake Filtration Plant handling of sludge volume is quite troublesome. In this case such a coagulant is required which shows good results but at the expense of less sludge volume. Handling of huge sludge volume is not only difficult but also it adds cost to the overall treatment process. Since PACl gives lowest dose than other two coagulants therefore most probably PACl gives the less sludge volume than Alum and Ferric chloride but it needs to be further investigated through experiments.

- Settling of sludge is also a complex phenomenon. It is associated with the floc characteristics, floc size, adhesion forces and terminal velocity of the flocs etc. Among all these, the floc characteristic of each coagulant was need to be studied.

- Use of polyelectrolytes is becoming quite popular in the water treatment therefore effect of synthetic and natural polyelectrolytes on Rawal Lake Filtration Plant was need to be investigated. Natural polyelectrolytes were quit cheaper than synthetic coagulants and also show excellent results.

- Comparison of synthetic and natural polyelectrolytes with each other and with the results of this study also gives a very good picture.

- A study of the adsorption isotherms of the three coagulants used in this study on the basis of Freundlich, Langmuir and BET isotherm models can also be made.

REFERENCES

American Water Works Association, (1999) "Water Quality and Treatment, A Handbook of Community Water Supplies", 5th Edition, McGraw-Hall: New York.

Arun K. Vuppaladadiyam, Sowmya V., Pallavi Dasgupta (2013) "Comparative Study on Coagulation Process for Vellore Municipal Drinking Water Using Various Coagulants" Universal Journal of Environmental Research and Technology, Volume 3, Issue 1: 119-126.

Aylin Devrimci H., A. Mete Yuksel, F. Dilek Sanin (2012) "Algal alginate: A potential coagulant for drinking water treatment" Desalination 299: 16–21.

Aguilar, M.I, J. Sa´ez, M. Llore´ns, A. Soler, J.F. Ortun˜o, V. Meseguer, A. Fuentes (2005) "Improvement of coagulation–flocculation process using anionic polyacrylamide as coagulant aid" Chemosphere 58: 47–56.

Akshaya Kumar Verma, Rajesh Roshan Dash, Puspendu Bhunia (2012) "A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters" Journal of Environmental Management 93: 154-168.

April 1999 9-3 EPA Guidance Manual Turbidity Provisions.

Brian Bolto, John Gregory (2007) "Organic polyelectrolytes in water treatment" Water Research (41) 2301 – 2324.

Cuizhen Sun , Qinyan Yue , Baoyu Gao , Ruimin Mu , Jing Liu , Yanxia Zhao , Zhonglian Yang, Weiying Xu (2011) "Effect of pH and shear force on flocs characteristics for humic acid removal using polyferric aluminum chloride–organic polymer dual-coagulants" Desalination 281: 243–247.

D´esir´e Dihang, Pierre Aimar, Joseph Kayem, Sylv`ere Ndi Koungou (2008) "Coagulation and flocculation of laterite suspensions with low levels of aluminium chloride and polyacrylamids" Chemical Engineering and Processing 47: 1509–1519.

European Commission on Drinking (1998) Water Quality Standards, Turbidity U.S. Geological Survey (USEPA) TWRI Book 9.

Faust S. D. and Aly O. M., (1998) "Chemistry of Water Treatment", Second Edition, Ann Arbor Press.

Gao, B. Q. Yue and J. Miao (2002). "Evaluation of polyaluminium ferric chloride (PAFC) as a composite coagulant for water and wastewater treatment" Water Science and Technology, 47(1): 127-132.

Hale Aylin Coruh (2005) "Use of Calcium Alginate as A Coagulant in Water Treatment" MS thesis.

Kawamura, S. (1991). Effectiveness of Natural Polyelectrolytes in Water Treatment, Journal of AWWA.

Ki-Chang Lee, Kwang-Ho Choo, (2013). "Hybridization of TiO2 photocatalysis with coagulation and flocculation for 1, 4-dioxane removal in drinking water treatment" Chemical Engineering Journal 231: 227–235.

Lin, W. W., Sung, S. S., Chung, H. Y., Chen, L. C., Wang, C.C, Wu, R.M., Lee, D.J., Huang, Chihpin (2004). "Treating High-Turbidity Water Using Full-Scale Floc Blanket Clarifiers", Journal of Environmental Engineering, Vol. 130, No. 12, pp. 1481-1487.

Lin, W. W., Sung, S. S., Chung, H. Y., Chen, L. C., Wang, C.C, Wu, R.M., Lee, D.J., Huang, Chihpin (2004). "Treating High-Turbidity Water Using Full-Scale Floc Blanket Clarifiers", Journal of Environmental Engineering, Vol. 130, No. 12, pp. 1481-1487.

Michael I., A. Panagi, L.A. Ioannou, Z. Frontistis, D. Fatta-Kassinos, (2014) "Utilizing solar energy for the purification of olive mill wastewater using a pilot-scale photocatalytic reactor after coagulation-flocculation" Water Research (60) 28 -40.

Metcalf and Eddy, Inc., (1993). "Wastewater Engineering", 3rd Edition, McGraw-Hill, New York, USA.

Nozaic, D. J.; Freese, S.D.; Thompson, P., Longterm "Experience in The Use of Polymeric Coagulants at Umgeni Water, Water Science and Technology": Water Supply, 1 (1), 43-50, 2001.

Ng Mega, Sanly Liu, Christopher W.K. Chow, Mary Drikas, Rose Amal, May Lim (2013) "Understanding effects of water characteristics on natural organic matter treatability by PACl and a novel PACl-chitosan coagulants" Journal of Hazardous Materials (263) 718– 725.

O'Melia R., Weber, W.J. (Ed.) (1972), Physicochemical Process for Water Quality Control, Wiley, New York, (Chapter2).

Pradhan M., S. Vigneswaran, J. Kandasamy (2014) "Assessment of fouling behaviour in submerged microfiltration system coupled with flocculation" Journal of Industrial and Engineering Chemistry (article is in press).

Peter Jarvis, Emma Sharp, Marc Pidou, Roger Molinder, Simon A. Parsons, Bruce Jefferson (2012) "Comparison of coagulation performance and floc properties using a novel zirconium coagulant against traditional ferric and alum coagulants" water research 46: 4179 – 4187.

Pritchard M., T. Craven, T. Mkandawire, A.S. Edmondson, J.G. O'Neill (2010) "A comparison between Moringa oleifera and chemical coagulants in the purification of drinking water – An alternative sustainable solution for developing countries" Physics and Chemistry of the Earth 35: 798–805.

Peter Gebbie, (2001). "Using Polyaluminium Coagulants in Water Treatment", 64th Annual Water Industry Engineers and Operators' Conference, Bendigo.

Pakistan Environmental Protection Agency (Pak EPA), (2008), "National Standards for Drinking Water Quality" (NSDWQ).

Ray, B. T., "Environmental Engineering, Southern Illinois University", PWS Publishing Company, 1993.

Raghunath Das, Soumitra Ghorai, Sagar Pal (2013) "Flocculation characteristics of polyacrylamide grafted hydroxypropyl methyl cellulose: An efficient biodegradable flocculant" Chemical Engineering Journal 229 144–152.

Sabir Hussain, John van Leeuwen , Christopher Chow , Simon Beecham , Mohammad Kamruzzaman, Dongsheng Wang, Mary Drikas, Rupak Aryal (2013) "Removal of organic contaminants from river and reservoir waters by three different aluminum-

based metal salts: Coagulation adsorption and kinetics studies" Chemical Engineering Journal 225: 394–405.

Sonu Malhotra, (1994) "Poly aluminium chloride as an alternative coagulant" 20th WEDC Conference, Affordable Water Supply and Sanitation, Colombo, Sri Lanka.

Shuang Zhao, Baoyu Gao , Xiangzuo Li, Min Dong, (2012)   "Influence of using Enteromorpha extract as a coagulant aid on coagulation behavior and floc characteristics of traditional coagulant in Yellow River water treatment", Chemical Engineering Journal 200–202: 569–576.

Singh R.P., Nayak B.R.,· Biswal D.R.,· Tripathy T., Banik K .(2003). "Biobased polymeric flocculants for industrial effluent treatment", Mat. Res. Innovat. 7: 331-340.

Teh Chee Yang, Ta Yeong Wu, Joon Ching Juan (2014) "Optimization of agro-industrial wastewater treatment using unmodified rice starch as a natural coagulant" Industrial Crops and Products 56: 17–26.

Ting Liu, Zhong-lin Chen, Wen-zheng Yu, Ji-min Shen, John Gregory (2011) "Effect of two-stage coagulant addition on coagulation ultrafiltration process for treatment of humic-rich water" water research 45: 4260 – 4268.

TorOve Leiknes (2009). "The effect of coupling coagulation and flocculation with membrane filtration in water treatment: A review." Journal of Environmental Sciences 21: 8–12.

Thuy Khanh Trinh, Lim Seok Kang (2011) "Response surface methodological approach to optimize the coagulation–flocculation process in drinking water treatment" chemical engineering research and design 8 9: 1126–1135.

Wen-zheng Yu, Hui-juan Liu, Lei Xu , Jiu-hui Qu , Nigel Graham (2013)   "The pre-treatment of submerged ultrafiltration membrane by coagulation—Effect of polyacrylamide as a coagulant aid" Journal of Membrane Science 446: 50–58.

Water Research Commission (2002). No: TT 181/02, First Edition, The Department of Water Affairs and Forestry, The Department of Health, Water Research Commission.

World Health Organization (WHO), (2008), "Guidelines for Drinking-water Quality" Vol. 1, Third Edition.

Zhen Yang , Hu Wu, Bo Yuan , Mu Huang , Hu Yang , Aimin Li , Junfeng Bai , Rongshi Cheng (2014) "Synthesis of amphoteric starch-based grafting flocculants for flocculation of both positively and negatively charged colloidal contaminants from water" Chemical Engineering Journal 244: 209–217.

Zhao,Y.X., B.Y. Gao, B.C. Cao, Z.L. Yang, Q.Y. Yue, H.K. Shon, J.-H. Kim (2011) "Comparison of coagulation behavior and floc characteristics of titanium tetrachloride (TiCl4) and polyaluminum chloride (PACl) with surface water treatment" Chemical Engineering Journal 166: 544–550.

Zhao, Y.X., Y. Wang, B.Y. Gao , H.K. Shon , J.-H. Kim, Q.Y. Yue (2012) "Coagulation performance evaluation of sodium alginate used as coagulant aid with aluminum sulfate, iron chloride and titanium tetrachloride" Desalination 299: 79–88.

APPENDEX-A

Coagulant = FCL, R.W Turbidity = 120 NTU, pH = 7.41

Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	TDS	EC	Color (pt. Co)	Fecal Coliform(col./100ml)	Residual Alkalinity as CaCO$_3$	
30	3	7.26	93.95	6.59	276	460	23	48	155	
60	6	0.725	99.3958333	6.4	282	470	28	40	127.5	
90	9	0.303	99.7475	6.16	321	535	25	18	125	
120	12	0.22	99.8166667	5.88	307.2	512	16	13	75	
150	15	0.247	99.7941667	5.6	329.4	549	22	39	62.5	

Coagulant = PACl, R.W Turbidity = 120 NTU, pH = 7.41

Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	TDS	EC	Color	Fecal Coliform (col./100ml)	Residual Aluminium(ppm)	Residual Alkalinity as CaCO$_3$
30	3	2.12	98.23333333	6.72	249.6	416	19	37	0.05	167
60	6	1.04	99.13333333	6.72	264	440	17	33	0.07	145
90	9	0.37	99.69166667	6.69	272.4	454	3	0	0.12	130
120	12	0.53	99.55833333	6.65	282	470	12	20	0.12	130
150	15	0.69	99.425	6.62	309	515	18	43	0.18	120

Coagulant = Alum, R.W Turbidity = 120 NTU, pH = 7.41

Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	TDS	EC	Color	Fecal Coliform (col./100ml)	Residual Aluminium(ppm)	Residual Alkalinity as CaCO$_3$
35	3.5	2.62	97.82	6.6	260.4	434	18	65	0.12	165
70	7	1.34	98.88	6.6	261.6	436	14	45	0.31	145
105	10.5	1.19	99.01	6.6	262.8	438	15	40	0.37	135
140	14	0.46	99.62	6.3	266.4	444	13	32	0.44	120
175	17.5	2.46	97.95	6.1	268.8	448	16	20	0.48	90

PACl, R.W. Turbidity = 120 NTU, pH 7.41					PACl, R.W. Turbidity = 120 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
85	8.5	1.06	99.1166667	6.7	56	5.6	1.01	99.1583333	5.81
88	8.8	1.02	99.15	6.68	58	5.8	0.94	99.2166667	5.8
91	9.1	0.93	99.225	6.68	60	6	0.62	99.4833333	5.8
94	9.4	0.35	99.7083333	6.67	62	6.2	0.48	99.6	5.78
97	9.7	0.85	99.2916667	6.65	64	6.4	0.71	99.4083333	5.76
PACl, R.W. Turbidity = 120 NTU, pH 7					PACl, R.W. Turbidity = 120 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
86	8.6	1.12	99.0666667	6.65	112	11.2	1.314	98.905	7.45
88	8.8	0.864	99.28	6.65	115	11.5	0.78	99.35	7.41
90	9	0.31	99.7416667	6.63	118	11.8	0.632	99.4733333	7.40
92	9.2	0.44	99.6333333	6.60	121	12.1	0.771	99.3575	7.40
94	9.4	0.62	99.4833333	6.60	124	12.4	0.78	99.35	7.38
PACl, R.W. Turbidity = 80 NTU, pH 7.27					PACl, R.W. Turbidity = 80 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
76	7.6	1.42	98.225	7.02	56	5.6	1.34	98.325	6.02
78	7.8	1.05	98.6875	6.98	58	5.8	0.95	98.8125	6.01
80	8	0.96	98.8	6.97	60	6	1.12	98.6	5.98
82	8.2	0.56	99.3	6.94	62	6.2	1.64	97.95	5.96
84	8.4	1.15	98.5625	6.90	64	6.4	1.92	97.6	5.96
PACl, R.W. Turbidity = 80 NTU, pH 7					PACl, R.W. Turbidity = 80 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
76	7.6	2.04	97.45	6.78	86	8.6	3.34	95.825	7.58
78	7.8	1.35	98.3125	6.76	88	8.8	1.97	97.5375	7.55
80	8	0.42	99.475	6.75	90	9	1.67	97.9125	7.55
82	8.2	0.71	99.1125	6.70	92	9.2	1.14	98.575	7.55
84	8.4	1.18	98.525	6.69	94	9.4	1.38	98.275	7.52

PACl, R.W Turbidity = 40 NTU, pH 8.21					PACl, R.W Turbidity = 40 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
56	5.6	1.34	95.5333333	7.85	36	3.6	1.4	95.3333333	6.09
58	5.8	0.82	97.2666667	7.81	38	3.8	0.65	97.8333333	6.08
60	6	0.08	99.7333333	7.79	40	4	1.26	95.8	6.11
62	6.2	0	100	7.78	42	4.2	2.34	92.2	6.07
64	6.4	0	100	7.75	44	4.4	2.4	92	6.1
PACl, R.W Turbidity = 40 NTU, pH 7					PACl, R.W Turbidity = 40 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
53	5.3	0.45	98.5	7.06	45	4.5	4.95	83.5	7.71
56	5.6	0	100	7.13	48	4.8	2.57	91.4333333	7.7
59	5.9	0	100	7.07	51	5.1	0.7	97.6666667	7.7
62	6.2	0	100	7.04	54	5.4	0.54	98.2	7.65
65	6.5	0	100	7.04	57	5.7	0	100	7.61
Alum, R.W Turbidity = 40 NTU, pH 8.21					Alum, R.W Turbidity = 40 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
70	7	1.06	97.35	7.29	46	4.6	1.73	95.675	6.04
72	7.2	0.96	97.6	7.31	48	4.8	1.42	96.45	6.04
74	7.4	1.02	97.45	7.31	50	5	0.46	98.85	6
76	7.6	1.08	97.3	7.31	52	5.2	0.38	99.05	6.04
78	7.8	1.26	96.85	7.26	55	5.4	1.51	96.225	6
Alum, R.W Turbidity = 40 NTU, pH 7					Alum, R.W Turbidity = 40 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
60	6	1.52	96.2	6.91	65	6.5	1.72	95.7	7.3
62	6.2	1.23	96.925	7	68	6.8	1.53	96.175	7.33
64	6.4	0.11	99.725	6.99	71	7.1	0.87	97.825	7.33
66	6.6	0.32	99.2	7.04	74	7.4	1.14	97.15	7.36
68	6.8	0.67	98.325	7.05	77	7.7	1.25	96.875	7.37

Alum, R.W Turbidity = 80 NTU, pH 7.27					Alum, R.W Turbidity = 80 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
116	11.6	1.82	97.725	6.81	85	8.5	1.06	98.675	5.7
118	11.8	1.12	98.6	6.8	87	8.7	0.82	98.975	5.66
120	12	1.32	98.35	6.8	91	9.1	0.67	99.1625	5.62
122	12.2	1.41	98.2375	6.78	94	9.4	0.85	98.9375	5.57
124	12.4	1.66	97.925	6.76	97	9.7	0.95	98.8125	5.54
Alum, R.W Turbidity = 80 NTU, pH 7					Alum, R.W Turbidity = 80 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
95	9.5	2.04	97.45	6.55	115	11.5	2.63	96.7125	7.12
97	9.7	1.75	97.8125	6.52	117	11.7	1.48	98.15	7.10
101	10.1	1.21	98.4875	6.50	121	12.1	1.35	98.3125	7.05
104	10.4	0.88	98.9	6.48	124	12.4	1.08	98.65	7.03
107	10.7	1.15	98.5625	6.45	127	12.7	1.18	98.525	6.98
Alum, R.W Turbidity = 120 NTU, pH 7.41					Alum, R.W Turbidity = 120 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
132	13.2	1.36	98.86666667	6.4	85	8.5	1.07	99.10833333	5.74
135	13.5	1.03	99.14166667	6.38	88	8.8	1.01	99.15833333	5.7
138	13.8	0.872	99.27333333	6.35	91	9.1	0.735	99.3875	5.7
141	14.1	0.91	99.24166667	6.3	94	9.4	0.31	99.74166667	5.64
144	14.4	1.14	99.05	6.29	97	9.7	0.53	99.55833333	5.6
Alum, R.W Turbidity = 120 NTU, pH 7					Alum, R.W Turbidity = 120 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
116	11.6	1.12	99.06666667	6.46	136	13.6	1.96	98.36666667	6.30
119	11.9	1.03	99.14166667	6.44	139	13.9	1.66	98.61666667	6.28
122	12.2	0.841	99.29916667	6.40	142	14.2	1.43	98.80833333	6.28
125	12.5	0.422	99.64833333	6.38	145	14.5	1.12	99.06666667	6.27
128	12.8	0.72	99.4	6.35	148	14.8	1.45	98.79166667	6.25

FCL, R.W Turbidity = 40 NTU, pH 8.21					FCL, R.W Turbidity = 40 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
62	6.2	1.74	95.65	7.18	42	4.2	1.56	96.1	5.74
64	6.4	0.96	97.6	7.15	44	4.4	1.32	96.7	5.72
66	6.6	0.81	97.975	7.15	46	4.6	1.13	97.175	5.70
68	6.8	0.42	98.95	7.13	48	4.8	0.87	97.825	5.70
70	7	0.75	98.125	7.10	50	5	0.98	97.55	5.69
FCL, R.W Turbidity = 40 NTU, pH 7					FCL, R.W Turbidity = 40 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
51	5.1	1.48	96.3	6.91	58	5.8	2.01	94.975	7.25
54	5.4	1.07	97.325	6.90	60	6	1.87	95.325	7.23
57	5.7	0.06	99.85	6.90	62	6.2	0.4	99	7.20
60	6	0.33	99.175	6.88	64	6.4	0.74	98.15	7.18
63	6.3	0.84	97.9	6.87	66	6.6	1.02	97.45	7.17
FCL, R.W Turbidity = 80 NTU, pH 7.27					FCL, R.W Turbidity = 80 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
86	8.6	1.08	98.65	6.8	56	5.6	1.04	98.7	5.38
88	8.8	0.86	98.925	6.78	58	5.8	0.72	99.1	5.32
90	9	0.52	99.35	6.76	60	6	0.54	99.325	5.27
92	9.2	0.34	99.575	6.76	62	6.2	0.41	99.4875	5.23
94	9.4	0.75	99.0625	6.72	64	6.4	0.85	98.9375	5.08
FCL, R.W Turbidity = 80 NTU, pH 7					FCL, R.W Turbidity = 80 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
85	8.5	1.32	98.35		96	9.6	1.02	98.725	
88	8.8	0.71	99.1125		98	9.8	0.96	98.8	
91	9.1	0.86	98.925		100	10	0.72	99.1	
94	9.4	0.89	98.8875		102	10.2	0.84	98.95	
97	9.7	0.83	98.9625		104	10.4	1.21	98.4875	

FCL, R.W Turbidity = 120 NTU, pH 7.41					FCL, R.W Turbidity = 120 NTU, pH 6				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
116	11.6	1.15	99.0416667	5.91	85	8.5	0.835	99.3041667	5.21
118	11.8	0.961	99.1991667	5.9	88	8.8	0.661	99.4491667	5.17
120	12	0.412	99.6566667	5.9	91	9.1	0.721	99.3991667	5.14
122	12.2	0.37	99.6916667	5.87	94	9.4	0.775	99.3541667	5.06
124	12.4	0.46	99.6166667	5.84	97	9.7	1.26	98.95	5.01
FCL, R.W Turbidity = 120 NTU, pH 7					FCL, R.W Turbidity = 120 NTU, pH 8				
Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH	Dose (mg/L)	Vol used (ml)	Residual Turbidity	% Removal	pH
113	11.3	1.04	99.1333333		117	11.7	2.15	98.2083333	
116	11.6	0.195	99.8375		120	12	1.08	99.1	
119	11.9	0.202	99.8316667		123	12.3	0.74	99.3833333	
122	12.2	0.32	99.7333333		126	12.6	0.571	99.5241667	
125	12.5	0.38	99.6833333		129	12.9	1.02	99.15	

Optimum Coagulant doses at 120, 80 and 40 NTU (Fig 4.23, 4.24, 4.25)

			Initial pH			
		Coagulant	Natural	6	7	8
Raw Water Turbidity (NTU)	120	PACl	94	62	90	118
		Ferric Chloride	122	88	116	126
		Alum	138	94	125	145
	80	PACl	82	58	80	92
		Ferric Chloride	92	62	88	100
		Alum	118	91	104	124
	40	PACl	62	38	56	57
		Ferric Chloride	68	48	57	62
		Alum	72	52	64	71

*(Coagulant Doses are in mg/L)