



OPTIMIZATION OF COAGULATION-FLOCCULATION IN THE TREATMENT OF CANAL WATER

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Abstract

A study was conducted for the treatment of canal water using coagulation-flocculation-sedimentation process. Different coagulants i.e. alum, ferric sulfate and ferric chlorides were used. The effect of pH and mixing condition i.e. rapid mixing energy and time and slow mixing energy and time on the performance of coagulants were studied. Jar test apparatus was used to conduct the studies. The results of the study demonstrated that pH and mixing conditions affect the efficiency of the coagulant and there exist particular conditions for achieving maximum efficiency of a coagulant at an economical cost. Among different coagulants tested, alum was found to be a suitable coagulant for canal water on the basis of removal of turbidity and cost of treatment. The optimum dose of alum was found to be 12 mg/L at an optimum rapid mixing energy of 100 sec⁻¹ and mixing time of 1 minute and slow mixing energy of 35 sec⁻¹ and mixing time of 20 minutes and 30 minutes of sedimentation time. At the optimum dose, alum removed 99.5% turbidity and 94.4% fecal coliforms. The cost of alum to treat one cubic meter of canal water was 2.55 US\$. Sludge production at optimum dose of alum was 2.4 mL/L.

Key words: canal water, coagulation, flocculation, surface waters, water treatment

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1. Introduction

Pakistan possesses both ground and surface water sources. For public water supplies both ground and surface water sources are used. According to an estimate 30% of water supplies in Pakistan are drawn from different surface water sources (Aziz, 2005). These include dams, lakes, rivers and canals. A large number of water supplies in Punjab and Sindh are based on raw canal water. The normal practice is to draw the canal water through an intake structure, settle the water in a sedimentation tank and pass it through a slow sand filter before being supplied to the consumers without disinfection. A schematic diagram of the entire process is shown in Fig. 1.

The turbidity of canal water is usually high and varies widely in a range of 10-90 NTU (Ahmad, 2009). Chemical coagulation is not employed on most of the public water supply projects. As such, turbidity is not reduced to a substantial level in plain sedimentation, which results in high suspended solids

load on slow sand filter. This high load considerably reduces the filter run. Since the filters are not regularly cleaned, especially in rural areas and small towns, therefore, it results in poor treated water quality.

The process train selected for public water supplies (Fig. 1) for canal water treatment is not satisfactory due to its high turbidity. It is proposed to include chemical coagulation and flocculation before sedimentation for canal waters. The chemical coagulation refers to the addition of a suitable coagulant in raw surface water in a small compartment/basin where it is rapidly mixed (Banihashemi et al., 2008). The purpose of rapid mixing is to thoroughly disburse the coagulant in the water to neutralize the charge on colloidal particles. Afterwards, the water is shifted to a second compartment i.e. flocculator, where it is slowly mixed (Mihai et al., 2008). This slow mixing aids in the formation of bigger flocs that can easily settle in sedimentation tank leaving a clear supernatant for

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slow sand filters. It has been observed that the turbidity of raw canal water may be reduced to 1-2 NTU by proper application of coagulation-flocculation-sedimentation process. Thus a significant reduction in turbidity would reduce the suspended solids load on slow sand filters to result in longer filter run, less maintenance and good treated water quality. The schematics of the proposed treatment train are shown in Fig. 2.

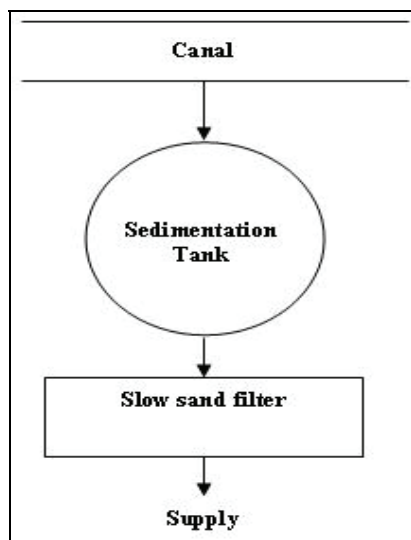


Fig. 1. Schematic diagram of prevailing canal water treatment

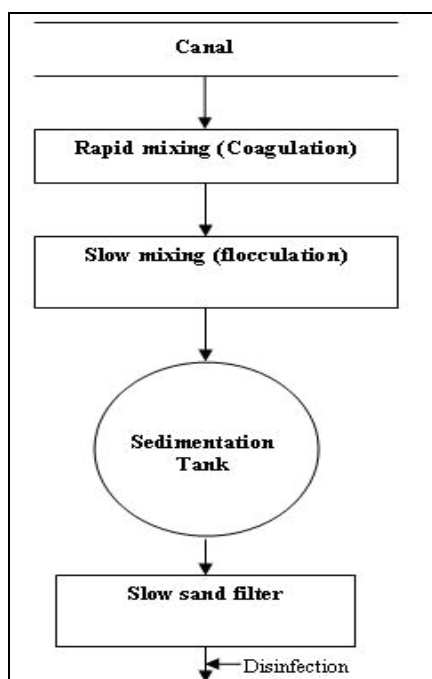


Fig. 2. Schematic diagram of proposed canal water treatment

A number of coagulants are available in the market that may be used for the treatment of canal water in Pakistan. Moreover, a wide range of mixing energies and timings are reported in the literature for rapid and slow mixing (Adin et al., 1998;

Amirtharajah and O'Melia, 1990; Cabral et al., 1999; Hudson and Wagner, 1981; Kawamura, 1976; Letterman et al., 1973; Lurie and Rebhun, 1997; O'Melia, 1972; Rebhun and Leentvaar, 1983; Rossini et al., 1999; Yu, 2000). Selection of a suitable coagulant and optimum mixing energies and times for a specific source of water involve experimentation. Therefore, the present study was undertaken with the following objectives: (1) selection of suitable coagulant for canal water treatment and determination of its optimum dose and the optimum pH range; (2) determination of optimum mixing energies and timings for rapid and slow mixing conditions for the canal water treatment. Fecal coliform removal by the coagulants and sludge production was also investigated.

2. Materials and methods

2.1. Sampling

Canal water samples were collected from Bambanwali Ravi Bedian Depalpur (BRBD) canal passing through the Lahore city. The sampling point selected was Dharampura crossing railway bridge on the canal. There was a limitation on the collection of the maximum volume of the canal water sample. The maximum volume that could be preserved in the laboratory was 40 liter, thus the same volume was collected at a time. Since more than 50 jar tests were conducted, therefore, 15 water samples were collected to complete the study.

2.2. Coagulants used

It was decided to use three different commonly available coagulants for the clarification of BRDB canal water for comparing their efficiencies and indicating the best one. A list of the coagulants used and their chemical composition is given in Table 1.

Table 1. Coagulants used in the study

Coagulant	Chemical composition
Alum	$Al_2(SO_4)_3 \cdot 14(H_2O)$
Ferric Sulfate	$Fe_2(SO_4)_3 \cdot 4.5(H_2O)$
Ferric Chloride	$FeCl_3 \cdot 6(H_2O)$

All alum doses expressed in this paper are as $Al_2(SO_4)_3 \cdot 14(H_2O)$, ferric sulfate doses are as $Fe_2(SO_4)_3 \cdot 4.5(H_2O)$ and ferric chloride doses are as $FeCl_3 \cdot 6(H_2O)$.

2.3. Research methodology

A bench scale jar test apparatus PB-900 series with programmable unit and illuminated base was used for the treatment of canal water (Fig. 3). Illuminated base helps in the observation of flocs. Jar test apparatus is usually used to simulate coagulation-flocculation-sedimentation in the laboratory (O'Melia, 1972; Wong et al., 2006).

The whole study was divided into two phases. In Phase-I, a trial dose of each coagulant was initially determined. This trial dose was then employed for the determination of (i) optimum pH; (ii) optimum rapid and (iii) optimum slow mixing energy and time. In Phase-II, optimum conditions determined in Phase-I were used to find out (i) optimum coagulant dose for maximum removal of turbidity; (ii) fecal coliforms removal at the optimum conditions and (iii) sludge production at optimum conditions.

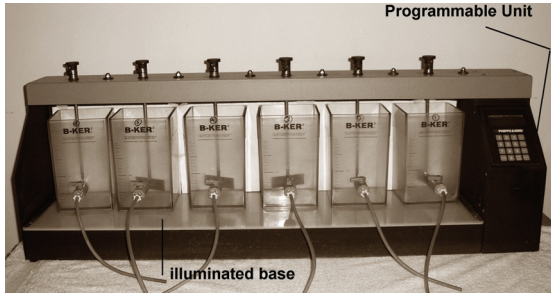


Fig. 3. Jar test apparatus with programmable unit and illuminated base

Phase-I of the study

2.3.1. Determination of trial dose

Initially it was decided to determine a trial dose of the selected coagulants at which maximum removal of turbidity would occur. For this purpose, the dose of coagulants was varied from 5 to 30 mg/L in jar 1 to 6 with an interval of 5 mg/L. The canal water sample was poured in a bucket, shaken well and then 2 liter was added to each jar. For administering a specific dose of the coagulant, its 0.5% stock solution was prepared in the distilled water. To simultaneously add the doses to all jars a test tube stand was used (ASTM Standards, 2004).

For trial dose mixing energies and timings were selected from the literature (Adin et al., 1998; Amirtharajah and O’Melia, 1990; Cabral et al., 1999; Hudson and Wagner, 1981; Kawamura, 1976; Letterman et al., 1973; Lurie and Rebhun, 1997; O’Melia, 1972; Rebhun and Leentvaar, 1983; Rossini et al., 1999; SenthilKumar et al., 2010; Yu, 2000). Samples in the jars were rapidly mixed at a velocity gradient (G) of 380 sec⁻¹ for one minute, slow mixed at a G value of 50 sec⁻¹ for 15 minutes and then settled for 30 minutes. Afterwards, treated samples were drawn from the sampling port furnished in the jars and examined for turbidity. The dose giving the minimum residual turbidity was selected as trial dose for Phase-I.

2.3.2. Optimum pH

For the determination of optimum pH for the maximum removal of turbidity in coagulation-flocculation-sedimentation, pH of the canal water was varied from 4 to 10 in different jars. Trial dose, as determined in section 2.3.1 was added to all the jars. For pH adjustment, 5% HCl and 1% NaOH solutions were used. Same mixing regime as used in section

2.3.1 was employed. Samples after jar test were tested for turbidity. The pH range at which residual turbidity was a minimum gave the optimum pH conditions for coagulation-flocculation.

2.3.3. Optimum rapid mixing energy and time

For the determination of optimum rapid mixing energy and time, the velocity gradient “G” was varied from 100 to 380 sec⁻¹ for mixing time of 1 and 5 minutes. A total of six experimental set ups as shown in Table 2 were tested. Same slow mixing energy and time (50 sec⁻¹, 15 minute) and settlement time (30 minutes) was used for all the set ups to study the effect of change in rapid mixing conditions. The experimental set up giving the minimum residual turbidity would define the optimum rapid mixing conditions.

Table 2. Experimental set ups for the determination of optimum rapid mixing conditions

<i>Experimental set ups</i>	
<i>G (sec⁻¹)</i>	<i>Time (min)</i>
100	1
230	1
380	1
100	5
230	5
380	5

2.3.4. Optimum slow mixing energy and time

For the determination of optimum slow mixing energy and time, the G was varied from 15 sec⁻¹ to 50 sec⁻¹ for mixing time of 10 and 20 minute. Rapid mixing energy and timing were fixed to determine the effect of slow mixing parameters. Optimum rapid mixing energy and time determined in section 2.3.3 was used for each coagulant. A total of six experimental set ups as shown in Table 3 were used. Sedimentation time was 30 minutes. The experimental set up giving the minimum residual turbidity would define the optimum slow mixing conditions for canal water.

Table 3. Experimental set ups for the determination of optimum slow mixing conditions

<i>Experimental set ups</i>	
<i>G (sec⁻¹)</i>	<i>Time (min)</i>
15	10
35	10
50	10
15	20
35	20
50	20

Phase-II of the study

2.3.5. Determination of optimum coagulant dose, fecal coliforms removal and sludge produced

The pH of canal water varied in range of 6.5 to 7.77. For the determination of optimum dose of a

coagulant, optimum mixing conditions determined in section 2.3.3 and 2.3.4 were used. It was decided to leave the pH to its natural value for the determination of optimum dose of a coagulant. It was done due to the fact that during actual water treatment, the pH of raw water is not adjusted due to large expenses involved in pH adjustment.

The dose of a coagulant was varied from 5 to 30 mg/L. The dose resulting in minimum residual turbidity was the optimum dose. Fecal coliforms were also determined at the optimum coagulant dose and compared with their number in the raw canal water to assess their removal. Sludge measurement at optimum coagulant dose was also made to investigate the resulting sludge volumes from coagulation-flocculation-sedimentation process.

Imhoff cone was used to measure the sludge volumes. Turbidity was measured using Hach, 2100 AN turbidimeter. pH was measured by using Hach Sension3 pH meter. All tests were conducted using procedures laid down in the APHA (1998), "Standard methods for the examination of water and wastewater".

3. Results and discussion

Phase-I of the study

3.1. Trial dose

The results of the jar tests to determine the trial doses of the coagulants have been shown in Fig. 4.

It can be seen in Fig. 4 that minimum residual turbidity for alum and ferric sulfate occurred at 15 mg/L and for ferric chloride at 10 mg/L. Therefore the trial doses selected for next steps were 15, 15 and 10 mg/L for alum, ferric sulfate and ferric chloride, respectively. It can also be observed that the residual turbidity for FeCl₃ started increasing after a dose of 10 mg/L, whereas for alum the turbidity started increasing after a dose of 25 mg/L. The increase in turbidity shows charge reversal. Thus charge reversal for FeCl₃ occurred at a lower dose as compared to alum for canal water. Charge reversal for FeSO₄ did not occur even at the maximum dose of 30 mg/L. Perhaps it could have occurred if the dose was further increased. Charge reversal at different doses of coagulants may be due to specific characteristics of canal water which may affect the reaction of coagulants with the water.

3.2. Determination of optimum pH

For the determination of optimum pH for the coagulants, trial dose determined in section 3.1 was administered. The residual turbidity was measured. The results are shown in Fig. 5. It is evident from Fig. 5 that the optimum pH for alum, ferric sulfate and ferric chloride lies in a range of 6.3 to 7.8, 6.0 to 6.8 and 5.8 to 6.8, respectively.

3.3. Determination of optimum rapid mixing energy and time

The results of six different experimental set ups (Table 2) for alum, ferric sulfate and ferric chloride are presented in Figs. 6 - 8. Trial dose of each coagulant as determined in section 3.1 was administered to all the six jars. For a particular experimental set up, raw canal water was fed to all the six jars. After the jar test, the residual turbidity in all the six jars was determined and average value was calculated for that experimental set up. This average value is reported in Figs. 6 - 8. Turbidity of the raw sample used for the jar tests has also been shown on each figure.

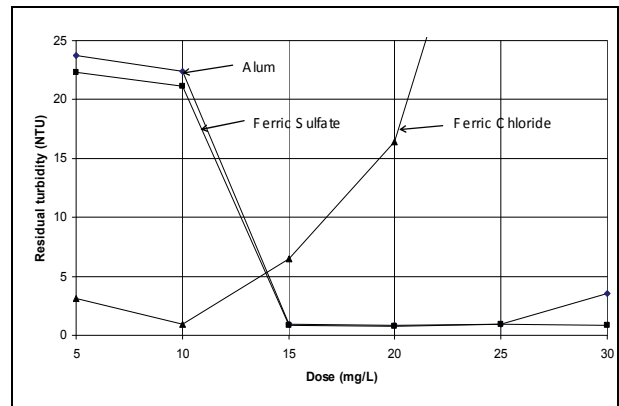


Fig. 4. Determination of trial doses for different coagulants

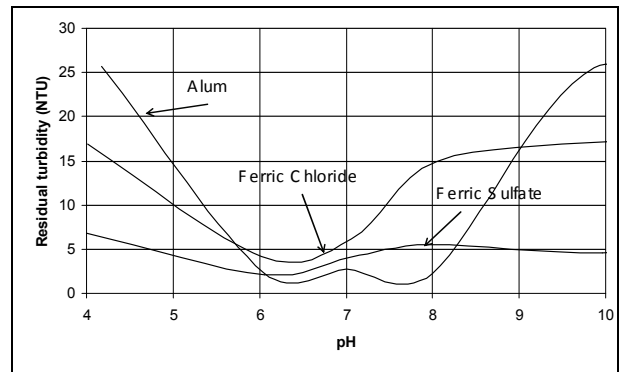


Fig. 5. Determination of optimum pH

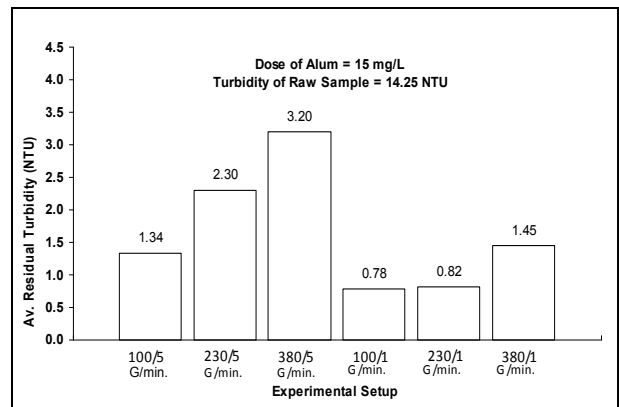


Fig. 6. Optimum rapid mixing energy and time for alum

It can be seen in Fig. 6 that the optimum mixing energy for alum was 100 sec^{-1} and optimum mixing time was 1 minute, which resulted in minimum residual turbidity of 0.78 NTU after the jar test. Similarly, for both ferric sulfate and ferric chloride the optimum mixing conditions were similar and were 100 sec^{-1} for 5 minutes (Fig. 7 and 8). However with these mixing conditions the obtained residual turbidity was higher than the one obtained through the use of alum.

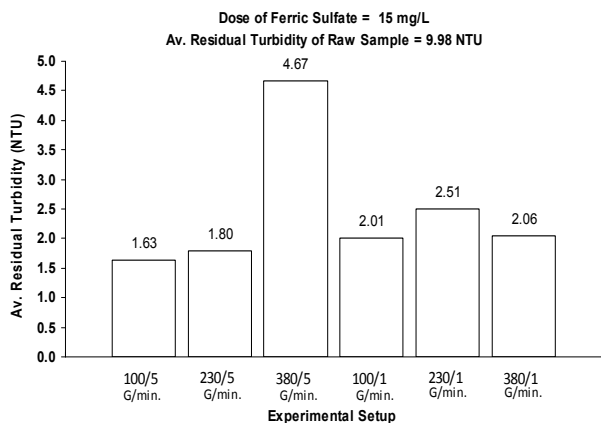


Fig. 7. Optimum rapid mixing energy and time for ferric sulfate

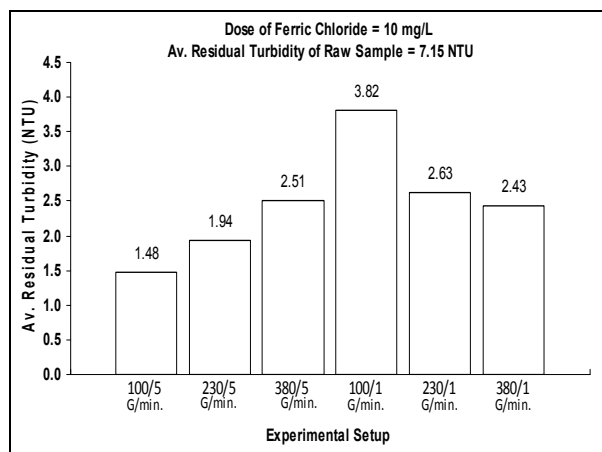


Fig. 8. Optimum rapid mixing energy and time for ferric chloride

3.4 Determination of slow mixing energy and time

The results of six different experimental set ups for the determination of optimum slow mixing energy and time (Table 3) for the coagulants used are shown in Figs. 9 to 11.

It is evident from Fig. 9 that optimum mixing energy, for alum was 35 sec^{-1} and optimum mixing time was 20 minutes, which resulted into the minimum residual turbidity of 1.08 NTU. For ferric sulfate the optimum slow mixing conditions were 35 sec^{-1} for 20 minutes and for ferric chloride the optimum slow mixing conditions were 35 sec^{-1} for 10 minutes.

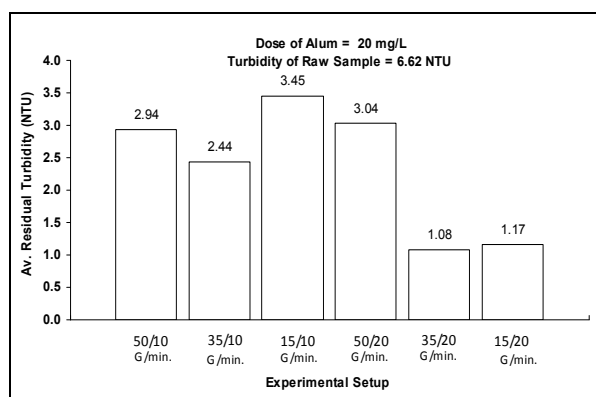


Fig. 9. Optimum slow mixing energy and time for alum

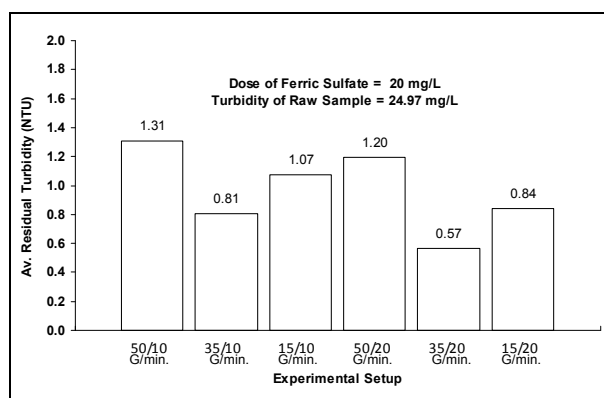


Fig. 10. Optimum slow mixing energy and time for ferric sulfate

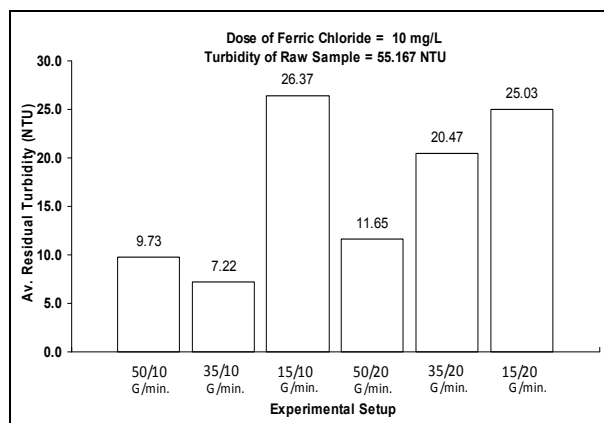


Fig. 11. Optimum slow mixing energy and time for ferric chloride

Phase-II of the study

3.5. Determination of optimum doses of coagulants

After determining optimum mixing conditions (rapid and slow), these were used simultaneously to find out the optimum dose of the coagulants used. The pH was not adjusted to the optimum value for the reasons stated in section 2.3.5. The dose of the coagulants was varied from 5 to 30 mg/L. The jar test was performed in triplicate for each coagulant and the results shown are the mean values for the triplicate analysis. The results for alum are shown in Fig. 12.

The turbidity values plotted are average of the triplicate jar tests. The standard deviation in the triplicate results has also been shown as vertical error bars on the figure. It can be seen in Fig. 12 that the optimum alum dose for canal water was about 12 mg/L. Results for ferric sulfate and ferric chloride are shown in Figs.13 and 14. The optimum doses of ferric sulfate and ferric chloride from Figs. 13 and 14 appear to be 20 mg/L and 13 mg/L.

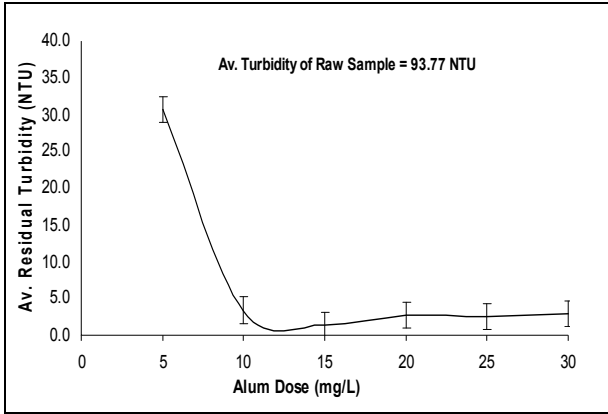


Fig. 12. Determination of optimum dose of alum at optimum rapid and slow mixing conditions

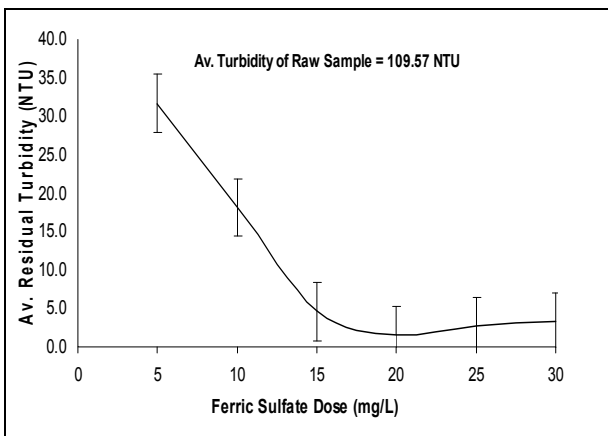


Fig. 13. Determination of optimum dose of ferric sulfate at optimum rapid and slow mixing conditions

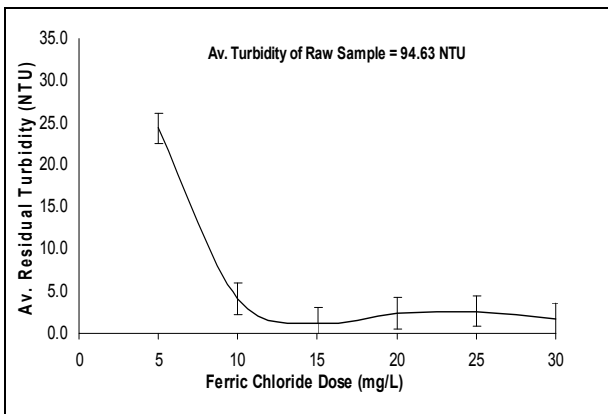


Fig. 14. Determination of optimum dose of ferric chloride at optimum rapid and slow mixing conditions

Turbidity of raw canal sample, residual turbidity at the optimum dose and mixing conditions and percentage removal are presented in Table 4. It is evident from Table 4 that alum has the highest removal efficiency.

Furthermore, it was also observed that the flocs formed with alum and ferric sulfate were heavier and settled faster as compared to ferric chloride. Since the doses of all coagulants are small, therefore, the dominant mechanism of removal appears to be charge neutralization.

3.6. Fecal coliform removal

Fecal coliforms were also studied and the results are shown in Table 5.

It can be seen in Table 5 that a fecal coliforms removal in a range of 88-97% was achieved with the coagulants. However, the residual values were quite high and required disinfection.

3.7. Sludge production with different coagulants

Sludge production with different coagulants was also evaluated. Measurements were made at the optimum dose and optimum mixing conditions.

The results are shown in Fig. 15 from where it can be observed that alum produced maximum volume of sludge. Perhaps it is due to the formation of gelatinous $Al(OH)_3$ gel, which adds to the volume of sludge produced.

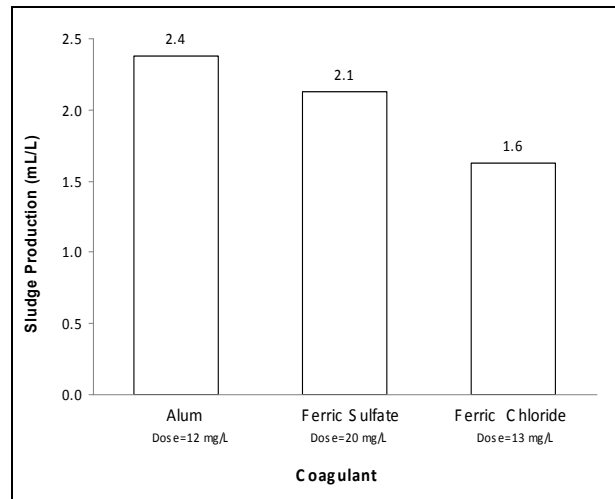


Fig. 15. Sludge production at optimum dose

3.8. Cost of coagulants

Cost of coagulants is an important consideration in the final selection. The cost of different coagulants, at their optimum doses, to treat one cubic meter of canal water was calculated and is shown in Table 6. It can be seen in Table 6 that cost of alum and ferric chloride is comparable while that of ferric sulfate is almost double.

Table 4. Performance of the coagulants at optimum dose and mixing conditions

Coagulant	Optimum Dose (mg/L)	Av. Raw Sample Turbidity (NTU)	Residual Turbidity after treatment (NTU)	Turbidity Removal Efficiency (%)
Alum	12	93.77	0.5	99.5
Ferric Sulfate	20	109.57	1.5	98.6
Ferric Chloride	13	94.63	2.4	97.5

Table 5. Fecal coliform removal efficiency of the coagulants at optimum dose and mixing conditions

Coagulant	Optimum Dose (mg/L)	Fecal Coliform in Raw Sample (No/100mL)	Fecal Coliform after Jar Test (No/100mL)	Fecal Coliform Removed (No/100mL)	% age Removal
Alum	12	1,800,000	100,000	1,700,000	94.44
Ferric Sulfate	20	1,800,000	45,000	1,755,000	97.50
Ferric Chloride	13	380,000	45,000	335,000	88.16

Table 6. Cost of coagulants

Coagulant	Optimum Dose (mg/L)	Unit Cost (US\$/kg)	Cost of Chemical (US\$/m ³ of water)
Alum	12	0.188	2.55
Ferric Sulfate	20	0.235	5
Ferric Chloride	13	0.176	2.48

4. Conclusions

The above studies conclude that an optimum mixing energy and time exist for each coagulant that must be investigated before finalizing the design of a water treatment plant. On the basis of turbidity removal and the cost of the coagulant, alum was found to be the most appropriate coagulant for canal water treatment. For Alum, optimum rapid and slow mixing energy and time are 100 sec⁻¹ for 1 minute and 35 sec⁻¹ for 20 minute, respectively. Optimum pH for alum lies in a range of 6.3 to 7.8. The optimum dose for alum was found to be 12 mg/L with residual turbidity of 0.5 NTU producing a sludge of 2.4 mL/L.

Acknowledgements

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