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Study of Enteromorpha polysaccharides as a new-style coagulant aid in dye wastewater treatment

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ABSTRACT

Enteromorpha is one of the common fouling green algae, which has brought serious environmental problems in past years. This study was aimed to apply it in water treatment process. Enteromorpha polysaccharides (Ep) were used as a new-style coagulant aid to assess its effect on coagulation behavior and floc characteristics. Color removal was used to evaluate coagulation effects and floc properties were investigated by Photometric Dispersion Analyzer (PDA). Results showed that when Ep was used in combination with aluminum chloride (AC), color removal could be apparently improved, and the optimal solution pH ranged 6.0–8.0. The growth rate and average size of flocs formed by AC–Ep were larger than those by AC in steady-state after floc growth phase, and meanwhile the distribution of floc size had a wider range. Besides, floc recoverability could be significantly improved when Ep was used as coagulant aid.

1. Introduction

Textile dyes have synthetic origin and complex aromatic molecular structures, which make their decolorization or biodegradation difficult when discharged in the ecosystem. This kind of wastewater is a major source of industrial water pollution in developed countries (Lee, Chioi, Thiruvenkatachari, Shim, & Moon, 2006; Shi, Li, Wang, Feng, & Tang, 2007), and has attracted much concern because of its toxic aromatic intermediates and bio-recalcitrance properties (Joo et al., 2007; Tan, Qu, Zhou, Ma, & Li, 2009). Various methods such as granular activated carbon adsorption, chemical oxidation, coagulation-flocculation, electrochemical degradation, AOPs and combined AOP-biological treatment have been studied to treat dyeing wastewater (Abo-Farha, 2010; Al-Degs, El-Barghouthi, El-Sheikh, & Walker, 2008; He, Song, Zhou, Ying, & Che, 2007;Wang, Chen, Huang, Su, & Chang, 2008). Among others, coagulation is the most widely used method in developed countries due to its low cost and high color removal efficiency (Aboulhassan, Souabi, Yaacoubi, & Baudu, 2006; Gupta & Suhas, 2009). The most commonly used coagulants in dye wastewater treatment are Al (III) salts (Gao, Wang, Yue, Wei, & Li, 2007). However, there have been many drawbacks when they were applied in coagulation process. Recent epidemiological, neuropathological and biochemical studies suggest a possible link between the neurotoxicity of aluminum and the pathogenesis of Alzheimer's disease (Banks, Niehoff, Drago, & Zatta, 2006; Li, Zhou, Zhang, Wang, & Zhu, 2008; Polizzi et al., 2002). Therefore, it is necessary to decrease the dosage of traditional coagulants to reduce their negative effects. To achieve this purpose, many products, which are denominated as coagulant aids, can be used together with coagulants in water treatment process (Aguilar, Saez, Llorens, Soler, & Ortuno, 2009). In recent years, due to their advantages of biodegradability, safety to human beings and minimal second contamination, natural polymers have drawn great attention for future applications in water treatment (Divakaran & Pillai, 2002; Ozacar & Sengil, 2003).

Enteromorpha is distributed worldwide from the intertidal to the upper subtidal zones, which is one of the most common fouling green algae (Hayden et al., 2003; Lotze & Worm, 2002). As an opportunistic macroalgae, it can proliferate in a wide range of abiotic or biotic conditions. For the past decades, its large-scale blooms (the so-called "green tides") became more and more frequent due to global climate change and increasing eutrophication level in sea water (Hauxwell, Cebrián, Furlong, & Valiela, 2001). The outbreak of Enteromorpha has brought serious environmental problems, adverse public reactions and unpleasant odor, so local government had to spend much manpower and financial resources on cleaning it up every year. Currently, the usual way of Enteromorpha disposal is removing it from sea and then piling up in open air. As time passes, the piled up Enteromorpha become solid waste.

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Therefore it is of great significance to explore a way of reusing Enteromorpha with the aim of "treating waste with waste", but there has been little research on its reuse. The study by Xu and Lin indicated that the proportion of polysaccharides reaches 55.69% in dry matter (Lin, Zhu, Xu, Liu, & Jia, 2009; Xu, Huang, Yang, Wu, & Cao, 2003). In addition, according to the research by Qi et al. and Ray, molecular weight of Enteromorpha polysaccharides (Ep) ranges from 55 kDa to 511 kDa, which consists of xylose, rhamnose, galactose, arabinose and glucose, having the linkages of (1 → 4)-linked β-L-arabinopyranose (Qi, Mao, Gao, & Chen, 2012). Considering that Ep contains various substances with large molecular weight which can play positive bridging role in floc formation process, Ep was applied as a coagulant aid in dye wastewater treatment process. In this way, a new, cheap and non-toxic coagulant aid may be found, and a new solution to the Enteromorpha disaster can be provided.

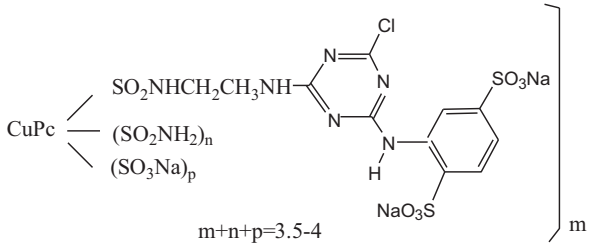
In this research, aluminum salts were selected as coagulant in dye wastewater treatment process, and Ep was used as a new kind of coagulant aid. The influence of Ep on coagulation efficiency and floc characteristic was studied through a series of contrast tests. Color removal efficiency was investigated in terms of UV_{610} removal efficiency, and meanwhile zeta potential was measured in order to study the coagulation mechanism. Furthermore, the formation kinetics, breakage and re-growth properties of flocs before and after Ep addition were also studied.

2. Materials and methods

2.1. Chemicals and synthetic water

The chemicals used in this study included HCl, NaOH and $Al_2(SO_4)_3{\cdot}18H_2O$, and $AlCl_3{\cdot}6H_2O$, which were all purchased from Sinopharm Chemical Reagent Co., Ltd., Beijing. All reagents used were of analytical grade. Deionized water was used to prepare all solutions.

The dye used in this paper was Reactive blue 14 (K-GL), which was obtained from Jinan No. 2 Textile Dyeing Mill, China. Its structural formula is shown below:



The synthetic dye wastewater was prepared by adding 0.1 g dye powder in 1.0 L tap water and its concentration reached 100 mg/L which was close to that in actual printing and dyeing wastewater (Hauxwell et al., 2001). The characteristic wavelength for this synthetic dye water was determined by a spectrophotometer (TU-1810, Pgeneral Instrument Co., Ltd., Shanghai, China). Results showed that the maximum absorbance wavelength was 610 nm. The relationship between the maximum absorbance and dye concentration was linear, which constituted the basis for conversion of absorbance value into an "equivalent" dye concentration. Therefore, color removal efficiency can be calculated by comparing the absorbance values of the treated wastewater with that of original dye wastewater (Wei, Gao, Yue, & Wang, 2009).

2.2. Coagulants

The coagulants – AS and AC ($Al_2(SO_4)_3{\cdot}18H_2O$ and $AlCl_3{\cdot}6H_2O$; analytic reagent), were purchased from Sinopharm Chemical Reagent Co., Ltd., Beijing, China. AS or AC solution with an alum concentration of 5.0 g/L, was prepared by dissolving it in deionized water respectively.

Fresh Enteromorpha was gathered from the No.1 Bathing Beach of Qingdao, China. The coagulant aid – Ep was prepared as follows: (1) cleaned Enteromorpha was stove dried at the constant temperature of 70 °C for 6 h; (2) dry sample was shattered into powder by magnetic crusher and then passed through a 100 meshes sieve; (3) screened Enteromorpha and deionized water were mixed at the mass ratio of 1:75 and then heated in water bath for 4 h at the constant temperature 90 °C; (4) the mixture was centrifugalized for 20 min at a speed of 5000 r/min and then the supernatant was concentrated by rotary evaporators; (5) purified Ep was obtained by freeze-dried after alcohol precipitation of concentrated liquor.

According to Gao et al., when organic polymer was used as coagulant aids, the best results were obtained when the polymer was added after the addition of the primary coagulant (Gao et al., 2007). In this comparative experiment, alum coagulants were added firstly at the start of rapid mixing phase (200 rpm), followed by Ep after 30 s. This dual-coagulant was denoted as (AS-Ep or AC–Ep). The dosage of AS or AC was calculated as mg/L of alum, and the dosage of Ep was calculated as mg/L.

2.3. Jar-test

Standard jar tests were conducted at room temperature (20 ± 1) °C. Coagulation experiments were conducted by a jar-test apparatus (ZR4-6, Zhongrun Water Industry Technology Development Co., Ltd., China) under different coagulant dosages of alum and Ep. During the rapid stirring at 200 rpm ($G = 51.6\ s^{-1}$), predetermined amount of coagulant was dosed to obtain a certain alum and Ep concentration. The doses of alum ranged from 10 mg/L to 30 mg/L, while Ep dose was 0.1, 0.3, and 0.5 mg/L, respectively. The coagulation procedure was as follows: rapid mixing (200 rpm) for 1.5 min followed by slow mixing (40 rpm) for 15 min and sedimentation for 20 min. After flocculation, supernatant samples were withdrawn from about 20 mm below the wastewater surface for absorbance measurement to analyze color removal efficiency. Furthermore, zeta potential was measured by JS94H micro-electrophoresis apparatus to analyze the coagulation mechanism.

2.4. Floc formation, breakage and re-growth

Flocs were formed by performing a series of jar tests. At the stage of floc growth, the mixing speed was adjusted to 40 rpm. After 15 min of slow growth phase, the effect of shear force was investigated by increasing mixing speed to 200 rpm on the jar tester for 5 min, followed by another slow mixing for 20 min for flocs to reform. In this study, Photometric Dispersion Analyzer 2000 (PDA2000) was used to monitor the formation of floc during coagulation process, and the typical curves which can be divided into five specific regions were shown in Fig. 1. During the coagulation periods, the suspension was continuously sampled by peristaltic pump (LEAD-1, Baoding Longer Precision Pump Co., Ltd., China). The inflow and outflow tubes were positioned opposite one another at a depth just above the paddle in the holding ports.

2.4.1. Floc formation

In the floc formation phase, three parameters were used to analyze the data collected by PDA2000 during the coagulation process: floc growth rate of the growth region, a time-weighted average steady-state ratio value and a time weighted ratio variance (TWV) of steady-state ratio value. These parameters of PDA 2000 have been reported in detail in some literatures. The slope of the growth

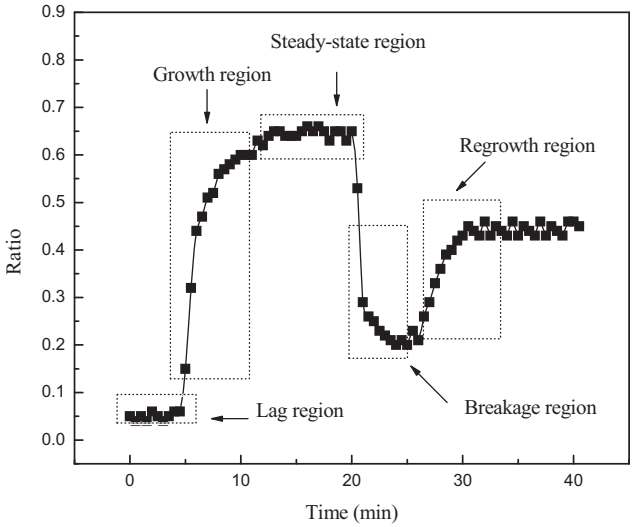


Fig. 1. Typical ratio curve as a function of coagulation time.

region indicated the floc growth rate which can be determined as (Wei et al., 2009):

$$\text{Floc growth rate} = \frac{\Delta \text{ratio}}{\Delta \text{time}} \quad (1)$$

In this study, the time-weighted average steady-state ratio value (denoted as Ratio) indicated floc size in the steady-state region, which was highly correlated with floc size and increased as flocs grew larger (Li, Zhu, Wang, Yao, & Tang, 2007). The parameter can be computed as (Pefferkorn, 2006):

$$\text{Ratio} = \frac{\sum_{i=1}^{N}(\text{ratio}_i \cdot \text{time}_i)}{\sum_{i=1}^{N}\text{time}_i} \quad (2)$$

The time-weighted ratio variance was computed using data from final steady-state portion of the ratio curve. It indicated the difference of floc size in steady-state region and can be calculated as follows (Hauxwell et al., 2001):

$$\text{Time-weighed variance(TWV)} = \frac{\sqrt{\sum_{i=1}^{N}[(\text{ratio}_i - \text{Ratio})^2\ \text{time}_i]}}{\left(\sum_{i=1}^{N}\text{time}_i\right)^2 \cdot \text{Ratio}} \times 100\% \quad (3)$$

2.4.2. Floc breakage and regrowth

Floc strength factor (S_f) and recovery factor (R_f) are well established parameters for describing floc strength and recoverability in different flocculated systems, and they can be calculated respectively as follows (Divakaran & Pillai, 2002; Li et al., 2007; Wei et al., 2009):

$$Sf = \frac{d2}{d1} \times 100 \quad (4)$$

$$R_f = \frac{d3 - d2}{d1 - d2} \times 100 \quad (5)$$

In the above formulas, d_1, d_2 and d_3 is the floc ratio of the steady phase before breakage, after floc breakage period and new steady phase after regrowth respectively. The strength factor as index properties of floc strength represents the ability to resist rupture, and larger values of strength factor indicate that the flocs are stronger than those with smaller strength factors. The recovery factor indicates recoverability of the flocs. Flocs with larger recovery factors generally show better recovery capacity after breakage.

3. Results and discussion

3.1. Effect of Ep on coagulation performance

Fig. 2 showed the color removal efficiencies as a function of coagulant doses. It can be seen that when AS or AC was used alone, the color removal efficiencies increased with the coagulant dosage increasing, which was in accordance with the increasing zeta potential. The maximum color removal (85% for AS coagulation system and 88% for AC coagulation system) was achieved at the alum dosage of 30 mg/L alum, when zeta potential reached −17 mV and −21 mV respectively. Pefferkorn suggested that if charge neutralization is the only path for coagulation, the zeta potential should be in excellent correlation with the coagulant dosage and optimal efficiency is achieved when zeta potential is close to zero (Pefferkorn, 2006). This indicated that charge neutralization is not the only mechanism in AS or AC coagulation system. Since the natural water was alkaline, significant precipitation of amorphous hydroxide would occur. Therefore, charge neutralization was likely to be achieved by adsorbed precipitate (Li et al., 2009; Pefferkorn, 2006). In this condition, coagulation was more affected by precipitate and the charge effects seemed less important. This also explained why efficient turbidity removal still occurred at low dosages, even though the zeta potentials were somewhat below zero.

Fig. 2 showed that the addition of Ep could improve the color removal effectively, but the zeta potential was below zero within the tested dosage range, and also decreased with the increase of Ep dose due to the negatively charged Ep (−35 mV to −40 mV). According to Pefferkorn's theory, multiple mechanisms other than charge neutralization occurred when Ep was used, such as adsorption/bridging mechanism. When alum salts were dosed firstly, they quickly adsorbed on the surface of the microflocs and effectively neutralized the negative charge, which resulted in weaker repulsion forces between the colloids. When Ep was dosed afterwards, the long carbon chains of the polysaccharide could absorb more suspension colloid particles and promote bridging effectively, which usually generated larger flocs with preferable settling velocity. In addition, the polar and unsaturated functional group of Ep can enhance the charged particles' adsorption effect. Therefore better coagulation efficiency could be achieved due to the addition of various polysaccharides. But when superfluous Ep was used, the coagulation efficiency decreased. As can be seen from the figure, AS-Ep and AC–Ep had the most apparent synergistic improvement in color removal when 0.5 mg/L Ep was used: the color removal rate of AS-Ep and AC–Ep exceeded 94% and 96% at the alum dosage of 25 mg/L, whereas the color removal achieved by AS and AC alone was only 85% and 88% respectively in the same condition. More dose of negatively charged Ep caused the zeta potential to increase to a higher absolute value (Fig. 2), which would result in stronger inter-particle repulsion. Therefore, the growth of flocs was restrained, and the coagulation efficiency was poor. The comparison of color removal efficiency in AS and AC coagulation system showed that, when AC was used, the color removal was higher and the synergistic effect between AC and Ep was more apparent. Consequently, AC was chosen in the following experiments as the optimal coagulant for the test water. Considering the coagulants cost and coagulation performance, the dosage of 25 mg/L and 0.5 mg/L for AC and Ep was selected as the optimal dosage.

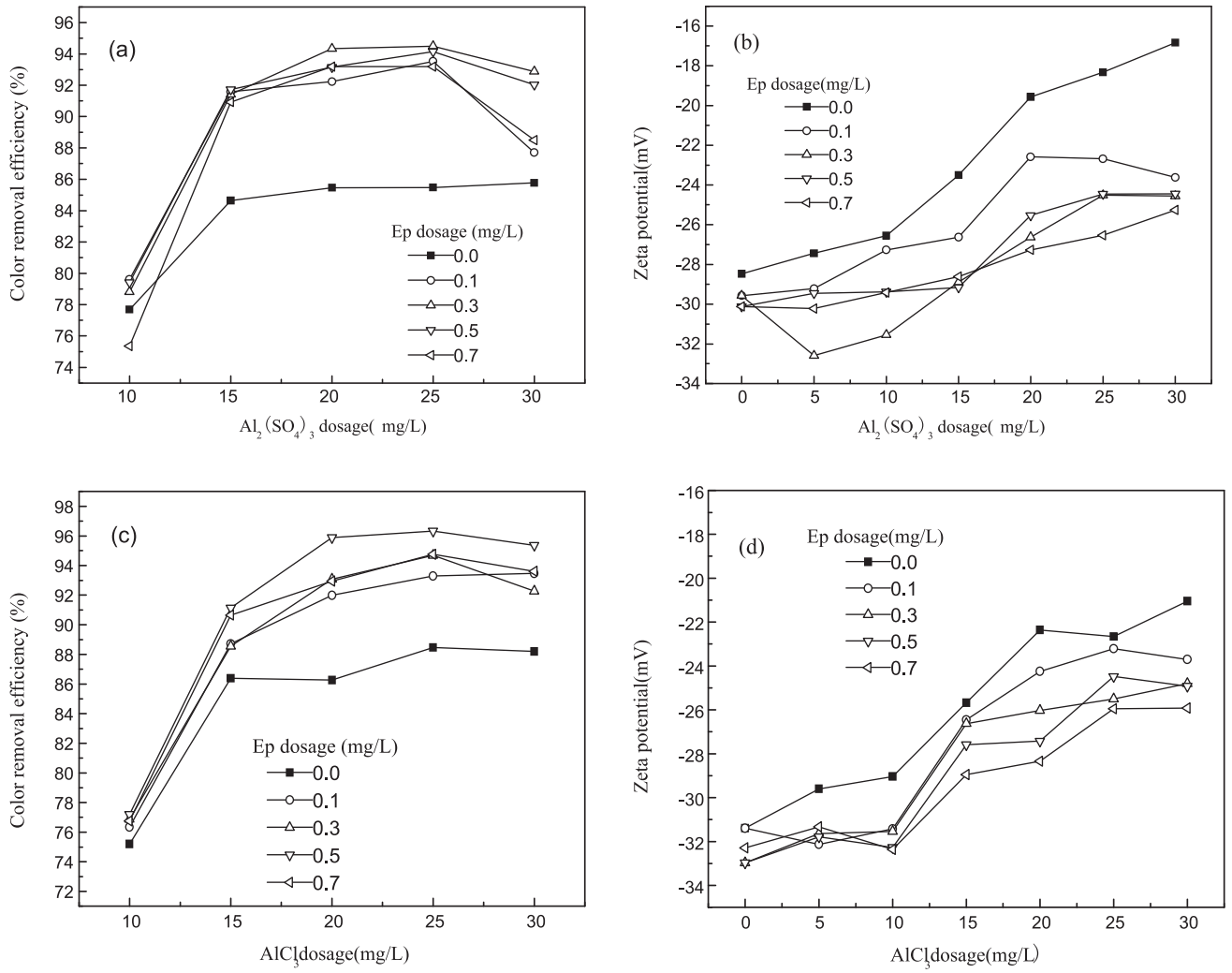


Fig. 2. Dosage effect of Ep on coagulation performance in alum salts system (a) AS color removal efficiency, (b) AS zeta potential and (c) AC color removal efficiency.

3.2. *Effects of pH on coagulation performance*

The initial pH of raw water was adjusted to 4.0–9.0 by additional HCl and NaOH. Fig. 3 showed that for both AC–Ep and AC, the suitable initial pH range was 6.0–8.0, which corresponded well with the reported optimums for AC (Shi, Li, Wang, Feng, & Tang, 2007). When AC was added to water, it rapidly dissociated to yield trivalent ions, which could hydrate to form aquometal complexes

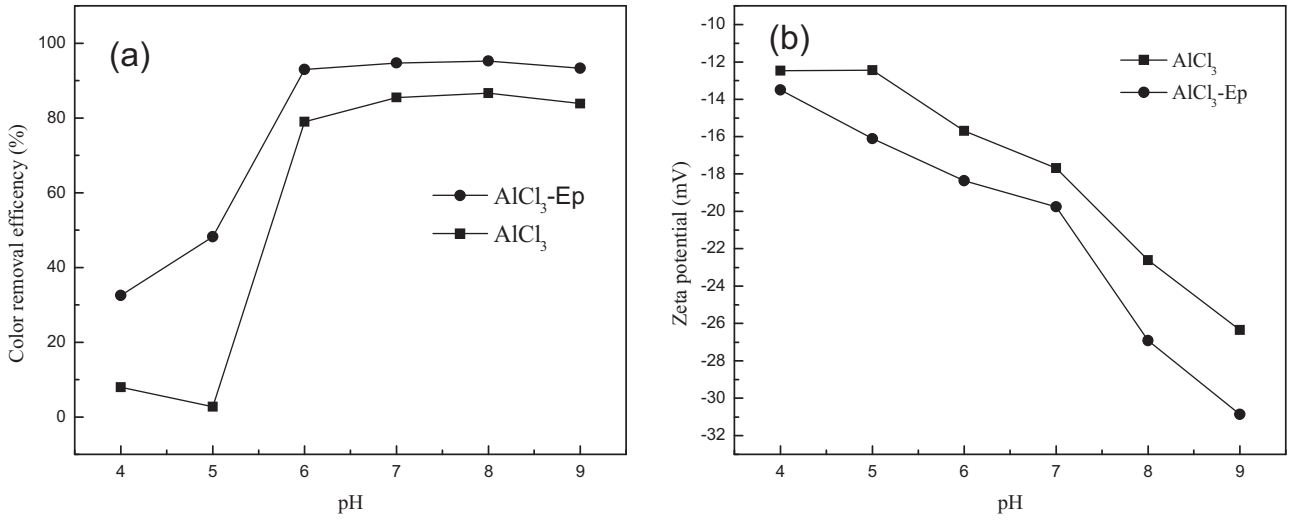


Fig. 3. pH effect on the coagulation performance.

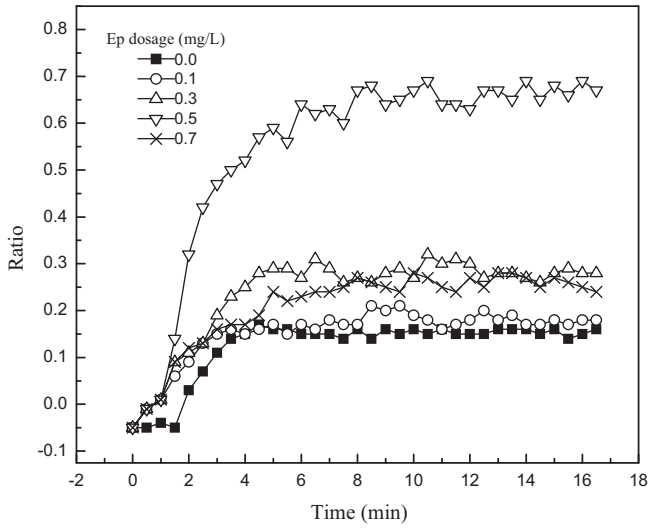


Fig. 4. The growth curves of flocs for different Ep dosages.

$Al(H_2O)_6^{3+}$. These complexes then underwent a series of hydrolytic reactions in which H_2O molecules in the hydration shell were replaced by OH^- to form a variety of soluble species such as $Al(OH)^{2+}$. These products are quite effective as coagulants as they adsorb very strongly onto the surface of most negative colloids (Li & Gregory, 1991). The solubility of $Al(OH)_3$ is minimal at a particular pH and increases as the pH increases or decreases from that value. In addition, charge on hydrolysis products and precipitation of metal hydroxides were both controlled by pH. Therefore, pH was an important criterion in the decolorization studies (Ray & Hogg, 2001). The optimum color removal in the alkaline pH range in this study was presumably due to adsorption onto hydroxide flocs.

Due to the coagulation aid effect of Ep, the coagulation performance of AC–Ep was better than that of AC within the whole pH ranges investigated. As indicated in Fig. 3(a), coagulation efficiency increased significantly with pH first, then showed a steady state, with the color removal of 96% and 88% at the optimum pH for AC–Ep and AC. It was found that zeta potentials of both AC and AC–Ep were all below zero under test pH range from 4.0 to 9.0 and decreased with increasing pH. The value of zeta became much lower when Ep was added at the same pH, as Ep was a highly negatively charged organic polymer. But the color removal of AC–Ep was always maintained in a higher level than that of AC, which could be attributed to macromolecular polysaccharide. Their long carbon chains could enhance the effect of bridge-aggregation and sweep-flocculation to generate flocs with larger size and better settleability. As a result, the color removal efficiency can be enhanced apparently when Ep was used.

3.3. *Effect of Ep on kinetics of floc formation*

Floc formation process in AC and AC–Ep coagulation system was monitored by PDA respectively. Fig. 4 shows the PDA monitor responses collected every 30 s and the results were plotted using the typical ratio obtained from the experiments. Compared with Fig. 1, the growth curves shown in Fig. 4 can be divided into lag region, growth region and steady-state region. That can be explained as follows: after the addition of coagulant, primary particles destabilize and come together to form small floccules which further aggregate to microflocs. During floc aggregation, the larger floc structure changes continually due to the flocs' internal bonds breaking under shear and reforming at more favorable points where the attractive force is greater or the repulsive force is lower; when a balance is reached between the rate of aggregation and the rate of breakage under a given shear condition, the process of floc formation is completed and the size of flocs reaches a steady plateau. As we can see from Fig. 4, the floc in the AC and AC–Ep flocculation process displayed a sharp increase in size during the first 5 min, achieving the largest Floc size, followed by a steady-state period during the next 10 min. According to the theory of Zhan et al., 2010, the sharp growth of Floc size in the first 5 min is likely due to the aggregation of particles and the stable phase indicated the balance between Floc growth and breakage.

Table 1
Growth characteristic of flocs under different Ep dosages.

Ep dosage (mg/L)	0.0	0.1	0.3	0.5	0.7
Ratio	0.16	0.22	0.28	0.65	0.27
Time to achieve steady state (min)	5.00	8.00	8.50	6.50	9.50
Growth rate (s^{-2})	0.03	0.03	0.04	0.10	0.03
TWA (%)	4.05	6.88	6.82	8.78	6.42

Three parameters (Floc growth rate, ratio and TWV) were obtained by the above mentioned Eqs. (1)–(3) and the results were shown in Table 1. As can be seen, it was apparent that Flocs in AC–Ep coagulation system had higher Ratio value and growth rate than those of AC. In practical engineering applications, a higher Ratio implied larger aggregate sizes. It was reported that larger particles generally settled down more quickly than smaller particles with similar density (Wei et al., 2009). So, as to AC–Ep, a short retention time coupled with larger Floc size formation can lead to smaller and more compact Flocculation and sedimentation units. For AC, aluminum hydroxide precipitates formed the primary particles of the Flocs. For AC–Ep, the initial microFlocs were formed due to the reaction of dye molecule with AC, and when Ep was dosed, microFlocs aggregated into larger ones due to the adsorption/bridging ability of polysaccharides. As they have high molecular weight and contain long chained structure, they offer a large number of available adsorption sites. The existence of adsorption and interparticle bridging between dye molecules and polysaccharides was due to the interaction of p-electron system of dyes and OH^- group of polysaccharides (Fig. 5(a)), which was first suggested by Yoshida et al. and then reviewed by Yin (Yin, 2010; Yoshida, Osawa, & Oda, 1964). Although the mechanism of coagulation with natural coagulant aid has not been extensively investigated, the presence of hydroxyl groups along the polysaccharide chain provided abundant adsorption sites. The polysaccharides in Ep were mainly xylose and rhamnose, the bridging effect of which between polysaccharide and dye molecule can be demonstrated in Fig. 5(b) and (c), which could generate larger Flocs with preferable settling velocity. Table 1 also showed that the maximum Ratio value and growth rate were achieved at Ep dosage of 0.5 mg/L. That result was consistent with the color removal efficiency. But the Floc size deceased when Ep dosage further increased, as well as Floc growth rate and color removal. This can be explained as follows: the bridge role of Ep led to the increase of aggregation at the initial aggregation. There were not enough macromolecule particles when Ep dosage was small, so the adsorption bridge effect would be enhanced with the increasing dosage of Ep. But all particles were positively aggregated and precipitated when Ep dosage was greater than 0.5 mg/L. The formed flocs may be covered by negative charges again due to superfluous addition of Ep. Consequently, the repulsion between particles led to unfavorable floc characteristic and coagulation efficiency.

The steady-state variance values (TWV) were also shown in Table 1. In general, a larger variance value indicates a wider range of floc size distribution, porous structure and low fractal dimension value. As can be seen, when Ep was used as the coagulant aid, the TWV was much larger than that of AC, which indicated that flocs produced in AC–Ep coagulation system gave a wider range of floc size distribution in the treatment of dye wastewater. It was

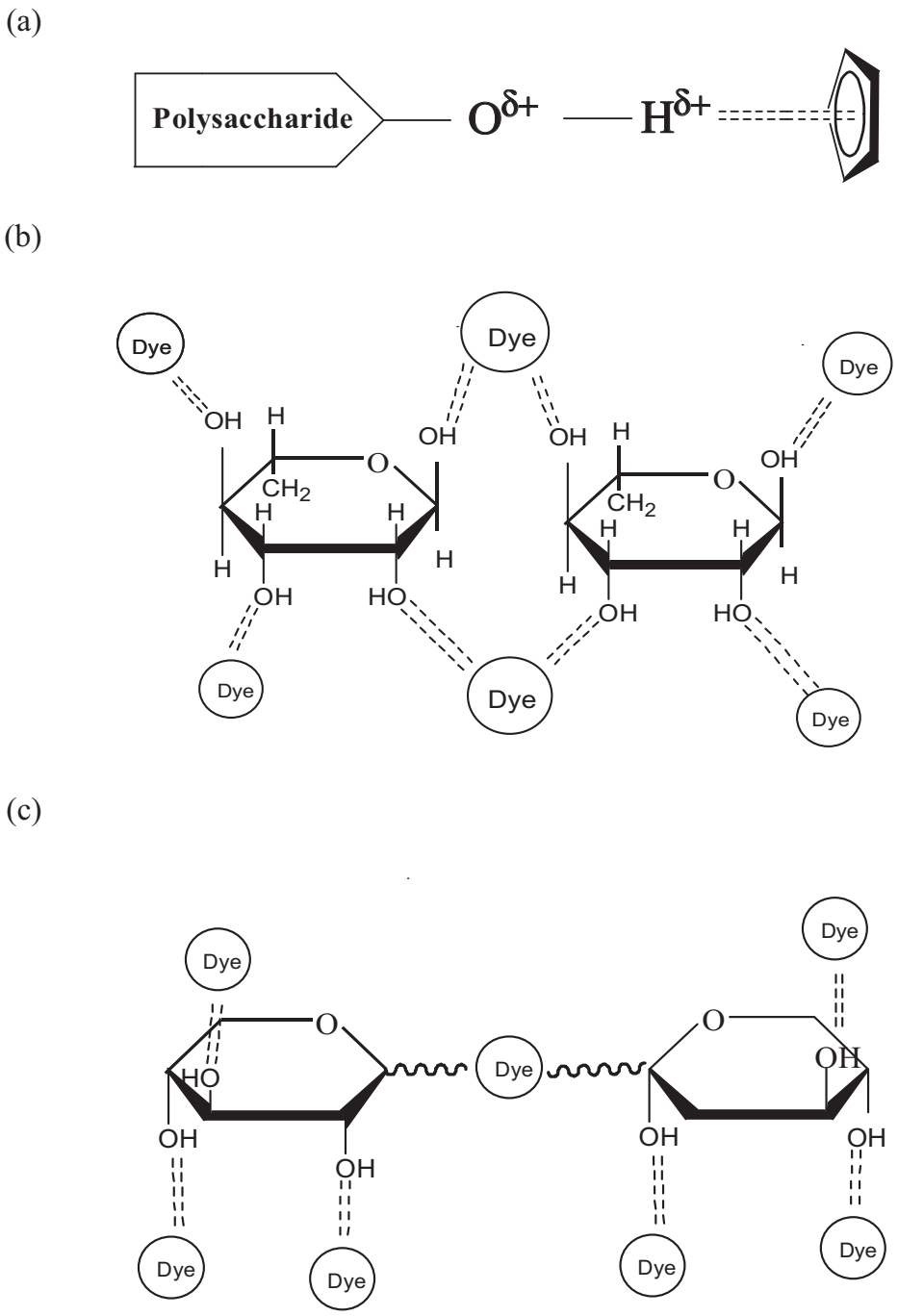


Fig. 5. Schematic representation of intermolecular interaction between dye molecule and hydroxyl group of polysaccharide.

consistent with the research of Hopkins and Ducoste who reported that flocs formed under sweep and bridging tended to have open structure. In contrast, charge neutralization created tighter and more condensed flocs with less variance in the distribution of floc size (Hopkins & Ducoste, 2003). This conclusion further confirmed that charge neutralization was not the mechanism of AC–Ep. In this case, AC–Ep produced flocs with more porous and open structure depending on its stronger bridging and sweep ability.

3.4. Effect of Ep on floc breakage and re-growth

Fig. 6 showed that the ratio value had a drastic drop the moment the shear was applied, and then had a gentle decrease. After the shear period of 5 min, the ratio of flocs was about 0.04 for AC. When Ep was used, the flocs sizes were 0.11, 0.15, 0.30 and 0.16 for 0.5 0.1 mg/L, 0.3 mg/L, 0.5 mg/L and 0.7 mg/L dosage, respectively. Once the original slow stir (40 rpm) was reintroduced, the floc began to re-grow. However, the floc could not re-grow to anywhere near their previous sizes in all conditions.

It can be seen from Table 2 that the floc strength factors produced by AC–Ep were in the range of 45%-50% in different Ep

Table 2
Strength and recovery factors of flocs under different Ep dosages.

Ep dosage (mg/L)	0.0	0.1	0.3	0.5	0.7
Strength factor (%)	26.24	47.84	49.97	49.01	46.41
Recovery factor (%)	18.39	40.76	57.94	58.99	27.02

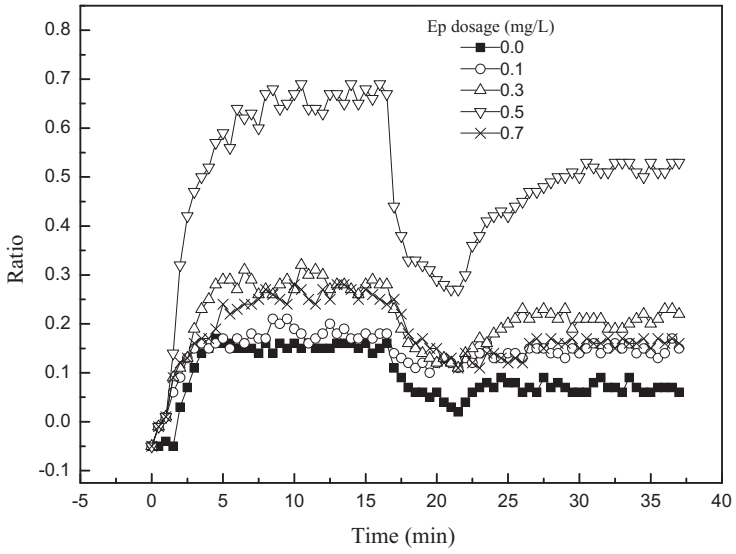


Fig. 6. The breakage and regrowth curves of flocs for different Ep dosages.

dosage conditions, but all the strength factor values were stronger than that of AC. It could be attributed to the bridging effect of polysaccharides in Ep. The result was in agreement with the conclusion by Aguilar et al. (Aguilar, Saez, Liorens, Soler, & Ortuno, 2003) who found that flocs generated by bridging were stronger than those generated simply by charge neutralization. It was suspected that the microflocs formed by AC were tightly connected by Ep molecules after Ep addition, which resulted in the increase of floc strength. It is just a hypothesis and needs further investigation. Table 2 also showed that when Ep was used as the coagulant aid, flocs formed by AC–Ep presented better reformation capacity than those by AC. For example, in the same dosage condition of AC, the recovery factor achieved 58.99 when 0.5 mg/L Ep was used, which is three times that of AC used alone (18.39). The result was consistent with the color removal efficiency. It can be explained as follows: the re-growth of flocs was partly controlled by coagulation mechanisms of different coagulants. As mentioned in Section 3.1, for AC, charge neutralization was not only the mechanism involved in color removal, physical entrapment of colloids within coagulant precipitates and adsorption, but also play an important role. It has been reported that the flocs formed by charge neutralization have total recoverability, while sweep and adsorption flocs have poor re-growth after breakage (Aguilar et al., 2003). So, the flocs formed by AC showed less ability to resist shear and worse re-growth after breakage. When Ep was used in coagulation process, the produced flocs could undergo scission under high shear rate. Meanwhile, the adsorbed polymer could reform on the particle surface (Chaignon, Lartiges, ElSamrani, & Mustin, 2002). Therefore, after the flocs were broken, the Ep with special structure attraction and Van der Waals on newly exposed flocs surface may bond the floc fragments together, resulting in the good recoverability of the AC–Ep flocs.

4. Conclusions

In this study, the effect of a new coagulant aid-Enteromorpha polysaccharide on coagulation performance and floc characteristics in synthetic dying wastewater treatment was evaluated. The following conclusions can be obtained:

(1) When Ep was used in combination with alum coagulants, the color removal was improved to varying degrees depending on the doses of Ep, and the maximum color removal was achieved when 0.5 mg/L Ep was used, and the optimal solution pH range was 6.0–8.0.
(2) The growth rate and average size of flocs formed by AC–Ep were larger than those by AC in steady-state after floc growth phase, and the distribution of floc size had a wider range.
(3) Floc generated in AC–Ep coagulation system was stronger and had a better ability to revive than that of AC.
(4) Ep played a positive aid role by adsorption bridging in dye wastewater treatment. Therefore, better coagulation performance and floc characteristic of AC–Ep can be achieved by a combination of precipitate charge neutralization and adsorption bridging.

Acknowledgements

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