Feasibility and optimization of wastewater treatment by chemically enhanced primary treatment (CEPT): a case study of Huangshi

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ABSTRACT
Carbon and nutrients as well as suspended solids (SS) removal by chemically enhanced primary treatment (CEPT) were conducted in the Qingshan wastewater treatment plant in Huangshi, Hubei Province. Feasibility of this process for wastewater treatment were investigated in detail by comparing the removal performance of three inorganic chemical coagulants (polyaluminium chloride, polyaluminium ferric chloride [PAFC] and poly ferric sulfate) individual or couple with poly acrylamide, optimizing the conditions during CEPT by both single factor analysis and orthogonal test designs. The results of this study demonstrated that CEPT turned out to be an effective method for wastewater treatment, with PAFC as the optimal coagulant, which showed preeminent removal capacity for chemical oxygen demand, total phosphorus and SS. The optimal working condition could be at pH 7.0, settling time 15 min, and velocity gradient of 174.80 and 15.56 s\(^{-1}\) for mixing and reaction phase respectively. While the coagulant dosage depends on raw water attributes, which had a decisive effect on CEPT treatment performances. However, the three coagulants behaved poorly in nitrogen removal.

1. Introduction
Chemically enhanced primary treatment (CEPT), or advanced primary treatment (APT) refers to the process which applies chemicals, typically metal salts and polymers in the form of organic polyelectrolytes, for coagulation, flocculation and precipitation of particulate/dissolved solids.[1] The suspended particles clump together through the processes of coagulation and flocculation. The particles aggregates, or flocs, settle faster, thus enhancing treatment efficiency.[2]

In recent years, CEPT technology has been used at various wastewater treatment plants (WWTP), targeting at clarification of wastewater, phosphate removal, reduction in sludge volume, and increase in surface overflow rates.[1,3] Apart from carbon and nutrients, CEPT can also remove other contaminants, such as heavy metals,[4] polycyclic aromatic hydrocarbons (PAHs) [5] and helminth eggs [6] associated with particles. However, research conducted on the selection of chemicals for CEPT is scarce. The related parameters during this process depend on the primary objective of application.

Herein we conducted jar tests in a local WWTP in Huangshi City, Hubei Province to investigate the treatability of three kinds of chemicals coagulant and one kind of coagulant aid using CEPT technology. Conditions optimization was realized by single factor analysis and orthogonal test designs. The objectives of this study are to (1) select an optimal coagulant for CEPT process; (2) evaluate the influence of agitation, coagulation time, settling time, pH and dosage thus determining an optimal working conditions combination.

2. Material and methods
2.1. Raw water quality
The experimental plant is located in the Qingshan Lake WWTP (Huangshi, Hubei Province), of which the influent is dominant by domestic wastewater. The experiment was conducted during the winter, when there was little rain. However, there were still some fluctuations of influent wastewater (Figure S1). Raw wastewater used in our study was collected from the effluent of vortex grit chamber. Raw water quality was shown in Table 1. In the long run, it’s required that the effluent should meet the grade-1B criteria of discharge standard,[7] partly of which was shown in Table S1.
values 6.7 ~ 6.9 53 ~ 234 49 ~ 111

Table 1. Quality of effluent of vortex grit chamber.

| Parameters (unit) | pH   | COD (mg L⁻¹) | BOD₅ (mg L⁻¹) |
|-------------------|------|--------------|--------------|
| Values            | 6.7  | 6.9          | 5.3 ~ 234    |
|                   |      | 49 ~ 111     |              |

2.2. CEPT process

Regarding the aim of our study, the experiment was divided into two phases. Batch tests were applied to select an optimal chemical coagulant from polyaluminium chloride (PAC), polyaluminium ferric chloride (PAFC), poly ferric sulfate (PFS) (individual or couple with poly acrylamide [PAM]) during the first phase. At the second phase, parameters for coagulation were optimized by both batch and orthogonal tests.

Jar tests were performed on carbon and nutrients removal using a six-paddle stirrer. Each 1 L of raw wastewater of various concentrations was dosed with certain amount of coagulants (PAC, PAFC and PFS, respectively) with or without PAM (0.5 mg L⁻¹ PAM was dosed at phase 1 only), then rapidly mixed by predetermined mixing speed and time. After a slow mixing and quiet settling, the supernatant was taken at 2 cm below the water surface using a pipette to determine the residual carbon and nutrients concentrations.

2.3. Analytical methods

The analysis of water quality parameters in our study included chemical oxygen demand (COD), total phosphate (TP), suspended solids (SS), nitrogen (total and ammonia nitrogen included). Determination methods were adhered to those of the standard methods.[8]

3. Results and discussion

3.1. Coagulant selection

Batch experiments were carried out to investigate carbon and nutrients removal performance of three chemical coagulants, aiming to select an optimal coagulant.

3.1.1. COD removal

COD removal performance by individual chemical coagulant and couple with PAM at various dosages was present in Figure 1(A) and (B), respectively. The experiments were conducted at various initial COD from 60 to 167 mg L⁻¹ (average COD 105 mg L⁻¹). It’s obvious from Figure 1(A) that effluent COD reached the criteria for it’s always lower than 60 mg L⁻¹. In addition, PAFC exhibited outstanding removal capacity for COD, since the removal rate was 5.4–14.8% higher than that by another two coagulants. However, there was little discrepancy between removal performance of PAC and PFS.

As to remove COD (initial COD 93 mg L⁻¹) by couple coagulants with PAM, it was found difficult to meet the discharge standard, unless at higher dosages for certain coagulants (Figure 1(B)). It’s apparent that inorganic coagulant PAM could hardly contribute to COD removal when coupling with coagulants, unless for PFS at dosage higher 20 mg L⁻¹. To obtain effluent reaching criteria, the best combinations were PAC couple with PAM (25 and 0.5 mg L⁻¹, respectively), PAFC (20 mg L⁻¹) and PFS (mg L⁻¹), respectively.

Given COD removal performance described above and characteristics of chemical coagulants, the optimal coagulant combination for our study was selected as PAFC, for its great COD removal capacity as well as its non-toxic property. These results were in accordance with previous research,[9–11] which told an excellent capacity for PAFC as a coagulant. Aguilar et al. [12] illustrated that PAM could aid coagulation by accelerating settling speed of colloidal particles for its large molar and electric density, which resulted in a slight increase of COD in slaughterhouse wastewater. Ghafari et al. [13] revealed that there existed an optimal dosage for PAC, both higher or lower dosage resulted in decrease of removal rate. It’s been verified that PFS could act as an excellent coagulant for water treatment.[14] Besides, PAM has been acknowledged as a toxic chemicals even at concentration as low as several μg L⁻¹.[15]

3.1.2. TP removal

TP removal by CEPT was shown in Figure 1(C). It presented that at an average TP concentration of 1.68 mg L⁻¹, the effluent was lower than 1 mg L⁻¹ (grade-1A) at various dosages from 10 to 35 mg L⁻¹. Besides, residual TP decreased sharply with the increase of coagulant dosage. PFS behaved best in TP removal, while PAC and PAFC were closed in removal efficiency. According to Hauduc et al. [16], the high TP removal rate was due to chemical phosphate removal by ferric and aluminum ions co-precipitation.

There were a few discrepancies when couple with PAM for PAC, PAFC and PFS (data not shown). Therefore, PFS was the optimal coagulant for TP removal in our study.

3.1.3. SS removal

Figure 1(D) revealed SS removal by CEPT at an initial SS 134 mg L⁻¹. It’s apparent that over 90% of SS was removed for three coagulants at various dosages. In addition, the removal rate increased with higher dosage. Large flocs and nice settling performance were observed during the treatment process by PAC, PAFC and PAS. All three coagulants were ideal for SS removal in our study. According to previous studies,[13,14] these coagulants aided to coagulation and settling process and led to low effluent SS.

3.1.4. Nitrogen removal

TN and NH₄⁺–N removal by CEPT were illustrated in Figure 1(E). It could be seen that both TN and NH₄⁺–N had a poor removal rate by the three coagulants, since maximal removal rate was 22.6 and 7.2%, respectively.
However, the effluent could easily reach the criteria due to the low nitrogen loading of raw water. Therefore, the three coagulants were all suitable for our study. For TN removal, PAFC showed similar trend as PAC, while both were more effective than PFS especially at higher dosage. As for $\text{NH}_4^+$–N removal, the order was PAFC > PAC > PFS. It’s turned out that PAFC was most suitable for nitrogen removal in our study. It has been proven that nitrogen removal by coagulation only was somewhat ineffective, for the adsorption and meshing of nitrogen by coagulants was limited, which was always lower than 30 and 15% respectively.[17,18]

Regarding the removal performance and characteristics of coagulants, the optimal coagulant for our study was PAFC, which was used for further experiments.

### 3.2. Parameters optimization

#### 3.2.1. Single factor analysis

Pilot scale tests were conducted to investigate the effect of agitation intensity, coagulation time, settling time, pH and coagulants dosage on COD removal by CEPT (parameters variations were shown in Table S2). The results were presented in Figure 2.
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as for rapid mixing process, the increase of agitation intensity contributed to growth of flocs,[20] however, effluent COD remained unaffected when speed faster than 230 r min⁻¹.

Effluent COD at various coagulation time (both rapid mixing and slow mixing) decreased sharply with time increases (Figure 2(B)). Wang et al. [19] found that coagulation time was a vital factor for CEPT since longer time was more favorable for the growth of flocs and beneficial for complete contact and collision, which was also

It's apparent from Figure 2(A) that effluent COD increased with slow mixing speed overall (50.1–62.6 mg L⁻¹), while showing an opposite trend with rapid mixing speed (65.1–50.7 mg L⁻¹), though there still were some fluctuations. As a result, best COD removal was achieved at slow mixing speed 50 r min⁻¹ and rapid mixing speed 250 r min⁻¹, respectively. Combined with the morphological of flocs during experiments, it could be concluded that moderate agitation by slow mixing could aid to fulfill contact and collision, while slight mixing inhibited this process, intense mixing had an adverse effect due to its irreversible damage to flocs.[19]
in accordance with our observations. Given the COD removal, the optimal coagulation time for slow and rapid mixing was 11 min and 60 s, respectively.

Effect of settling time on COD removal by CEPT was shown in Figure 2(C). The effluent COD fluctuated around 30 mg L\(^{-1}\) and tended to be stable at dosage higher than 20 mg L\(^{-1}\). This was probably because the settling speed of large flocs was rather fast and this process could be completed within about 20 min.\(^{[21]}\) Therefore, 20 min was regarded as the optimal settling time for our study.

It could be seen from Figure 2(D) that removal performance was largely affected by raw water pH value. Effluent COD ranged between 79.6 and 46.8 mg L\(^{-1}\) with varying pH (4.96–8.77). Overall, an alkaline or neutral environment was more favorable for CEPT process. This was due to that metal ions in raw water precipitated in such environments, thus aid coagulation process by coagulant.\(^{[22]}\) That’s why flocs could be seen even without coagulants dosage in our study. Therefore, the original pH of raw water (6.82) was selected as the optimal pH.

In accordance with our results above, the effluent COD decreased with PAFC dosage. The criteria could be satisfied at a dosage of 25 mg L\(^{-1}\). So 25 mg L\(^{-1}\) was our optimal dosage. This result was also in agreement with that by Niu et al.\(^{[9]}\).

### 3.2.2. Orthogonal test design

Herein orthogonal experiments were carried out to obtain the optimal parameters combination for CEPT and the results were shown in Table 2.

During the first phase, a L\(_9\)\((3)^4\) orthogonal test was designed for optimal combinations of agitation intensity and coagulation time. Based on the responded effluent COD, the \(K, k\) and \(R\) values were calculated (Table 2, phase 1). As a result, the optimal combination was rapid mixing 270 r min\(^{-1}\) for 60 s, followed by slow mixing 45 r min\(^{-1}\) for 11 min. Apart from the slow mixing speed (higher than previous speed), this result was highly consistent with that by single factor test given above. This faster rapid mixing speed was also reasonable for intense agitation intensity led to complete mixing between coagulants and wastewater, thus contributing to CEPT process. In addition, experimental errors might also result in the discrepancy.

As for the optimization phase 2, a L\(_9\)\((3)^3\) orthogonal test design was conducted (Table 2, phase 2). Applying the same method as phase 1, the optimal combination drawn out was dosage 27.5 mg L\(^{-1}\), pH 7 and settling time 15 min. Compared with optimal values listed above (dosage 25 mg L\(^{-1}\), pH 6.8 and settling time 20 min) in single factor test, there showed some differences. It’s noted in accordance with our observations. Given the COD removal, the optimal coagulation time for slow and rapid mixing was 11 min and 60 s, respectively.

### Table 2. Orthogonal tests for CEPT optimization.

| Phases | Test no. | (A) Rapid mixing speed\(g\) | (B) Rapid mixing time\(h\) | (C) Slow mixing speed\(i\) | (D) Slow mixing time\(i\) | COD\(j\) |
|--------|----------|-----------------------------|---------------------------|---------------------------|---------------------------|-------|
| 1      | 1        | 230\(a\)                    | 55\(a\)                   | 45\(b\)                   | 9\(a\)                    | 59.395|
|        | 2        | 230                        | 60\(b\)                   | 50\(c\)                   | 11\(b\)                  | 44.69 |
|        | 3        | 230                        | 65\(c\)                   | 55\(d\)                   | 13\(c\)                  | 111.825|
|        | 4        | 250\(e\)                   | 55                        | 50\(f\)                   | 101.805                  |
|        | 5        | 250                        | 60                        | 55                        | 9                       | 111.02 |
|        | 6        | 250                        | 65                        | 45                        | 11                       | 93.79 |
|        | 7        | 270\(g\)                   | 55                        | 55                        | 11                       | 97.8   |
|        | 8        | 270                        | 60                        | 45                        | 13                       | 37.68  |
|        | 9        | 270                        | 65                        | 50                        | 9                       | 67.74  |
|        | K1\(d\) | 215.91                     | 259                       | 190.87                    | 238.155                  |
|        | K2\(d\) | 306.62                     | 203.22                    | 273.36                    | 251.31                   |
|        | K3\(d\) | 71.97                      | 86.33                     | 63.62                     | 79.385                   |
|        | k1\(e\) | 102.21                     | 64.46                     | 71.41                     | 78.76                    |
|        | k2\(e\) | 67.74                      | 91.12                     | 106.88                    | 83.77                    |
|        | k3\(e\) | 34.47                      | 26.66                     | 43.26                     | 5.01                     |
| Order  | C > A > B > D |

| Optimal combination | A3B2C1D2 |

| 2      | Test no. | (A) Dosage\(i\) | (B) pH | (C) Settling time\(i\) | COD\(j\) |
|--------|----------|-----------------|-------|------------------------|-------|
| 1      | 1        | 22.5\(f\)      | 6\(f\) | 15\(g\)                | 52.27 |
|        | 2        | 22.5           | 7\(g\) | 20\(h\)                | 44.53 |
|        | 3        | 22.5           | 8\(h\) | 25\(i\)                | 48.4  |
|        | 4        | 25\(i\)        | 6      | 20                     | 43.56 |
|        | 5        | 25             | 7      | 25                     | 50.335|
|        | 6        | 25             | 8      | 15                     | 48.4  |
|        | 7        | 27.5\(j\)      | 6      | 15                     | 38.72 |
|        | 8        | 27.5           | 7      | 15                     | 48.4  |
|        | 9        | 27.5           | 8      | 20                     | 48.4  |
|        | K1\(k\) | 146.17         | 141.325| 136.49                 | 95.365|
|        | K2\(k\) | 142.3          | 141.325| 144.23                 | 98.28 |
|        | K3\(k\) | 135.52         | 141.33 | 143.27                 | 91.84 |
|        | k1\(l\) | 48.72          | 47.108| 45.5                   | 48.08 |
|        | k2\(l\) | 47.43          | 47.108| 47.76                  | 48.08 |
|        | k3\(l\) | 45.17          | 47.11  | 47.76                  | 48.08 |
|        | R\(m\)  | 3.55           | 0.002  | 2.26                   | 48.08 |
| Order  | A > C > B |

| Optimal combination | A3B2C1 |

*Level 1; *Level 2; *Level 3; *\(K_i = \Sigma\) the amount of COD at level i; *\(k_i = K_i/3\); *\(R = \max k_i - \min k_i\); *Unit: r min\(^{-1}\); *Unit: sec; *Unit: min; *Unit: mg L\(^{-1}\).
that the settling time was 5 min less than that in previous test. It’s indicated that attributes of influent wastewater had a decisive effect on CEPT performance, since more suspended pollutants in this test led to larger flocs thus accelerating the settling speed. Besides, the dosage varied due to difference in raw water. Therefore, the dosage should be determined according to characteristics of influent. In general, it could reach the grade-1B at dosage 25 mg L$^{-1}$.[12]

Based on optimal by multiple factors tests, the velocity gradient (G) and the GT value were calculated and displayed in Table 3.[22] The velocity gradient was 174.8 and 45 s$^{-1}$ during the mixing and reaction phase respectively, close to 150 and 14 s$^{-1}$ by Haydar et al. [20].

## 4. Conclusions

Feasibility and optimization of low loading wastewater by CEPT was conducted in Qingshan Lake WWTP. Following conclusions could be drawn from the present study:

1. CEPT process turned out to be an effective method for wastewater treatment due to the removal capacity for SS, TP and nitrogen.
2. The optimal coagulant by CEPT for present work was PAFC.
3. PAM contributed less to removal performance by PAFC, PAC and PFS, however, the settling time could be shortened by 0.5 mg L$^{-1}$ PAM.
4. The optimal velocity gradient was 174.8 and 15.56 s$^{-1}$ for mixing and reaction phase, corresponding to GT values of 1.049 $\times$ 10$^{4}$ and 1.027 $\times$ 10$^{4}$, respectively.
5. The optimal pH was 7.0, settling time was 15 min, while the coagulants dosage depends on raw water quality.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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## References

[1] Mahmoud EK. Chemically enhanced primary treatment of textile industrial effluents. Pol J Environ Stud. 2009;4:651–655.
[2] Mahmoud EK. Application of cement kiln dust for chemically enhanced primary treatment of municipal wastewater. Desalin Water Treat. 2013;25–27:4698–4704.
[3] Xu GR, Yan ZC, Wang YC, et al. Recycle of alum recovered from water treatment sludge in chemically enhanced primary treatment. J Hazard Mater. 2009;2–3:663–669.
[4] Johnson PD, Girinathannair P, Ohlinger KN, et al. Enhanced removal of heavy metals in primary treatment using coagulation and flocculation. Water Environ Res. 2008;5:472–479.
[5] Murugesan K, Selvam A, Wong JW. Flocculation and dewaterability of chemically enhanced primary treatment sludge by bioaugmentation with filamentous fungi. Bioresour Technol. 2014;3:198–203.
[6] Exall K, Marsealek J. A coagulant survey for chemically enhanced primary treatment of synthetic CSOs. Water Air Soil Poll. 2013;214:1–9.
[7] EPA. Discharge standards of pollutants for municipal wastewater treatment plant (GB 18918-2002). Beijing: Standard Press of China; 2002.
[8] APHA. Standard methods for the examination of water and wastewater. Washington, DC: American Public Health Association (APHA); 2005.
[9] Niu X, Li X, Zhao J, et al. Preparation and coagulation efficiency of polyaluminium ferric silicate chloride composite coagulant from wastewater of high-purity graphite production. J Environ Sci. 2011;23:1122–1128.
[10] Zhang J, Yang T, Wang H, et al. Study on treating old landfill leachate by ultrasound-Fenton oxidation combined with MAP chemical precipitation. Chem Speciation Bioavailability. 2016;4:175–182.
[11] Comber SDW, Gardner MJ, Churchley J. Aluminium speciation: implications of wastewater effluent dosing on river water quality. Chem Speciation Bioavailability. 2005;17:117–128.
[12] Aguilar MI, Saez J, Llorens M, et al. Improvement of coagulation-flocculation process using anionic polyacrylamide as coagulant aid. Chemosphere. 2005;1:47–56.
[13] Ghaafari S, Aziz HA, Isa MH, et al. Application of response surface methodology (RSM) to optimize coagulation-flocculation treatment of leachate using poly-aluminum chloride (PAC) and alum. J Hazard Mater. 2009;2–3:650–656.
[14] Liang Z, Wang Y, Zhou Y, et al. Hydrolysis and coagulation behavior of polyferric sulfate and ferric sulfate. Water Sci Technol. 2009;6:1129–1135.
[15] Yu WZ, Liu HJ, Xu L, et al. The pre-treatment of submerged ultrafiltration membrane by coagulation-Effect of polyacrylamide as a coagulant aid. J Memb Sci. 2013;11:50–58.
[16] Hauduc H, Takacs I, Smith S, et al. A dynamic physicochemical model for chemical phosphorus removal. Water Res. 2015;73:157–170.
[17] Ryu HD, Cho YO, Lee SJ. Effect of ferrous ion coagulation on biological ammonium nitrogen removal in treating coke wastewater. Environ Eng Sci. 2009;12:1739–1746.
[18] Zhang HN, Gu L, Yu X. Pre-oxidation advances dissolved organic nitrogen removal in downstream coagulation. Fresen Environ Bull. 2012;21:460–467.
[19] Wang H, Li F, Keller AA, et al. Chemically enhanced primary treatment (CEPT) for removal of carbon and nutrients from municipal wastewater treatment plants: a case study of Shanghai. Water Sci Technol. 2009;60:1803–1809.
[20] Haydar SA, Ziz JA. Characterization and treatability studies of tannery wastewater using chemically enhanced primary treatment (CEPT)—a case study of Saddiq leather works. J Hazard Mater. 2009;2–3:1076–1083.
[21] Dai J, Jiang F, Shang C, et al. The impact of chlorine disinfection on biochemical oxygen demand levels in chemically enhanced primary treatment effluent. Water Sci Technol. 2013;68:380–386.

[22] Neupane DR, Riffat R, Murthy SN, et al. Influence of source characteristics, chemicals, and flocculation on chemically enhanced primary treatment. Water Environ Res. 2008;80:331–338.