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Coagulation efficiency and flocs characteristics of recycling sludge during treatment of low temperature and micro-polluted water

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Abstract

Drinking water treatment sludge, characterized as accumulated suspended solids and organic and inorganic matter, is produced in large quantities during the coagulation process. The proper disposal, regeneration or reuse of sludge is, therefore, a significant environmental issue. Reused sludge at low temperatures is an alternative method to enhance traditional coagulation efficiency. In the present study, the recycling mass of mixed sludge and properties of raw water (such as pH and turbidity) were systematically investigated to optimize coagulation efficiency. We determined that the appropriate dosage of mixed sludge was 60 mL/L, effective initial turbidity ranges were below 45.0 NTU, and optimal pH for DOMs and turbidity removal was 6.5–7.0 and 8.0, respectively. Furthermore, by comparing the flocs characteristics with and without recycling sludge, we found that floc structures with sludge were more irregular with average size growth to 64.7 μm from 48.1 μm. Recycling sludge was a feasible and successful method for enhancing pollutants removal, and the more irregular flocs structure after recycling might be caused by breakage of reused flocs and incorporation of powdered activated carbon into larger flocs structure. Applied during the coagulation process, recycling sludge could be significant for the treatment of low temperature and micro-polluted source water.

Key words: recycling sludge; sweep flocculation; adsorption; flocs characteristics

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Introduction

Waste residual streams or sludge, such as filter backwash, condensate of sedimentation tank, or the mixture of both from drinking water treatment plants are commonly characterized by elevated concentrations of suspended solids, total organic carbon (TOC) and inorganics as well as the chemical precipitates derived from the coagulants i.e., aluminum sulphate or poly-aluminum chloride. Large amounts of waste residual streams are generated all over the world everyday. The proper disposal, regeneration, or reuse of waste residual sludge has thus become a significant environmental issue.

During the coagulation of low temperature water, the removal ability of particulates and organic matters can become weaker due to the slower hydrolyzing process, higher aggregation shear and slower settling velocity. As a result, the corresponding chemical and microbial stability of effluent can decrease notably. Based on the existing process in drinking water treatment plants (DWTPs), the reuse of waste residual streams is an alternative method to enhance coagulation efficiency during cold periods. This process accomplishes the reuse and reclamation of water resources, and fulfills a low-operational cost due to low coagulant addition and sludge disposal. Specifically, recycled alum-sludge contains a large portion of insoluble aluminum hydroxides (Chu, 2001; Guan et al., 2005) that can be utilized as additional coagulant to enhance pollutants removal. The efficiency may be further improved if the recycled sludge contains powdered activated carbon (PAC), which is an excellent adsorbent commonly used for removal of organics including natural organic matter (NOM) and synthetic organic compounds (SOCs) (Li et al., 2003; Lee and Walker, 2006). Additionally, the retention time of PAC can be prolonged, as the retention time in conventional processes of PAC may be limited to only 10–20 min (AWWA, 1990).

Currently, there are four dominant issues regarding reuse of waste residual streams in drinking water treatment: (a) feasibility and safety evaluation of the recycled sludge (Lechevallier et al., 1991; Cornwell and Lee, 1994; States et al., 1995), (b) sludge recycled to raw water with or without pretreatment (US EPA, 2002), (c) appropriate recycling ratio of the sludge (Gottfried et al., 2008; Arora et al., 2001; Edzwald and Tobiason, 2002) and appropriate operating conditions, i.e., storage conditions or mixing conditions (Guan et al., 2005), and (d) mechanism of enhanced efficiency (Guan et al., 2005; Gottfried et al., 2008). Issues (a) and (b) are mutually correlative. The

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better point about pretreatment of the residual waste stream is that the higher chemical and microbial stability can be attained. The recycling ratio is responsible for the safety, that is, the larger the recycling ratio the heavier the burden for the existing process and the higher risk of the effluent. To evaluate coagulation performance of the reuse process, the recycling ratio was controlled at below 12% when untreated sludge was directly recycled to raw water. Additionally, the influence of water quality conditions i.e., initial turbidity and solution pH (Yan et al., 2008; Yang et al., 2010) on coagulation-sedimentation performance was also investigated in comparison to control tests.

Usually, during coagulation, metal hydroxide is the ultimate hydrolyzed product of the metal ions of the inorganic coagulation. The agglomeration of the hydroxide forms the visible and amorphous species, namely the flocs. Recent floc research has confirmed they are fractal objects (Xiao et al., 2009, 2010). However, few studies have reported on the morphology of flocs formed at low temperature (Xiao et al., 2010) or under sludge recycling conditions.

Therefore, the overall purpose of this project was to evaluate the coagulation sedimentation performance of recycled PAC and poly-aluminum chloride mixed sludge (PAS), to investigate the impact of initial turbidity and solution pH on the reuse process as well as determine the coagulation mechanism and analyze the flocs characteristics in terms of image, perimeter-based fractal dimension (D_{pf}) and average size with/without PAS recycled at low temperature.

1 Materials and methods

1.1 Materials and simulated raw water

All reagents used were of analytical grade. The PAC made of wood was 180 mesh (Actview Carbon Technology Inc., China); carbon size 98% < 180 mesh. The poly-aluminum chloride (PACl) used was reagent grade (with 28% Al_2O_3 content, Gongyi, China). The natural colloids stock solution (1000 NTU) was used as turbidity causing matter, which was prepared according to previous studies (Sun et al., 2009). Deionized (DI) water (Millipore Milli-Q, Billerica, MA) was used to prepare the coagulant and PAC stock solutions.

The raw water was prepared by adding natural colloids and filtered domestic wastewater to local tap water (Harbin, China) at a volumetric ratio of 3:5:142, then stabilized at 0–1°C in a refrigerator for 24 hr to simulate low temperature and micro-polluted surface water. Quality characteristics of the prepared water were as follows: temperature 2–4°C; pH 7.12–7.25; turbidity 8.32–11.3 NTU; DOC 3.147–3.727 mg/L; UV_{254} 0.040–0.045 cm^{-1}; and Zeta potential –18.6 to –19.8 mV.

1.2 Jar test

Bench-scale experiments were performed with 1 L of raw water in 1.4-L beakers with a sampling port located 3 cm below the water surface. A programmable jar testing apparatus (Zhong-Run Jar Test Instruments, China) was used with the following procedure: 20 mg/L of PAC was preloaded for 10 min adsorption at 60 r/min, then pre-determined dosage of PACl was added and 20–120 mL of PAS (recycling ratio 2%–12%) was recycled simultaneously at 300 r/min rapid mixing stage, subsequently 1 min slower mixing at 120 r/min, 15 min flocculation at 50 r/min, and 20 min settling. The recycling experiment was a simulated recycling flow diagram in the main water treatment train. In addition, control tests were performed in the absence of PAC and PAS. The characteristics of PAS consisting of 10 mg/L of PACl and 20 mg/L of PAC are as the following: solid content 0.078%–0.093%, *W/W*; sludge content 0.695–0.736 mg/L, pH 7.35–7.48; DOC 4.931–5.140 mg/L, and Zeta potential –4.42 to –5.15 mV. The solution pH was adjusted by adding 0.1 mol/L HCl or NaOH, which was dosed in raw water 30 sec prior to PAC. Initial turbidity was adjusted by adding pre-determined stock solution of natural colloids. The raw water was kept at the low temperature of 3–5°C during the experimental period. Treated water samples were taken after settling for later analyses. Each experiment was performed in duplicate.

1.3 Analytical methods

Dissolved organic carbon (DOC) was analyzed by a total organic carbon (TOC) analyzer (TOC-V_{CPN}, Shimadzu, Japan). The UV absorbance at 254 nm (UV_{254}) was determined using a spectrometer (UV754, Cany, China). Both DOC and UV_{254} were measured after filtration through 0.45 μm membranes. Zeta potentials of the PAS and raw water samples were measured with a Zeta potential analyzer (Nano-Z, England). Turbidity was measured by a Hach 2100P Turbidimeter (USA). The pH value was determined and calibrated daily using pH buffer solutions. Solid content was measured using standard methods.

1.4 Image analysis of the flocs

Among the methods for determining floc structural characteristics, microscopy is a relatively inexpensive and advantageous one which allows individual particles to be analyzed at high magnification. In this study, after adding pre-determined dosages of PACl and PAS simultaneously, samples of flocs were acquired at 4, 14, 17 min below the surface of the solution by a hollow plastic tube. The tube was open at both ends; one end of the tube was inserted gently about 25 mm into the coagulated solution to avoid contacting the stirrer. The flocs in the tube were withdrawn carefully by covering the other end of the tube with a finger. After transferring the sample to a flat microscope slide, the images of the flocs in the sample were captured by an optical microscope (Olympus, BX51TF, Japan) equipped with a video camera (Olympus, C-5050 200M, Japan). The camera had a sensor matrix consisting of 1360 (horizontal) × 1024 (vertical) pixels. Each pixel was recorded using 8-bit resolution, i.e., there were 256 gray levels for each image pixel. The floc dimensions were obtained by processing the floc image using Image J software to obtain average size, perimeter *P*, and projected area *A* values. The perimeter-based fractal dimension D_{pf}

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was obtained from Eq. (1) (Xiao et al., 2009, 2010). Thus, the $2/D_{pf}$ may be found as the slope of a plot of log$A$ versus log$P$. Unlike that of a Euclidean object, the value of D_{pf} of a fractal object is not an integer but a decimal, ranging from 1 (a circle) to 2 (a line). A larger value of D_{pf} represents a more irregular floc structure.

$$A \propto P^{2/D_{pf}} \tag{1}$$

2 Results and discussion

2.1 Characteristics of the raw water and PAS

The characteristics of the raw water and PAS used in this study are illustrated above. The prepared water was low in temperature (2–4°C) and turbidity (8.32–11.3 NTU) with moderate levels of organic carbon, which are the same characteristics as micro-polluted water during cold periods. A low solid content was typically found in the recycled sludge, indicating that the sludge had not undergone any thickening or dewatering. Both the raw water and the recycled sludge samples showed a negative Zeta potential. In addition, it has been proposed that the majority of absorbable DOC is enmeshed in alum flocs through coagulation in the main treatment train (Guan et al., 2005). Therefore, the DOC concentrations in the raw water as compared to those after treatment by recycling PAS strongly reflected the influence of residual aluminum hydroxides and PAC existing in recycled sludge on DOM elimination, depending on the removal from the water phase as well as on those released from the sludge.

2.2 Effect of sludge dosage on turbidity and DOMs removal

As indicated in Fig. 1a, the turbidity in raw water was 10.6–11.3 TUN, recycling ratio was under 12%, and turbidity removal efficiency was as high as 80% by reusing the PAS at recycling volume 120 mL/L. However, it was found that the resulting sludge volume increased linearly with the increase in the recycling ratio of PAS. Therefore, such a high PAS recycling ratio was not appropriate due to the huge sludge volume under these circumstances. To minimize the increase in sludge volume while maintaining high removal efficiency of turbidity, the PAS recycling volume 60 mL/L was considered adequate in this study. At this recycling ratio, the turbidity removal was about 73%, compared with 51% in conventional coagulation.

The enhancement was mainly attributed to physical adsorption and/or sweep flocculation by hydroxide precipitates and improved collision frequencies and efficiencies among particles. At the same time, PAC in reused PAS and fresh "preloads" can increase the concentration of the particles and become the condensation nuclei of flocs (Qi et al., 2009), which is very important in the reusing process for enhancing turbidity removal. The higher particle concentrations and diameters contributed to higher collision probability, which favored the flocculation process, especially for water with low turbidity according to Eq. (2).

$$N = 12\pi\beta n^2 d^3 \sqrt{\xi/\mu} \tag{2}$$

where, N (1/(cm^3·sec)) means frequency of collision; β (counts/cm^3) means constant; n means concentration of particles; d (cm) means diameter of particles; ξ means dissipation rate of water energy in per time per volume; and μ (Pa·sec) means dynamical viscidity degree of water.

As indicated from Eq. (2), the collision probability between particles was positively relative to d^3 and n^2. In the recycling process, PAC in PAS and fresh preloads significantly increased the number of particles, especially those with average sizes of 83 μm (180 mesh). Additionally, d was also improved since the diameters of the many recycled floc particles were larger than those in raw water. As a result, the collision frequencies and efficiencies were promoted.

Dissolved organic matter (DOM) is an important concern in drinking water treatment due to its potential hazard to human health and the difficulty in its removal by conventional treatment process. Both UV_{254} and DOC as surrogate parameters representing the content of DOMs are often used in drinking water treatment. In Fig. 1b, it can be observed that the removal capacity by reusing PAS process for UV_{254} was higher than conventional coagulation, while average UV_{254} concentration in raw water was 0.042 cm^{-1}. After 60 mL/L of PAS was recycled, the effluent concentration of UV_{254} was reduced to 0.018 cm^{-1}, with the removal

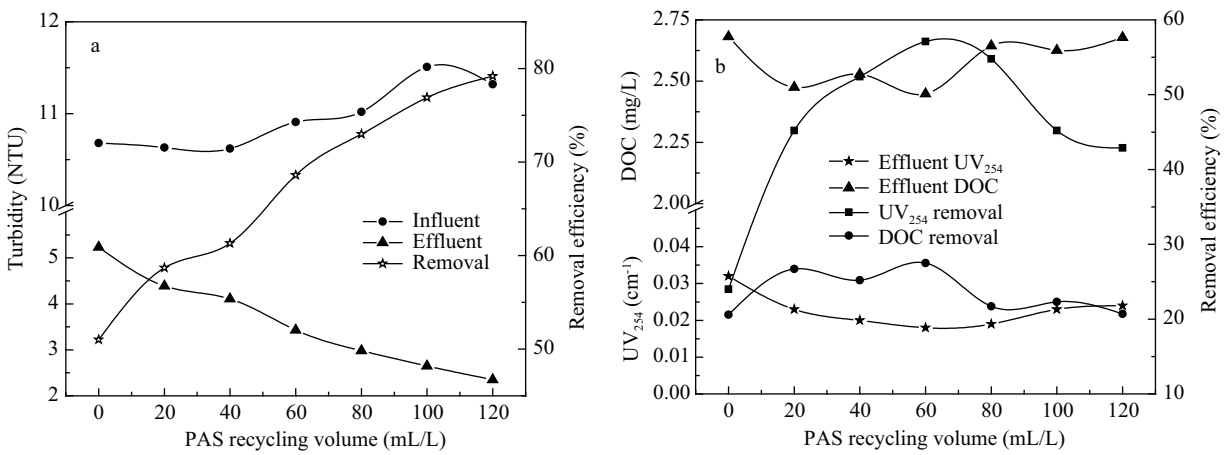

Fig. 1 Effect of sludge recycling volume (recycling ratio) on turbidity (a) and UV_{254} and DOC removal (b). Average turbidity: 10.9 TUN; UV_{254}: 0.042 cm^{-1}; DOC: 3.234 mg/L; temperature: 3°C; pH: 7.18 in raw water.

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efficiency reaching to 57.1%, which was 33.1% higher than traditional coagulation. Furthermore, the removal efficiency of DOC increased rapidly at lower recycling volume but decreased to a constant value at higher recycling volume. The reuse process decreased DOC from 3.147–3.321 mg/L in the raw water to 2.448 mg/L in the effluent with a removal efficiency of 27.5% when recycling 60 mL/L of PAS. Thus, the reuse process exhibited excellent potential for DOMs removal at a moderate recycling ratio.

Aluminum-based coagulation is often used for NOM removal, especially the removal of hydrophobic, charged, or large organic matter. The DOM removal in the current research was determined to the sludge recycling volume or ratio since the Zeta potential of suspension solution coagulated by 9 mg/L of PACl was –0.482 to –0.506 mV and the Zeta potential of PAS was –4.42 to –5.15 mV, which showed that charge neutralization plays limited positive role on DOM removal enhancement. At relatively low recycling ratio, NOM removal was mainly attributed to charge neutralization since medium-polymerized Al species (Al_b) were formed *in-suit*. With the increase in recycling ratio, sweep flocculation dominated NOM removal because of the transformation of Al_b into colloidal or solid Al species (Al_c). The Al_c precipitated easily when it adsorbed particles and NOM, even small DOM (Yan et al., 2009). Additionally, PAC is an excellent adsorbent for removal of NOM. Therefore, the enhanced organics removal in this research was attributed to the joint effects of complexation and adsorption by insoluble aluminum hydroxides existing in PAS and adsorption by PAC in PAS and fresh "preloads". However, the amount of organic matter released from the alum-sludge was related to the recycling ratio of the alum sludge. The trapped organic matters released at higher recycling ratio could increase the concentration of organics and lead to removal efficiency decline. Therefore, the enhancement of DOMs removal by recycled sludge depended on the DOM removed from the water phase as well as released from the sludge.

Based on these results, the appropriate recycling volume was 60 mL/L (recycling ratio 6%), which was used as the operation parameter to investigate the effects of initial turbidity and solution pH in the following experiments. Enhanced removal for turbidity, UV_{254} and DOC was 73%, 57.1% and 27.5%, which was 22%, 33.1% and 13.4% respectively higher than conventional coagulation. However, the appropriate recycling ratio of PAS requires verification by a full-scale trial.

2.3 Effect of solution pH

Solution pH varied in the range of 6–9 by adding 0.1 mol/L HCl or NaOH 30 sec prior to PAC. The particulates and organics concentration were consistent with the frontal experiments, and the PAS recycling ratio was 6%. The removal of turbidity, UV_{254} and DOC by the reuse experiments compared to the control trials (recycling ratio 0%) are shown in Fig. 2.

Figure 2a shows that pH had a critical influence on turbidity removal. At the recycling ratio of 0%, the turbidity removal was maximal at pH 8.0 and decreased at pH 8.5–9.0, but more than at pH 6.0–7.0. At a recycling ratio of 6%, average turbidity removal was improved with an increase in pH. At pH 8.0, turbidity removal reached 78.5%, which was 9.8% more than that at recycling ratio 0% (68.7%). Solution pH not only affected the surface charge of the colloids in water, but also had a significant effect on the hydrolysis species of PACl. Moreover, the hydrolysates distribution of aluminum hydroxide contained in recycling sludge was significantly influenced by solution pH. The enhanced removal of turbidity at high solution pH was attributed to the synergetic effect of these three aspects induced by pH. Additionally, as to the weak alkaline solution, the metal hydrolyzing complex ions might be formed directly. It can be assumed that the tendency to be absorbed, even against electrostatic repulsion, was especially pronounced for poly-nuclear poly-hydrolyzing species. The chemical interaction and van der Waals attractive forces between negative metal hydrolyzing complex ions and charged colloidal particles through hydroxyl sorption were stronger than electrostatic repulsion.

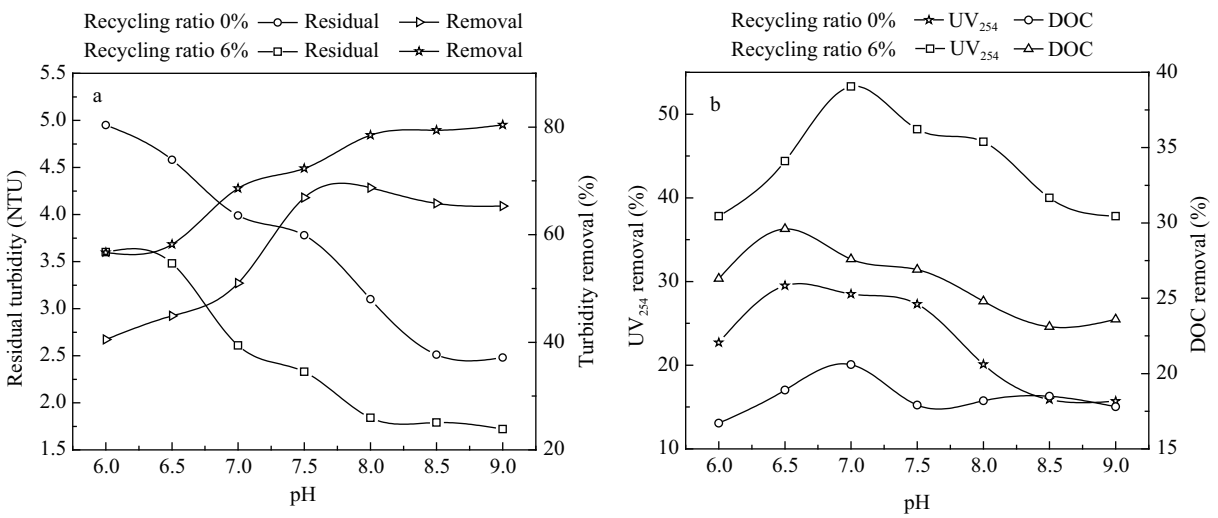

Fig. 2 Effect of pH by reusing PAS compared to control trials on turbidity (a), UV_{254} and DOC removal (b). Average UV_{254}: 0.042 cm^{-1}; DOC: 3.437 mg/L; temperature: 4°C; pH: 7.18 in raw water. 20 mg/L PAC was preloaded and 60 mL/L PAS was recycled at rapid mixing stage in reusing experiments.

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Conversely, UV_{254} and DOC removal were higher in the weak acid range (6.0–7.0) than in the basic pH range (7.5–9.0) in both recycling ratio of 0% and 6% (Fig. 2b). The enhanced UV_{254} and DOC removal efficiency reached 44.4%–53.3% and 27.6%–29.6%, respectively, in pH 6.5–7.0 in the reuse experiments, which may account for the relatively high PACl hydrolyzed speciation Al_b content *in-suit* and higher Zeta potential (Yan et al., 2008, 2009), as well as the good adsorption capacity of PAC in acidic solution. Furthermore, pH also affected the physical and chemical properties of organics, such as humic acid in water (Yang et al., 2010). The humic substances were less hydrophilic and protonation was improved at lower pH, and thus more easily charge-neutralized and destabilized. Solution pH affected the balance between the reactions of organic functional groups with hydrogen ions and Al hydrolysis products. At lower pH, hydrogen ions out-competed the metal hydrolysis products for organic ligands; thus, the amount of unsatisfied organic ligands decreased and the DOMs were removed more efficiently by PACl (Yan et al., 2008; Yang et al., 2010).

2.4 Effects of initial turbidity

Quantitative study about the effect of initial turbidity may provide information on the adaptability of the reusing process and define different mechanisms, such as physical (i.e., increased collision sites due to improved particle number concentration), chemical (i.e., increased collision sites and sweep flocculation mechanisms due to insoluble aluminum hydroxides in recycled sludge), or physical-chemical mechanisms (i.e., sorption by PAC). The effect of initial turbidity on the reusing experiments compared with the control trials on turbidity, UV_{254} and DOC removal is shown in Fig. 3, under the PAS recycling ratio of 6%.

In Fig. 3a, it can be seen that the removal capacity of reusing PAS for turbidity increased rapidly at lower initial turbidity ranges (less than 25.0 NTU). With the increase in initial turbidity, the removal ability stabilized and reached up to 90% at both recycling 0% and 6% processes. The high turbidity in raw water means the higher concentration of the particles that would improve collision frequencies and efficiencies among particles. In the recycling process, PAC in PAS and fresh "preloaded" can increase the concentration of the particles and become the condensation nuclei of flocs. Sun et al. (2009) reported that recycled sludge showed less potential of favoring coagulation, indicating that the coagulating activities of recycled sludge were negligible, and the increasing of seeding and nuclei was more significant. It could be postulated that PAC played key roles in the enhancement of turbidity removal due to increasing the concentration of the particles and being the condensation nuclei of flocs.

From Fig. 3b it can be seen that UV_{254} removal in reusing PAS was always higher than the control tests, but DOC removal was enhanced under raw turbidity of less than 10.0 NTU or from 25.0 to 45.0 NTU. The most effective removal efficiency for UV_{254} was 51.7% when initial turbidity was 10.0 NTU, and for DOC was 33.7% when initial turbidity was 45.0 NTU. The higher turbidity in raw water was able to form larger flocs, which incorporated PAC into their structure and reduced the efficiency of mixing and the bulk diffusion kinetics for the organic molecule. Additionally, organic contents were higher with increased amounts of natural colloids, which could impede PAC adsorption of organics. On the other hand, it is obvious that enhanced DOMs removal could be attained at lower initial turbidity (below 45.0 NTU) and fluctuated with the increase of initial turbidity, which demonstrated that DOMs removal was mainly due to the physical-chemical adsorption of PAC in PAS and fresh "preloaded", a small portion of increased collision sites by increasing initial turbidity or particles concentration.

2.5 Surface morphology of the flocs

We applied morphological analysis to study the physical property of the flocs. The size and concentration of particles directly impacts the density and sedimentation speed of flocs (Nan et al., 2009). In addition to particle

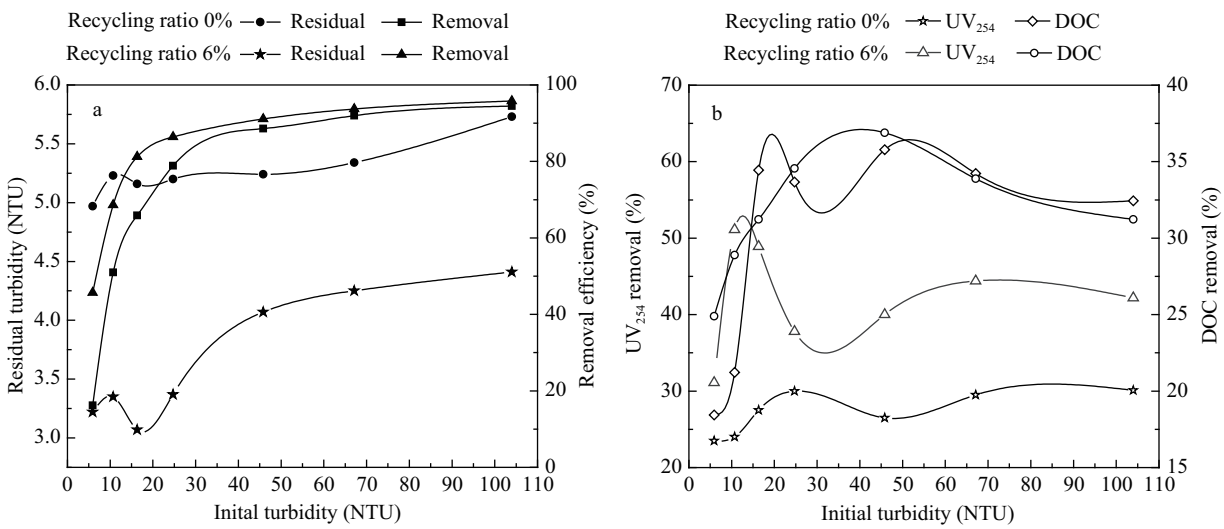

Fig. 3 Effect of initial turbidity by reusing PAS compared to control trials on turbidity (a), UV_{254} and DOC removal (b). Average turbidity: 8.32 TUN; UV_{254}: 0.045 cm^{-1}; DOC: 3.147 mg/L; temperature: 3°C; pH: 7.22 in raw water. 20 mg/L PAC was preloaded and 60 mL/L PAS was recycled at rapid mixing stage in reusing PAS experiments.

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Table 1 Flocs average size and perimeter-based fractal dimension D_{pf} at three sampling times

Samples	Sampling time (min)	Perimeter-based fractal dimension		Average size (μm)	Number of aggregates
		D_{pf}	R^2		
Recycling ratio 0%	4	1.499 ± 0.053	0.89	34.6	97
	14	1.295 ± 0.068	0.82	36.8	82
	17	1.057 ± 0.075	0.67	48.1	97
Recycling ratio 6%	4	1.863 ± 0.266	0.89	36.1	7
	14	1.655 ± 0.098	0.93	54.0	23
	17	1.459 ± 0.044	0.89	64.7	134

size, surface morphology of the flocs also affects the behavior of aggregated particles, particularly with regard to collision efficiency and settling rates. In recent years, irregular aggregate shapes have been described in terms of two-dimensional perimeter-based fractal dimension. The microscope images of the PAS flocs are shown in Fig. 4, for PACl at dosage of 10 mg/L and PAC 20 mg/L. Derived floc average sizes and perimeter-based fractal dimension D_{pf} for three sampling times with and without PAS recycled are shown in Table 1.

As indicated in Table 1, the perimeter-based fractal dimension decreased with coagulation time at both recycling ratios (0% and 6%). The decrease in perimeter-based fractal dimension was associated with an increase in floc size. The average sizes of the flocs increased with coagulation time and grew to 64.7 μm, which was 25.7% larger than the control trials (48.1 μm). Furthermore, the perimeter-based fractal dimension at recycling ratio 0% was lower than that at recycling ratio 6% at the end of the coagulation stage (17 min), which indicated that the flocs formed at recycling ratio 6% were more irregular than at recycling ratio 0%.

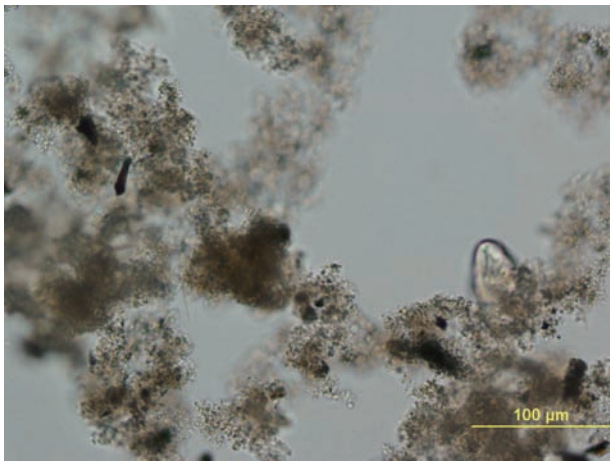

Fig. 4 Microscope image of the PAS flocs (200× magnification) produced by 10 mg/L PACl and 20 mg/L PAC.

There are three reasons accounting for the more irregular floc structures: (1) at recycling ratio 6%, the perimeter-based fractal dimension was higher than that at a moderate temperature. Although the fundamental cause for the more irregular flocs in the cold was not clear, it may relate to increased floc porosity. It is well known that the solubility of many gases, such as carbon dioxide and oxygen, increase as the solution temperature decreases. Inevitably, those gases were involved in the formation of flocs and thus increased their porosity (Xiao et al., 2009); (2) PAC played an important role in increasing the concentration of the particles and being the condensation nuclei of flocs, with larger flocs incorporating PAC into their structure; (3) the breakage of flocs occurred when exposed to high shear at rapid mixing stage, and the broken flocs formed by PACl and organics was difficult to recover to their initial size before breakage (Yu et al., 2010). After breakage and recovery, the small flocs increased, which can affect the calculation of perimeter-based fractal dimension from the data of flocs size.

Figure 5 shows the images of flocs captured in different cases. In this study, a large number of flocs were involved

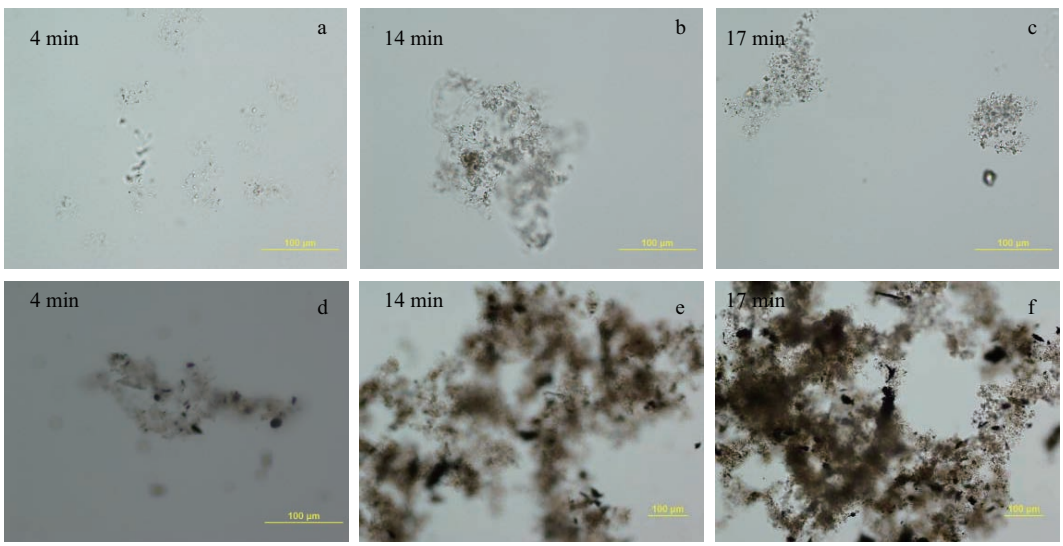

Fig. 5 Images of the flocs (200× magnification) formed at 4, 14, 17 min. (a–c) recycling ratio 0%; (d–f) recycling ratio 6%.

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in the calculation of D_{pf} and average size, and it is therefore not possible to determined solely from Fig. 5 that the floc structures formed at recycling ratio 6% were more irregular. However, Fig. 5 clearly shows that the flocs sizes at recycling ratio 6% were larger and more compact than those of the control trials, with larger flocs incorporating PAC into their structure, which may have increased the settling rate of the resulting flocs.

3 Conclusions

The main conclusions are as follows: (1) The coagulation efficiency of the reusing process was greatly influenced by sludge recycling volume and solution pH. We determined that effective turbidity removal could be obtained by recycling 60 mL/L of mixed sludge, when pH was 8.0, the additive dosage of PACl was 10 mg/L and PAC was 20 mg/L. Conversely, DOC and UV_{254} removals were higher in the weak acid range 6.5–7.0 than that at basic pH range, and reached 29.6% and 53.3%, respectively. (2) Through the quantitative study about the effect of initial turbidity, we postulated that the adsorption of PAC and a large number of $Al(OH)_3$ complexes and precipitates for the foulant molecules might be an important mechanism. (3) The structure of the flocs formed by recycling experiments was more irregular than that in the control trials, and PAC in reusing PAS experiments played a negative role on perimeter-based fractal dimension, but a positive role on flocs formation. The decrease in perimeter-based fractal dimension was associated with an increase in floc size. Average floc size reached 64.7 μm, which was 25.7% larger than that in the control trials (48.1 μm).

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