Pilot-scale treatment of waste-water from carbon production by a combined physical–chemical process

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Abstract

BACKGROUND: Due to its strong colour, high concentrations of fluorides and chemical oxygen demand (COD_{Cr}) and large amount of suspended solids (SS), the waste-water from carbon production (WCP) seriously affects the stability of the circulating system of Guizhou Branch, Aluminium Corporation of China. In this paper, the performance of a pilot-scale (24 m³ d⁻¹) combined treatment plant, consisting of chemical precipitation, coagulation, and Fenton oxidation, for the treatment of WCP was investigated.

RESULTS: Lime precipitation and hydrated ferrous sulphate (HFS) coagulation, with polyacrylamide (PAM) as a coagulation aid, proved to be effective in the removal of colour (>70%), suspended solids (SS) (>90%) and fluoride (>80%) from the WCP. Subsequent Fenton oxidation combined with coagulation as a final treatment efficiently removed SS, F⁻, COD_{Cr}, dissolved organic carbon (DOC) and colour. The average total removal efficiencies of these parameters in the pilot-scale combined technology were as follows: SS = 98.8%, F⁻ = 95.7%, COD_{Cr} = 94.8%, DOC = 91.8% and colour = 98.3%, giving an average effluent quality: colour 24 (multiple), COD_{Cr} 168 mg L⁻¹, DOC 80 mg L⁻¹, F⁻ 38 mg L⁻¹ and SS 44 mg L⁻¹, consistent with the reusable water limits for the process.

CONCLUSIONS: The current experimental results and the economic evaluation suggest that the combined process could be advantageous and feasible for the treatment of WCP.

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Keywords: waste-water; carbon production (WCP); aluminium smelting; lime precipitation; coagulation; Fenton oxidation; decolouration; fluoride removal

INTRODUCTION

Water shortage and water pollution are global crises we are facing today. To minimize these problems, some factories that use large amounts of water have taken effective measures to reuse industrial water. The Guizhou Branch of the Aluminium Corporation of China, established an industrial water reuse system (50 000 m³ d⁻¹), in which all of the industrial water is suitably treated, and then reused in different manufacturing processes. Unfortunately, the waste-water from carbon production (WCP) seriously affects the stability of the circulating system due to its strong colour, high concentration of fluorides and chemical oxygen demand (COD_{Cr}) and large amounts of suspended solids (SS).

Carbon, such as pre-baked anodes, is the main auxiliary material for the production of aluminium ingot. During the baking cycles, asphalt fume and fluorides emitted from the pre-baked anode production and sulphur dioxide (SO₂) produced from heavy oil combustion result in serious environmental problems. Much effort has been taken to treat asphalt fume and to remove fluorides and SO₂.^{1,2} Wet electrostatic collection is the traditional and effective method for purifying asphalt fume.^{3–5} Moreover, wet flue gas desulphurization (WFGD) technology is a well-established process for removing SO₂. The Guizhou Branch of the Aluminium

Corporation of China uses a wet electrostatic collection process. The waste-water produced from the wet scrubbers contains appreciable quantities of fluorides, metallic ions and organic compounds and so is not easily amenable to chemical or biological treatment.⁶ Moreover, because the WCP is circulated many times, it exhibits an intense dark colour (over 2000 multiples), high SS, high concentration of dissolved salts and highly fluctuating pH (6–10). Due to the complexity of the WCP, any single treatment

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method would be inadequate, and to date literature regarding WCP treatment has been scarce.

To meet the permitted value for reuse of WCP, it is necessary to develop cost-effective processes to remove the F^- , COD_{Cr} , SS and colour. Generally, there are several methods for removing fluoride, such as membrane, adsorption, chemical precipitation, and electrochemical coagulation.^{7–13} When the fluoride concentration is high, chemical precipitation of CaF_2 by the addition of calcium salt, such as $CaCl_2$ is commonly used.¹² However, the introduction of Cl^- would inevitably cause the severe corrosion of metallic pipelines and other equipment. The addition of lime or calcium hydroxide is a practical alternative to avoid this problem.¹³ Additionally, the formation of fine CaF_2 particles during precipitation increases the requirement for solid–liquid separation. Aluminium and ferric/ferrous salts, typically used as coagulants following calcium precipitation for the destabilization of CaF_2 precipitates, also contributes to the removal of fluoride. The effects of co-precipitation and adsorption reactions may occur in the lime precipitation/coagulation process.

Although chemical precipitation and coagulation are effective in removal of fluoride and SS, they are largely ineffective in removing COD_{Cr} , dissolved organic carbon (DOC) and colour. On the other hand Fenton oxidation has been demonstrated to be quite effective in treating different industrial waste-waters.^{14–24} Fenton oxidation tends to destroy the recalcitrant organic chemicals in the waste-water, resulting in the removal of COD_{Cr} , DOC and colour. Unfortunately, it is much too expensive to employ Fenton oxidation directly to treat the raw waste-water. Thus, a novel pilot-scale combined process, consisting of chemical precipitation, coagulation, and Fenton oxidation, was proposed in this study to treat the WCP. The aim was to produce an effluent consistent with the reusable water limits for the carbon works and even for the whole waste-water recycling system of Guizhou Branch of the Aluminium Corporation of China.

MATERIALS AND METHODS

The research was divided into two experimental phases. The first phase was laboratory studies including raw waste-water analysis, the optimization of lime precipitation and coagulation, the effect of Fe^{2+} and H_2O_2 dosage on COD_{Cr} removal, etc. Based on the laboratory results, in the second phase a pilot-scale system was constructed and was operated for two months to obtain the optimum parameters for the waste-water treatment engineering of WCP.

Materials

Hydrated ferrous sulphate ($FeSO_4 \cdot 7H_2O$, HFS), ferric chloride ($FeCl_3$), poly-aluminium chloride (PACl), hydrogen peroxide (H_2O_2 , 30% w/w), polyacrylamide (PAM), sulphuric acid (95%, w/w), calcium chloride ($CaCl_2$) and lime (CaO) of commercial grade were utilized in the experiments. Lime was prepared in the form of slurry (10%, w/w). HFS was also prepared as a 10% (w/w) solution and PAM as a 1‰(w/w) solution.

Batch experiments

To investigate the behaviour of fluoride removal by lime, experiments were performed in a 1 L conical flask. Appropriate amounts of lime slurry (10%, w/w) were added to the WCP and the slurries were continuously mixed with a Teflon-coated magnetic stirrer bar at room temperature ($25 \pm 0.5^\circ C$). After the reaction, small samples (typically 10 mL) were taken, filtered through a $0.45 \mu m$ membrane syringe filter, and analysed for fluoride.

Coagulation tests were performed using a Phipps and Bird six-paddle stirrer. HFS with PAM was used as coagulant. The procedure consisted of a 1 min rapid mix (200 rpm), 15 min slow mix (30 rpm), and a 30 min settling period. The F^- , COD_{Cr} , DOC, and colour of the water samples were then analysed.

Fenton oxidation experiments were conducted using 30% H_2O_2 and 10% $FeSO_4 \cdot 7H_2O$ solutions. The pH of WCP was adjusted using sulphuric acid (95%, w/w). Then, different dosages of H_2O_2 and $FeSO_4 \cdot 7H_2O$ were added to the 500 mL samples. Mixing at 120 rpm for 30 min followed by settling for 30 min was applied to the samples. After the reaction, lime slurry was added to the system to perform secondary coagulation and sedimentation, and then the COD_{Cr} , DOC, and colour of the supernatant water were analysed.

Pilot-scale system description

Figure 1 shows the schematic diagram of pilot-scale WCP treatment system with capacity of $24 m^3 d^{-1}$.

WCP from the sedimentation channel was first homogenized in an equalization tank, and then pumped into the chemical precipitation tank, into which the lime slurry was added by a metering pump. There the precipitation reaction of lime and F^- took place. After that, HFS solution was added to the system and the water was lifted to an inclined-board sedimentation tank. Then, the sludge was pumped into the sludge thickener, and the supernatant was circulated to the washing tower or to the acidified and equalization tank. Following the addition of Fenton reagent, the WCP was then treated by Fenton oxidation. This reaction was terminated by the addition of a lime slurry. Then, secondary coagulation and sedimentation were carried out as a

Figure 1. Flow diagram of the pilot-scale WCP treatment system: (1) equalization tank, $V = 5 m^3$; (2) chemical precipitation tank, $V = 1 m^3$; (3) coagulation and sedimentation tank, $V = 1 m^3$; (4) acidification and equalization tank, $V = 3 m^3$; (5) oxidation tank, $V = 2 m^3$; (6) second coagulation and sedimentation tank, $V = 1 m^3$.

final treatment. The main functions and design parameters for each unit are as follows:

- **Equalization tank:** the effective volume of the equalization tank is approximately 5 m³ and the hydraulic retention time (HRT) about 5 h.
- **Chemical precipitation tank:** lime slurry (10% w/w) and WCP are pumped into the chemical precipitation tank, and are mixed by a blade stirrer at 30 rpm. The effective volume of the chemical precipitation tank is approximately 1 m³ and the HRT is about 1 h.
- **Coagulation and sedimentation tank:** the effective volume of the sedimentation zone is approximately 1 m³ and the HRT is about 1 h. The coagulants used were hydrated ferrous sulphate (10%w/w) and polyacrylamide (PAM, 1‰).
- **Acidification and equalization tank:** the pH value of the WCP was maintained in the range 3.0 ± 0.5 using sulphuric acid (95% w/w) in the acidification and equalization tank. The effective volume of the equalization tank is approximately 3 m³ and the HRT is about 3 h.
- **Oxidation tank:** the effective volume of the oxidation tank is approximately 2 m³ and the HRT is about 2 h.
- **Secondary coagulation and sedimentation tank:** lime slurry was pumped into the effluent from the oxidation tank, and the Fenton oxidation reaction was also terminated. Concurrently, the tank has functions of coagulation, sedimentation, and sludge exclusion. The effective volume of the sedimentation zone is approximately 1 m³ and the HRT is about 1 h.

Analytical methods

The performance of the combined system was monitored by analysing the parameters: colour, F⁻, COD_{Cr}, DOC, SS, pH, and conductivity. All the samples were collected intermittently and analysed during experiments for about 2 months. COD_{Cr} was measured using a COD_{Cr} meter (Hachi, USA). The DOC concentration in water was measured by a multi N/C 3000 (Analytik Jena AG, Germany). SS was measured using the gravimetric method. The pH was measured with a digital pH meter (Hachi, USA). The waste-water colour was determined by the standard dilution multiple method. The UV/Vis spectra were recorded on a U-3010 UV/Vis spectrophotometer (Hitachi Co., Japan) in 10 mm quartz cuvettes. Conductivity was determined by a DDS-307 digital conductivity meter (Hachi, USA). Fluoride, sulphate/sulphite were determined by an ion chromatograph (Metrohm 861, Switzerland).

RESULTS AND DISCUSSIONS

Characteristics of WCP

The waste-water was obtained from the Carbon Plant of the Guizhou Branch, Aluminium Corporation of China located in the south-west of China. The raw water used in the laboratory scale experiments was drawn from the effluent of the sedimentation channel below the washing tower, and its characteristics are presented in Table 1, together with the limits for discharge and reuse in the washing tower. To avoid adverse effects on the quality of the whole industrial water reuse system the discharge limits from Carbon Production require that colour, F⁻, SS, COD_{Cr}, and DOC of the waste-water should be lower than 100 (multiple), 100 mg L⁻¹, 100 mg L⁻¹, 200 mg L⁻¹ and 100 mg L⁻¹, respectively. As for the water being recycled to the washing tower, the limits for fluoride and SS should be lower than 500 mg L⁻¹ and 240 mg L⁻¹, respectively.

Table 1. Characteristics of WCP

Parameter	Value	Reuse limits for washing tower	Discharge limits ^a
Colour (multiple)	1460	–	100
SS (mg L ⁻¹)	4200	240	100
COD _{Cr} (mg L ⁻¹)	3250	–	200
DOC (mg L ⁻¹)	1180	–	100
Sulphate (mg L ⁻¹)	23460	–	–
F ⁻ (mg L ⁻¹)	1370	500	100
pH	10.0	>9	–
Conductivity (mS cm ⁻¹)	41	–	–

^a Discharge limits for the wastewater from carbon production at the wastewater treatment system of Guizhou Branch of the Aluminium Corporation of China.

Under basic conditions the WCP was observed to exhibit a strong dark colour, that dramatically decolourized under acidic pH conditions (pH = 5.8). After being treated by anion exchange resin, the colour of WCP completely disappeared. The UV/Vis spectrum of the raw WCP (pH = 10.0), acidified WCP (pH = 5.8) and the anion exchanged WCP (pH = 13.0) were measured. The absorbance of these three samples in the visible light zone (>400 nm), exhibited no characteristic absorbance peak. In the UV zone (200–400 nm), however, some strong characteristic absorbing peaks appeared at 260 nm, 290 nm, 332 nm, and 362 nm, indicating the presence of aromatic compounds in WCP.^{17,25–26} These functional groups were the main factor contributing to the dark colour of WCP. Interestingly, the characteristic absorbing peaks mentioned above disappeared in the spectra of the anion exchanged WCP (pH = 13.0), which indicated that the aromatic compounds under basic conditions were mainly anionic species.

Chemical precipitation

A lime slurry (10%, w/w) was proposed to be used as precipitant for the removal of high concentrations of fluoride, and the removal efficiencies of colour and COD_{Cr} were also investigated (Fig. 2).

Figure 2. Fluoride, COD_{Cr} and colour removal efficiency at different lime dosages.

Lime slurry showed a good capability for removal of fluoride, colour, and COD_{Cr} , and more significant removal of fluoride was observed. The higher dosage of lime slurry did not lead to corresponding higher removal efficiency of these pollutants when the lime dosage was $>1 \text{ g L}^{-1}$. The lime dose at 1 g L^{-1} gave removal efficiencies of 81.1%, 42.5%, and 20.2% for fluoride, colour, and COD_{Cr} , respectively, with residual concentrations of fluoride 259 mg L^{-1} , colour 840 multiples, and COD_{Cr} 2594 mg L^{-1} . Thus, a lime dose of 1 g L^{-1} was applied in the pilot-scale WCP treatment system.

It was difficult to achieve a low concentration of fluorides through slurry lime precipitation, except by the addition of excess amounts of precipitant (i.e. slurry lime), although the theoretical solubility of fluorite in water (CaF_2) is 17 mg L^{-1} at 25°C .¹² However, with the high concentration of competing anions, the K_{sp} of CaF_2 was modified in the WCP system mainly due to the formation of soluble fluoride complexes and the salt effect. As a result, the solubility of CaF_2 is enhanced, with the consequent risk of reduced fluoride removal efficiency. Moreover, with $\text{pH} > 9.0$, another problem associated with calcium precipitation was that the particles of CaF_2 were too fine to be removed by sedimentation. Consequently, a coagulation unit was necessary.

Coagulation

HFS, FeCl_3 , PACI coagulants with PAM were applied to test the capability for WCP coagulation. The results indicated that they were all efficient for the removal of SS, but only contributed to the limited removal of COD_{Cr} and DOC (data not presented). In comparison, HFS exhibited the highest coagulation efficiency, resulting in the highest colour removal at pH values >9.0 . Additionally, HFS avoided the introduction of chloride into the circulating system. Based on this, HFS was chosen as the coagulant. Experiments were run during which HFS was applied at an increasing concentration while the pH was controlled >9.0 by using a lime slurry.

After lime precipitation at a dose of 1 g L^{-1} for 1 h, the combination of HFS and PAM were used as coagulants. As shown in Fig. 3, the removal efficiency of F^- , COD_{Cr} , DOC, and colour increased with higher dosages of HFS. For example, HFS at 1000 mg L^{-1} (with 5 mg L^{-1} PAM) led to a removal efficiency of 56.8%, 23.7%, 25%, and 52.4% for F^- , COD_{Cr} , DOC, and colour, respectively.

Figure 3. F^- , COD_{Cr} , DOC and colour removal efficiency at different HFS dosages.

The higher HFS dosages did not contribute significantly to an increase of the removal efficiency for F^- , COD_{Cr} , DOC and colour. Considering the problem of sludge treatment, the HFS dosage of 1000 mg L^{-1} was applied in the pilot-scale WCP treatment processes.

After chemical precipitation and coagulation, the residual effluent concentrations of F^- , COD_{Cr} , DOC and colour of the WCP were 112 mg L^{-1} , 1980 mg L^{-1} , 720 mg L^{-1} , and 400 multiples, which corresponded to the total removal efficiency of 91.8%, 39.1%, 38.9%, and 72.6%. This indicated that the combined process of chemical precipitation and coagulation was promising for fluoride removal. Unfortunately, the COD_{Cr} , DOC, and colour in the effluent were still above the required standard for the reusing system. Generally, these pollutants were mainly refractory compounds which were difficult to deal with by conventional processes. Advanced oxidation processes (AOPs) may be feasible for further treatment, among which the Fenton oxidation process appeared to be a potential and economical way to eliminate these pollutants. The Fenton oxidation process minimized the introduction of pollutants into the WCP, which were valuable for the stability of the reusing system.

Fenton oxidation and coagulation

Effect of pH on the COD_{Cr} and colour removal efficiency

The treatment efficiency of Fenton oxidation is highly pH dependent.^{15,17} It is believed that the pH value has to be in the acidic range to generate the maximum amount of hydroxyl radicals to oxidize the organic compounds. Research proved that the generation of hydroxyl radicals is slower in pH values >4 because of the formation of ferric-hydroxo complexes.¹⁷ However, Tekin *et al.*²⁷ report that no significant differences in treatment efficiency were observed within the initial pH range 3.0–4.5, so in this study, the removal of COD_{Cr} and colour was investigated within the pH range 2–4.5. With this pH range, the removal efficiency of COD_{Cr} generally increased to maximum values at $\text{pH} = 2.5$, after which there were no significant changes to pH 4, and then the removal efficiency decreased with pH values >4 . The optimum pH range for colour removal was found in the pH range 3–3.5. Quantitatively, the maximum removal efficiency of COD_{Cr} and colour was about 90% and 95%, respectively.

At low pH ($\text{pH} < 2.5$), the oxidization ability of Fenton's Reagent is quite poor in destroying the recalcitrant groups within the aromatic compounds.¹⁷ Consequently, the removal efficiency of COD_{Cr} and colour were limited. The removal efficiency started to decrease at pH 4, due to the increasing rate of auto-decomposition of H_2O_2 , deactivation of iron ion into iron oxyhydroxides, and the increased scavenging effect of $\cdot\text{OH}$ resulting in the decreased oxidation potential of $\cdot\text{OH}$.¹⁸ The results showed that high COD_{Cr} and colour removal efficiency could only be achieved effectively in a narrow pH range. It was better to keep the pH value in the range 2.5–3.5 for the treatment of WCP by Fenton oxidation. The aim in the water treatment process was to optimize the operational conditions to achieve maximum treatment efficiency while minimizing the use of chemicals such as acid and base for pH adjustment. Taking both COD_{Cr} and colour removal into consideration, pH 3.5 was chosen for the Fenton reaction in this study.

Effect of H_2O_2 dosage on the removal efficiency of COD_{Cr} and colour

To investigate the treatability and the optimal operational conditions for WCP effluent from the acidification process using Fenton reagent, two sets of experiments were performed on a

Figure 4. Effect of H₂O₂ dosages on COD_{Cr} and colour removal efficiency (Fe²⁺ 184 mg L⁻¹; pH 3.5).

laboratory scale to study independently the effect of initial Fe²⁺ and H₂O₂ concentrations at pH 3.5 and room temperature for practical and economic reasons.

Figure 4 shows the removal efficiency of colour and COD_{Cr} at different H₂O₂ dosages. With the H₂O₂ dosage increasing from 300–1500 mg L⁻¹, the COD_{Cr} and colour removal efficiency increased from 34.2–91.2% and from 22.5–95%, respectively. At higher H₂O₂ dosages, the removal of colour and COD_{Cr} showed no obvious increase, owing to the scavenging effect of H₂O₂ on •OH radicals, and so the optimum H₂O₂ dosage was 1500 mg L⁻¹.

Effect of Fe²⁺ dosage on the COD_{Cr} and colour removal efficiency

Figure 5 shows the effect of HFS dosage on COD_{Cr} and colour removal efficiency. It was observed that the removal efficiency of COD_{Cr} and colour increased with higher Fe²⁺ dosages, and the maximum removal of COD_{Cr} (91.6%) and colour (94.5%) was obtained with 184 mg L⁻¹ Fe²⁺. However, further increase in the Fe²⁺ dose gave no further increase in removal efficiency, mainly through the •OH being scavenged by the reaction with hydrogen peroxide and/or Fe²⁺ species as shown below:¹⁸

The Fe³⁺ formed can react with H₂O₂ as well as with •OH, regenerating the Fe²⁺ in solution, resulting in a decrease of the removal efficiency of COD_{Cr} and colour. The scavenging effect of high doses of Fe²⁺ on •OH radicals also contributed to the results in Fig. 5.

The concentrations of F⁻, COD_{Cr}, DOC, SS, and colour in the effluent from the Fenton oxidation/coagulation were 42 mg L⁻¹, 172 mg L⁻¹, 78 mg L⁻¹, 60 mg L⁻¹, and 20 (multiple) respectively, which satisfied the discharge and circulation limits for WCP.

Performance of continuous system and economic evaluation of this process

Design of the continuous pilot-scale system

Based on the batch study, a pilot-scale WCP treatment system with a capacity of 24 m³ d⁻¹ was established and operated continuously for about 2 months to evaluate its feasibility for the treatment of WCP. Figure 1 shows a schematic of the system. The

Figure 5. Effect of Fe²⁺ dosages on COD_{Cr} and colour removal efficiency (H₂O₂: 1500 mg L⁻¹; pH 3.5).

main operational parameters were: (1) chemical precipitation: lime slurry (10%, w/w) 10 mg L⁻¹, HRT 1 h; (2) coagulation: HFS 1000 mg L⁻¹, HRT 1 h; (3) equalization/acidification: HRT 3 h; (4) Fenton oxidation: Fe²⁺ 184 mg L⁻¹, H₂O₂ 1500 mg L⁻¹, HRT 2 h, pH 3.5.

Performance of the continuous system

Table 2 shows the steady decrease in the levels of these pollutants from each unit process. Similar to the results of the batch scale study, the chemical precipitation and coagulation process led to high efficiency of F⁻ and SS removal and Fenton oxidation significantly decreased the concentrations of COD_{Cr}, DOC and colour. The effluent concentrations of F⁻, SS, COD_{Cr}, DOC, and colour from the combined processes were: 38 mg L⁻¹, 44 mg L⁻¹, 168 mg L⁻¹, 80 mg L⁻¹, and 24 (multiple), respectively satisfying the discharge limits for the reusing system.

Economic evaluation of this process

The economic performance was evaluated based on the cost of chemical reagents used in this process (Table 3). The price of total reagents (US\$ per m³) is 2.661 US\$ m⁻³. H₂O₂ is the most expensive reagent and accounts for 53.7% of the total cost. Additionally, the cost of lime precipitation and primary coagulation is 0.558 US\$ m⁻³, and the Fenton oxidation and secondary coagulation is 2.103 US\$ m⁻³. The sludge generated in this process will be disposed of in the sludge disposal system of Guizhou Branch of the Aluminium Corporation of China and is only a very small addition to the disposal capacity. So sludge treatment and disposal was not considered in the economic evaluation. It should also be noted that the effluent from primary coagulation may be recycled as washing water to the washing tower, and the overall cost is acceptable in practice.

The results of the pilot scale study further demonstrated the feasibility of employing the combined process for the treatment of WCP in practice.

CONCLUSIONS

A combined WCP treatment system consisting of chemical precipitation, coagulation, and Fenton oxidation on a pilot-scale of 24 m³ d⁻¹ was studied and the performance of the system measured for about 2 months. The results showed that the average

Table 2. Pollutant reduction of WCP at each unit of combined system

	Raw WCP		Chemical precipitation/coagulation		Fenton oxidation/coagulation		Total removal
	Range	Mean	Range	Mean	Range	Mean	efficiency %
Colour(multiple)	1200–1600	1400	300–600	400	20–40	24	98.3
SS (mg L ⁻¹)	3000–5000	3530	77–156	97	38–70	44	98.8
COD _{Cr} (mg L ⁻¹)	2500–4300	3250	1800–3420	1960	140–278	168	94.8
DOC (mg L ⁻¹)	750–1200	980	550–878	730	65–148	80	91.8
F ⁻ (mg L ⁻¹)	600–1400	880	88–167	106	22–67	38	95.7

Table 3. Evaluation of the reagent cost for this process

Chemical reagent and dosages	Price (US\$ kg ⁻¹)	Cost (US\$ m ⁻³)
Lime slurry (10%, w/w; 10 kg m ⁻³)	0.043	0.430
FeSO ₄ · 7H ₂ O (1 kg m ⁻³)	0.114	0.114
PAM (5 g m ⁻³)	2.857	0.014
Cost of lime precipitation and primary coagulation		0.558
H ₂ O ₂ (30%) (5 kg m ⁻³)	0.286	1.430
FeSO ₄ · 7H ₂ O (0.9 kg m ⁻³)	0.114	0.103
H ₂ SO ₄ (5 kg m ⁻³)	0.114	0.570
Cost of the Fenton oxidation and secondary coagulation		2.103
Total cost		2.661

removal efficiencies of F⁻, COD_{Cr}, DOC, SS and colour were 95.7%, 94.8%, 91.8%, 98.8% and 98.3%, respectively, with average effluent quality of F⁻ 38 mg L⁻¹, COD_{Cr} 168 mg L⁻¹, DOC 80 mg L⁻¹, SS 44 mg L⁻¹ and colour 24 (multiple). The effluent quality was better than the standards for the reusing system established in the aluminium factory in Guizhou, Southwest China. From the results of the pilot-scale system and the cost evaluation, it can be concluded that the combined process can serve as an attractive solution for WCP treatment. Further research will focus on the mechanisms of the considerable synergistic effect on pollutants removal.

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