Enhanced Removal of Heavy Metals in Primary Treatment Using Coagulation and Flocculation

Authors:

Pauline D. Johnson[1*],

Padmanabhan Girinathannair[2],

Kurt N. Ohlinger[3],

Stephen Ritchie[4],

Leah Teuber[1],

Jason Kirby[5]

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[1] Department of Civil Construction and Environmental Engineering, University of Alabama, Tuscaloosa.

[2] Golder Associates, Cherry Hill, New Jersey.

[3] Department of Civil Engineering, California State University, Sacramento.

[4] Department of Chemical and Biological Engineering, University of Alabama, Tuscaloosa.

[5] Department of Civil Engineering University of Alabama-Birmingham.

[*] University of Alabama, Department of Civil Construction and Environmental Engineering, 7th Ave. and Campus Drive, 260 H.M. Comer, Tuscaloosa, Alabama 35487; e-mail: paulinej@coe.eng.ua.edu.

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ABSTRACT:

The goal of this study was to determine the removal effi- ciencies of chromium, copper, lead, nickel, and zinc from raw wastewater by chemically enhanced primary treatment (CEPT) and to attain a total sus- pended solids removal goal of 80%. Operating parameters and chemical doses were optimized by bench-scale tests. Locally obtained raw wastewater samples were spiked with heavy metal solutions to obtain representative concentrations of metals in wastewater. Jar tests were conducted to compare the metals removal efficiencies of the chemical treatment options using ferric chloride, alum, and anionic polymer. The results obtained were compared with those from other studies. It was concluded that CEPT using ferric chloride and anionic polymer is more effective than CEPT using alum for metals removal. The CEPT dosing of 40 mg/L ferric chloride and 0.5 mg/L polymer enhanced heavy metals removal efficiencies by over 200% for chromium, copper, zinc, and nickel and 475% for lead, compared with traditional primary treatment. Efficient metals capture during CEPT can result in increased allowable headworks loadings or lower metal levels in the outfall. *Water Environ. Res.*, **80**, 472 (2008).

INTRODUCTION

The presence of heavy metals in the influent to municipal waste- water treatment plants can adversely affect the performance of bio- logical treatment processes and quality of the effluent and influence decisions regarding the reuse and land application of biosolids. These negative effects can result in limits on the allowable head- works metals loadings. Preventing heavy metals from reaching downstream processes and the receiving waters can be accomplished by removing the heavy metals using chemically enhanced primary treatment (CEPT) and can result in increased allowable headworks metals loadings or lower metal levels in the outfall.

Chemical precipitation by coagulation and flocculation by trivalent metal salts is a century old and proven technology. Common applications are municipal water supply for dissolved and colloidal impurities and industrial wastewater treatment for metals capture. Modern applications of precipitation technologies to enhance the primary treatment of municipal wastewater evolved from the need for phosphorous removal from primary wastewater effluents to curb eutrophication of receiving waters. Current applications of CEPT serve to enhance conventional treatment through improved removal of suspended solids, biochemical oxygen de- mand, and phosphorous during primary treatment. The CEPT is also used as an alternative to secondary treatment in applications requiring economy of cost and space (Harleman and Murcott, 2001). Recent studies have shown that CEPT is also effective in metals capture from municipal wastewater (Ridge and Sedlak, 2004; Sedlak, 2005). However, it is important to note that the presence of synthetic chelating agents, such as ethylenediaminetetraacetic acid (EDTA), in wastewater can inhibit the metals capture process (Ridge and Sedlak, 2004).

A preliminary study conducted by Ohlinger (1993) at the Sacramento Regional Wastewater Treatment Plant (SRWTP) (California) to evaluate the effectiveness of using CEPT to remove organic and inorganic constituents demonstrated that ferric chloride ($FeCl_3$) and anionic polymer offer the potential to remove heavy metals during primary treatment. Studies agree that ferric chloride is more effective than alum for metals capture from wastewater. Scott et al. (1995) reported that ferric chloride outperformed alum in arsenic removal efficiency, with 81 to 96% arsenic removal using ferric chloride. Hudson and Wagner (1981) found a similar correlation for turbidity removal in studies comparing ferric chloride with alum. Amirtharajah and O'Melia (1990) reported that both anionic and nonionic polymers are used in conjunction with iron salts. Most studies agree that a polymer dose of 0.5 mg/L (0.5 ppm) is optimal for metals capture, with the coagulant dose varying with wastewater characteristics. Ohlinger (1993) found that the best removal efficiency at the SRWTP was obtained using a dosage of 40 mg/L FeCl3 and 0.5 mg/L (0.5 ppm) anionic polymer. In another jar test study, Poon and Chu (1999) reported optimum total suspended solids (TSS) removal from wastewater using 30 mg/L $FeCl_3$ with 0.5 mg/L (0.5 ppm) anionic polymer.

The goal of this study was to determine the effectiveness of alum, ferric chloride, and polymer on the removal efficiencies of chromium, copper, lead, nickel, and zinc from raw wastewater by CEPT, while attaining a TSS removal goal of 80%. The objectives were to define optimal system operating parameters, compare chemical performance, quantify chemical dose, and assess the effect of CEPT on allowable headworks loadings. Bench-scale treatability studies of chemical coagulation and flocculation were performed. The metals of interest for this study

Table 1—Raw wastewater influent data.

Location/ reference	Details	Concentration (lg/L)					
		Chromium	Copper	Lead	Nickel	Zinc	Iron
Tuscaloosa (this study)	Raw wastewater	<LOD	<LOD	<LOD	5.40	54.03	292.99
	Wastewater replicate (mean)	75.93	112.70	85.24	659.60	476.84	296.35
	Spiked wastewater (control)	86.79	149.93	84.37	353.58	550.03	331.11
Lynchburg (2000)	Influent wastewater (mean)	10	58	17	6	170	N/A
Ohlinger (1993)	Influent wastewater (mean)	18.0	52.1	13.1	20.0	82.7	N/A

were chromium, copper, lead, nickel, and zinc. Raw wastewater samples were obtained from a wastewater treatment plant in Tuscaloosa, Alabama. As the raw wastewater samples did not contain detectable quantities of dis- solved metals, the wastewater samples were spiked with metals of interest to obtain representative concentrations of metals in wastewater.

Jar tests were used to evaluate the efficiency of ferric chloride and anionic polymer for dissolved metals capture. Jar testing is an important tool, not only for the determination of the best chemical dosing regime, but also for optimizing operational parameters, which determine the efficiency of the treatment system (Hudson and Wagner, 1981). Before conducting the treatability study, jar test procedures were performed to optimize operating parameters, such as rapid mixing and slow mixing speed and time, settling time, and chemicals and doses. Eighty percent suspended solids removal was selected as the performance criteria for the optimization of the jar testing procedure to expand on earlier studies conducted by Ohlinger (1993). In those earlier studies of CEPT for reducing seasonal organic and solids loading to secondary treatment, 80% solids removal was selected as the target goal because of the need for loading reductions. This removal rate was established based on the performance of chemical treatment

of the primary processes at four California wastewater treatment plants (Ohlinger, 1993). Metals removal was a minor aspect of that earlier work, and the objective of current work is to further study metals reduction using CEPT.

Metal removal efficiencies were compared with those obtained by Ohlinger (1993), the Lynchburg Wastewater Treatment Plant Local Limit Evaluation (Lynchburg, 2000), and U.S. Environmental Protection Agency (Washington, D.C.) (U.S. EPA) Guidance Manual # 833B87202 (U.S. EPA, 1987). Influent data for this study, Ohlinger's study, and the Lynchburg study can be found in Table 1.

Because removal efficiency during primary treatment is one of the factors that affects the allowable headworks loadings, the treatability data was used to evaluate the effect of CEPT on the allowable headworks metals loadings. The results were applied to the Lynchburg Wastewater Treatment Plant in Virginia to show the effect of increased metals removal efficiencies translated into allowable headworks loading. Maximum headworks metals loading and rates are established for wastewater treatment plants by the U.S. EPA and state regulations. The criteria for the establishment of these loadings are sludge inhibition, discharge permit limits, receiving water quality criteria, sludge disposal

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standards, and sludge incinerator air emission standards. Implementation of each of these criteria applied to the data will yield a result for allowable headworks loading. After considering the range of data generated by all of the criteria, the most stringent value is selected as the maximum allowable headwork loading (U.S. EPA, 1987).

The minimum reported inhibition thresholds were obtained from the *Guidance Manual on the Development and Implementation of Local Discharge Limitations Under the Pretreatment Program* (U.S. EPA, 1987). The method of headworks allocation assessment and metals loading limits used for this evaluation was based on the potential for inhibition of the activated sludge process. The allowable headworks loading for each metal of interest based on activated sludge inhibition was calculated using eq 1 (U.S. EPA, 1987). The study compared the existing headworks loading with the enhanced headworks loading resulting from chemical treatment, to achieve the threshold inhibition level for the activated sludge process.

$$L_{IN} = \frac{(0.001)(C_{CRIT})(Q_{POTW})}{(1 - R_{PRIM})} \qquad (1)$$

Where

L_{IN} 5 Allowable headworks loading (kg/d);

Q_{POTW} 5 POTW flow (m³/d);

C_{CRIT} 5 Threshold inhibition level (mg/L); and

R_{PRIM} 5 Removal efficiency across primary
           treatment, as a decimal.

Materials and Methods

Analytical Methods. *Total Suspended Solids Analyses.* The TSS concentration was measured by the standard filtration method. A preweighed Whatman GF/C glass microfiber filter (Whatman International Ltd., Maidstone, England) was placed in the vacuum filtration device and wetted with a small amount of deionized water. A well-mixed 200-mL wastewater sample was filtered, and the filter was washed with three successive 20-mL volumes of deionized water. The filter paper was then carefully removed from the filtration device and dried for 1 hour at 1058C. Filter paper was cooled in a desiccator and weighed to the nearest 0.001 g. The TSS was calculated from the difference between the initial and final weights of the filter paper.

Metals Analyses. Aliquots of 5 mL were prepared for metals analysis by filtration through Millipore 0.45-micron membrane filters (Millipore Corporation, Bedford, Massachusetts) into polycarbonate sample vials and preserved with concentrated high-purity nitric acid to a 2% solution. Metals analyses were conducted using a dual-view model Perkin Elmer Inductively Coupled Plasma– Optical Emission Spectrophotometer (ICP-OES) DV3000 (Perkin Elmer Corporation, Waltham, Massachusetts), according to U.S. EPA method 200.7 (U.S. EPA, 1991).

Quality Assurance and Quality Control. Equipment preparation and sample preservation protocols for the metals of concern followed U.S. EPA standard methods (U.S. EPA, 1991). All metals contacting equipment were washed in dilute high-purity nitric acid solution and triple rinsed with deionized .18 Mohm resistivity water.

Data quality was guaranteed through the use of blanks (laboratory blanks, equipment blanks, method blanks, and matrix blanks), National Institute of Standards and Technology (NIST, U.S. Department of Commerce) traceable standards from two independent sources, spikes (matrix spike), and matrix spike duplicates. For quality control, laboratory replicates and sample duplicates were also run. The range of metal concentrations in the samples guided the selection of appropriate internal standards and delineation of the range and matrix for the calibration solutions. Multielement calibration standards were also used to matrix match samples. Quality control

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Table 2—Average LOD and LOQ for the ICP analysis.

	Chromium	Copper	Nickel	Lead	Zinc
LOD	0.57 lg/L (0.57 ppb)	1.25 lg/L (1.25 ppb)	0.59 lg/L (0.59 ppb)	1.13 lg/L (1.13 ppb)	0.49 lg/L (0.49 ppb)
LOQ	1.89 lg/L (1.89 ppb)	4.16 lg/L (4.16 ppb)	1.96 lg/L (1.96 ppb)	3.77 lg/L (3.77 ppb)	1.63 lg/L (1.63 ppb)

Table 3—Concentrations of the spiking solutions.

Heavy metals	Metal salt	Measured concentration of spiking solution
Chromium	Chromium (ic) nitrate	546 mg/L
Copper	Cupric nitrate	468 mg/L
Lead	Lead nitrate	752 mg/L
Nickel	Nickelous nitrate	809 mg/L
Zinc	Zinc nitrate	1890 mg/L

standards were included at the beginning and end of each analytical run and repeated every 10 samples throughout the run, to ensure accuracy of the analysis. To ensure quality assurance, quality control standards were selected from a vendor other than the source of the calibration standards.

Coagulation and flocculation tests were conducted using two sets of test jars operating in parallel, with a control jar in each set. During every sampling event, duplicate samples were withdrawn from each jar. The results of the duplicate metals analyses from each sampling event were averaged to obtain the final metal concentration for each jar. Final metal removal efficiencies were determined by averaging metal removal efficiencies of the two test jars. This was compared with the metal removal efficiency of the control sample.

Limits of Detection and Quantification.
Throughout the study, limits of detection (LOD) and limits of quantification (LOQ) were determined for each metal during each ICP run. Sufficient matrix blanks (a minimum of 7 per run) were analyzed to determine the LOD/LOQ for each metal. The average LODs and LOQs for the ICP analyses over the duration of the study are reported in Table 2.

Metals Solutions. The metal stock solutions were prepared by dissolving dried analytical-grade nitrate salts of the metals of interest in deionized >18 Mohm resistivity water. The solutions were preserved by adding 2 mL of concentrated nitric acid per 1000-mL flask. For metals analyses, duplicate 10-mL aliquots of solution were withdrawn, filtered, and preserved, as detailed above. The average metal concentration of each stock spiking solution is presented in Table 3, and the initial concentrations of spiked raw wastewater solution can be found in Table 4.

General Jar Testing Procedures. The jar test apparatus used in the current study was a Phipps and Bird model 7790-400 (Phipps and Bird, Richmond, Virginia). To minimize metal sorption and metals contamination, jar tests were conducted with 2-L polypropylene beakers fitted with acrylic plastic baffles. Jar tests were conducted as described in Figure 1.

Selection of Optimum Operating Parameters.
Impeller Speed and Power Input. A mean velocity gradient of 411 second[-1] and corresponding range of velocity gradient-time product (*GT*) between 20 000 and 50 000, suggested by Clark and Stephenson (1999) for ferric chloride, was chosen

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Table 4—ICP analysis results of jar tests.

Samples	Chromium	Copper	Lead	Nickel	Zinc
Metal concentration in raw wastewater after spiking before coagulation (µg/L)	75.93	112.70	85.24	329.80	476.84
Metal removal after coagulation (%)	92	79	95	17	57
Metal removal (control) (%)	34	35	20	7	23
Improvement in metals removal over control (%)	270	225	475	242	247

Raw wastewater → Temperature and pH were measured → Two 10ml samples taken for ICP analysis

Raw wastewater divided into 3 samples of 2L each of identical consistency

Temperature and pH were measured

Spike two samples with 1 ml each of the metal spiking solutions. Third jar is kept as control → Two 10ml samples from each jar taken for ICP analysis

40 ppm Ferric Chloride was added to each jar and the samples were rapid mixed at 160 rpm for 1 minute

After the rapid mix, the stirrers were stopped and 0.5 ppm anionic polymer was added to each jar

The samples were stirred at 20 rpm for 25 minutes for flocculation

After 25 minutes, the stirring was stopped and the samples were allowed to settle for 25 minutes → Temperature and pH were measured → Two 10ml samples from each jar at a depth of 5 cm

Figure 1—Flow chart procedure of jar test experiments (0.5 ppm = 0.5 mg/L).

Table 5—Jar test operating parameters.

Type of mixing	G (second $^{-1}$)	GT	Selected G (second $^{-1}$)	r/min	Selected GT	Mixing time (minutes)
Rapid mixing	411	20 000 to 50 000	411	160	24 660	1
Slow mixing	10 to 60	30 000 to 60 000	20	20	30 000	25

as the initial jar test power input parameter during rapid mixing. From the velocity gradient plot for a 2-L sample with stators at 20°C (Camp, 1968), the mixing speed for a mean velocity gradient of 411 second $^{-1}$ was found to be 160 r/min. The value of GT was calculated to be 24 660 for a mixing time of 1 minute, which was within the desired range. For flocculation, the mean velocity gradient was selected as 20 second $^{-1}$, and the value of *GT* was selected as 30 000, based on design recommendations (AWWA and ASCE, 1997). This value of velocity gradient was plotted on the 20°C curve on Camp's velocity gradient calibration curve, and the slow mixing speed was selected as 20 r/min. The slow mixing time of 25 minutes was calculated from the value of *GT* and velocity gradient.

Settling Time. The optimum settling time was determined by monitoring TSS. The objective of this experiment was to determine the time beyond which the removal efficiency showed no significant increase compared with the time required for settling. Optimum settling time was determined using the jar test procedure described previously. Jar 1 was dosed with 40 mg/L (40 ppm) FeCl$_3$ and 0.5 mg/L (0.5 ppm) anionic polymer; jar 2 was dosed only with 40 mg/L (40 ppm) FeCl$_3$; and jar 3, the control, received no chemicals. Jar tests and sampling were conducted as described previously. In addition, upon completion of the slow mixing phase, samples were extracted from each jar at a depth of 5 cm below the water level, at regular time intervals, for 85 minutes. The TSS of each sample was then measured, using the methods described below, and TSS removal efficiencies at each sampling event time were

calculated and plotted. The time beyond which the removal efficiency showed no significant increase was adopted as the optimum settling time for all subsequent jar tests.

A summary of the operating parameters selected for subsequent tests is presented in Table 5. After operating parameters and settling time for rapid and slow mixing were established, the optimization of chemicals and chemical doses for metals and TSS removal was undertaken using jar tests.

Chemicals and Dosing Procedures. The coagulants chosen

for comparison tests were industrial-grade 44% FeCl$_3$, with specific gravity 1.4662 at 20°C (68°F) from Kemiron Pacific Inc. (Mojave, California), and laboratory-grade alum [Al$_2$(SO$_4$)$_3$ 14H$_2$O]. An- ionic polymer was selected as the flocculant. Upon selecting the chemicals, the optimum dose was determined by comparing suspended solids removal efficiencies at various chemical dosages.

Table 6—Selection   of coagulants.

Jar #	Alum (mg/L)	Jar #	FeCl$_3$ (mg/L)
1	20	5	20
2	30	6	30
3	40	7	40
4	50	8	50

This experiment compared the TSS removal efficiencies of alum and ferric chloride at various dosing concentrations. Jars were dosed with alum and ferric chloride concentrations of 20, 30, 40, and 50 mg/L, and the removal efficiencies were compared. The chemicals dosing regime is summarized in Table 6.

Upon selection of ferric chloride over alum for in-depth study, the optimization of ferric chloride and polymer doses was achieved by jar tests, during which, the concentration of one chemical was varied, while the concentration of the other was kept constant.

To optimize the coagulant dose, ferric chloride doses ranging from 20 to 50 mg/L (20 to 50 ppm) were added to four samples of wastewater and rapid-mixed for 1 minute at 160 r/min. A fifth control sample was not dosed with ferric chloride. Anionic polymer was then added to all five jars, to produce a polymer concentration of 0.5 mg/L (0.5 ppm) in the wastewater. The jars were flocculated at 20 r/min for 25 minutes, followed by a settling time of 25 minutes. A summary of experimental parameters for coagulant dose optimization is presented in Table 7. Duplicate samples were withdrawn from each jar for TSS analysis. Polymer dose was optimized by varying the concentration of the anionic polymer in the wastewater within the range 0.25 to 0.75 mg/L (0.25 to 0.75 ppm), while the concentration of ferric chloride was kept constant at 40 mg/L. In addition, jar tests dosed only with polymer were conducted to determine the efficiency of the polymer without coagulant chemicals. The dosage regime is presented in Table 8.

Table 7—Selection of coagulant dosage.

Jar #	Concentration of $FeCl_3$ (mg/L)	Concentration of polymer (mg/L [ppm])
1	20	0.5 (0.5)
2	30	0.5 (0.5)
3	40	0.5 (0.5)
4	50	0.5 (0.5)
5	Control	0.5 (0.5)

All jars were spiked with 1 mL of each metal spiking solution. Replicate jars were run in parallel, and a third control jar received no chemicals.

Coagulation with ferric chloride followed by flocculation with anionic polymer was conducted, with operating parameters as specified previously. The temperature and pH of the wastewater before and after chemical treatment were determined using an Accumet model-15 pH meter (Accumet Engineering Corporation, Hudson Massachusetts).

After sedimentation, two 10-mL samples were extracted from each jar for metals analysis by ICP, as described previously.

Table 8—Selection of polymer dosage.

Jar #	Concentration of $FeCl_3$ (mg/L)	Concentration of polymer (mg/L [ppm])
1	40	0.25 (0.25)
2	40	0.5 (0.5)
3	40	0.75 (0.75)
4	nil	0.25 (0.25)
5	nil	0.5 (0.5)
6	nil	0.75 (0.75)

Results and Discussion

The raw wastewater temperature range was 20 to 23°C and the pH range was 6.8 to 7.0. Throughout the experiments, no significant temperature change was observed, and only a slight pH reduction, with a minimum pH of 6.5, was recorded. Therefore, it was concluded that pH and temperature had no significant influence on metals speciation and that the observed metal removal was predominantly the result of coagulation and flocculation caused by the addition of chemicals and mixing.

Jar tests conducted to optimize the settling time yielded data on TSS removal efficiencies with time. The results, presented in Figure 2, show that ferric increased the rate of removal of TSS and decreased the optimum settling time, from 45 minutes for the control (no chemicals added), to 25 minutes for chemically enhanced sedimentation.

Hence, 25 minutes was selected as the settling time in subsequent jar test studies. Rapid-mix and flocculation speeds and times were calculated as described previously. The rapid-mixing speed of 160 r/min for period of 1 minute was calculated, from a recommended mean velocity gradient of 411 second $^{-1}$ and corresponding GT range between 20 000 and 50 000 (Clark and Stephenson, 1999). For flocculation, the slow- mixing speed was calculated as 20 r/min for a period of 25 minutes from a design mean velocity gradient of 20 second $^{-1}$ and GT value of 30 000 (AWWA and ASCE, 1997).
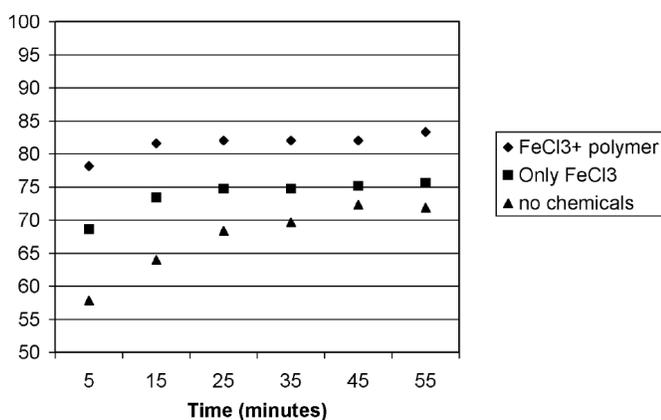
Figure 2—Selection of settling time.
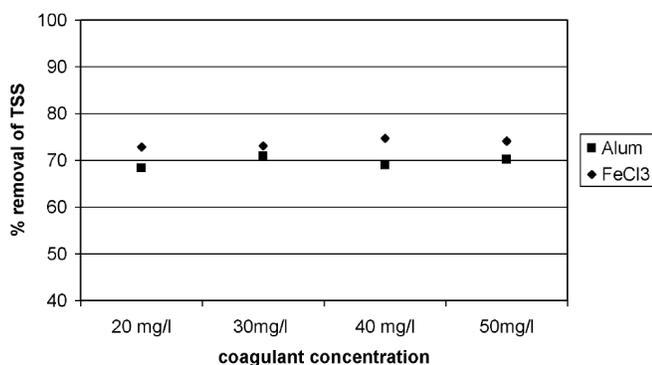
Figure 3—TSS removal efficiency with coagulant dose for ferric chloride and alum.

The TSS removal efficiency during jar testing was used to compare the performance of alum with ferric chloride. The results, presented in Figure 3, demonstrate that ferric chloride is

more effective for enhanced TSS removal than alum within the pH range 6.5 to 7.0. As a result, ferric chloride was selected as the coagulant in subsequent experiments.

The effect of polymer addition on the effectiveness of ferric chloride for TSS removal was investigated by varying the doses of these chemicals. The ferric chloride dose was optimized by adding polymer at a fixed concentration of 0.5 mg/L, as recommended in the literature (Sedlak, 2005), while varying the ferric chloride from 0 to 50 mg/L. The results, presented in Figure 4, show that concentrations of ferric chloride of 30 mg/L or greater met the enhanced TSS performance goal of 80%. Ferric chloride concentration of 40 mg/L in conjunction with 0.5 mg/L (0.5 ppm) anionic polymer produced the maximum TSS removal efficiency of 83%.
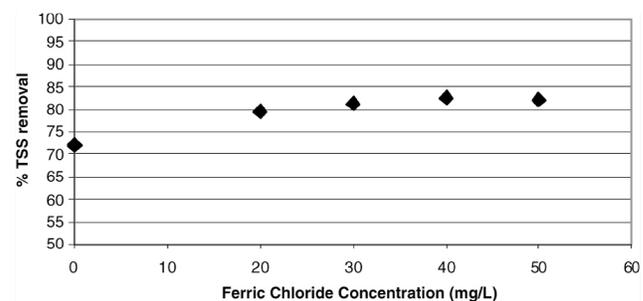

Figure 4—TSS removal efficiencies using ferric chloride with 0.5 mg/L polymer.

The optimum polymer dose was determined by evaluating TSS removal efficiencies for selected polymer concentrations ranging from 0 to 0.75 mg/L (0 to 0.75 ppm), with a fixed ferric chloride dose of 40 mg/L. The results of these tests are presented in Figure 5. The percentage of TSS removal for polymer with ferric chloride varied between 75 and 83%, with an optimum polymer dose of 0.5 mg/L. The control sample, dosing only polymer, shows that anionic polymer was not effective in the absence of coagulants. This was shown by a decrease in TSS removal from 72%, with no chemicals, to a minimum of 57%. A

polymer dose of 0.5 mg/L was selected, because it was effective, and similar values have been used at full-scale.

The summary of optimum operating parameters, chemicals, and their doses are as follows:

- Rapid mixing time and speed = 1 minute at 160 r/min;
- Slow mixing time and speed = 25 minutes at 20 r/min;
- Settling time = 25 minutes;
- Coagulant dose = 30 mg/L, ferric chloride; and
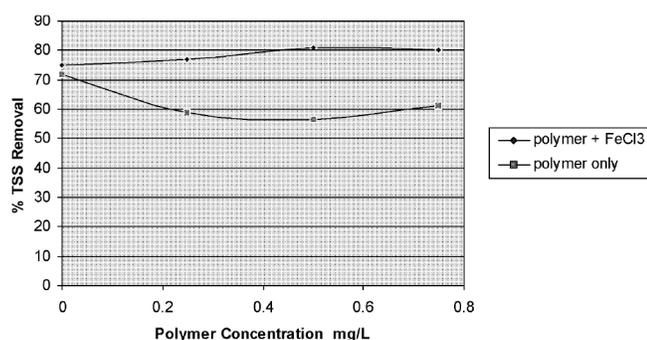- Flocculant dose = 0.5 mg/L (0.5 ppm) anionic polymer.

Figure 5—Comparison of TSS removal by anionic polymer at various concentrations with 40 mg/L ferric chloride.

The initial and final concentrations for test and control samples were determined as described in the Materials and Methods section. The percentage removal efficiencies for the metals of interest were calculated from the difference in concentration of metals in the liquid phase at the beginning and end of the jar test procedures.

On application of the optimized chemical-dosing regime, 40 mg/L $FeCl_3$ with 0.5 mg/L polymer, the overall percentage metals removal study resulted in removal efficiencies of 95% lead, 92% chromium, 79% copper, 57% zinc, and 17% nickel. The poor performance of CEPT for nickel capture was expected and can be explained

by its high solubility at the neutral pH range of the wastewater in this study, because nickel requires a pH>11 for effective removal from the aqueous phase (Patterson, 1985). Metals removal using CEPT was significantly higher than for traditional primary treatment, represented by the control. Table 4 presents a summary of initial metal concentrations, calculated percentage removal efficiencies of test and control samples, and percentage increased removal resulting from CEPT; comparison of percentage removal efficiencies of test with control samples is shown in Figure 6.
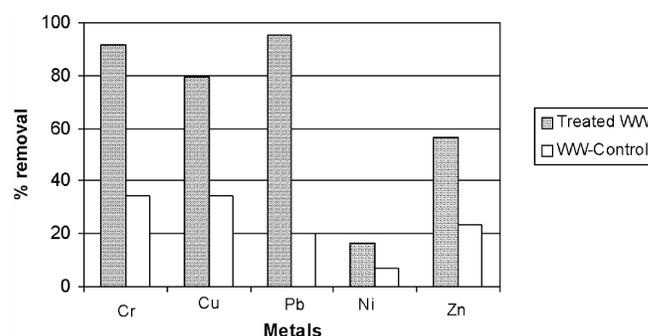

Figure 6—Comparison of chemically treated sample with control.

A comparison of the metal removal efficiencies obtained from the bench-scale study with other similar studies is presented in Table 9. The removal percentages for this study are substantially higher than percentages for the other studies. This is most likely the result of significantly higher influent concentrations in this study, which makes a high removal percentage more easily obtainable. In com- paring these studies, it appears that metals removal is site-specific, and jar testing should always be conducted until the metals removal process is better understood.

The allowable headworks loading based on activated sludge inhibition was calculated from the metal removal efficiencies of the present study and the Lynchburg Wastewater Treatment Facility using eq 1. The flowrate through the POTW was approximately 83 000 m^3/d (22 mgd).

Table 9—Comparison of bench-scale study with other studies.

Metal (total)	Average metal removal rate (%)			
	Bench-scale study	Ohlinger's study [a]	Lynchberg study [b]	U.S. EPA study [c]
Chromium	92	52.9	76.9	15
Copper	79	53.1	46.6	27
Lead	95	65.2	36.8	22
Nickel	17	297.5	25.4	14
Zinc	57	48.4	45.8	27

[a] Ohlinger, 1993.
[b] Lynchburg, 2000.
[c] U.S. EPA, 1987.

Table 10—Enhanced allowable headworks loading by metal removal using chemical treatment.

Metals	Minimum reported inhibition threshold [a] (mg/L)	Allowable headworks loading (kg/d [lb/d])		Increase in the allowable headworks loading (%)
		Present plant condition [b]	Enhanced metal removal [c]	
Chromium	1	360 (794)	1040 (2293)	85 (188)
Copper	1	156 (343)	396 (873)	70 (154)
Lead	0.1	13 (29)	166 (366)	528 (1164)
Nickel	1	111 (245)	100 (221)	24.5 (210)
Zinc	0.3	46 (101)	58 (128)	12 (26)

[a] Table 3.2 of U.S. EPA, 1987.

[b] The allowable headworks loading for present plant condition is calculated based on the existing metal removal efficiencies of Lynchburg Wastewater Treatment Plant, Virginia.

[c] The allowable headworks loading for enhanced metal removal is calculated based on the metal removal efficiencies obtained in this study.

The comparison of the allowable headworks loading given in Table 10 showed a considerable increase in the case of chromium (188%), copper (154%), and lead (1164%). Zinc also showed a 26% increase. Nickel did not show any increase in the allowable headworks loading, as all the studies showed low nickel removal during primary treatment at normal plant operating conditions.

Conclusions

Enhanced coagulation and flocculation by ferric chloride and anionic polymer can increase the dissolved metal removal efficiencies of chromium, copper, nickel, and zinc in the primary treatment in a POTW. This will increase the overall metal removal efficiency of the POTW or increase the allowable headworks metals loadings. The CEPT can also enhance the removal of TSS to more than 80%, thus reducing the total organic and solids loadings on the secondary processes.

The CEPT with alum and ferric chloride doses up to 50 mg/L caused only a slight decrease in the temperature and pH of the wastewater (0.5 pH unit maximum), which will not be detrimental to downstream processes. In addition, it implies that the mechanism for metals removal was coagulation and flocculation, caused by the addition of chemicals and mixing energy. Both alum and ferric increased the rate and extent of TSS removal and decreased the optimum settling time, from 45 to 25 minutes. Ferric chloride was slightly more effective than alum in TSS removal efficiency. Ferric chloride doses, equal to or greater than 30 mg/L with 0.5 mg/L polymer, met the 80% enhanced TSS goal. Only slightly increased removal efficiencies were observed at higher coagulant doses. A dose of 40 mg/L $FeCl_3$ with 0.5 mg/L produced the maximum TSS removal efficiency of 83%.

The percentage increases in metals removal by CEPT using 40 mg/L $FeCl_3$ and 0.5 mg/L polymer compared with the control were as follows: 475% lead, 270% chromium, 225% copper, 247% zinc, and 242% nickel.

Credits

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