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ORIGINAL PAPER

Enhancement of bio-sludge gravitational thickening with weak ultrasound

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Abstract Gravitational thickening is the prevailing method to reduce bio-sludge volume though the process is slow and usually requires addition of polyelectrolyte(s). This paper investigated the potential benefits of sonication on enhancing the bio-sludge gravitational thickening with very low energy dose, thereby called "weak ultrasound". Results showed that weak sonication significantly changed the bio-sludge settleability and the main mechanism was release of the loosely bound extracellular polymeric substances. The changes were strongly influenced by power density and sonication duration. Low frequency was better but the difference was insignificant. Weak sonication (<680 kJ/kg DS) improved the sludge gravitational thickening while high ultrasonic energy deteriorated the process. Considering both the sludge thickening efficiency and energy consumption, the optimum conditions were 0.15 W/ml, 7 s and 25 kHz. Under such conditions, the energy dose was only 155 kJ/kg DS, much lower than literature reports and the sludge settling time shortened from the original 24 to 12 h. Weak sonication could substitute expensive polyelectrolyte coagulant for bio-sludge thickening. Combination of weak sonication and polyelectrolyte could further reduce the settling time to 6 h. The final water content of the thickened bio-sludge was not changed after sonication and polyelectrolyte addition.

Keywords Activated sludge · Dry weight · Extracellular polymeric substances · Polyelectrolyte · Settleability · Sonication

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Introduction

Activated sludge treatments are dominating techniques in treating wastewater but these processes generate large amounts of bio-sludge, estimated at between 5 and 25% of the total volume of the treated water (Yin et al. 2004). With a water content of 99.2–99.8%, dewatering is the paramount important step in the bio-sludge handling to reduce the volume and, hence, the costs of transportation, treatment, and disposal. However, the bio-sludge is "super-compactable" and its dewatering is very difficult, expensive, and poorly understood (Chen et al. 2001; Feng et al. 2009). Sludge dewatering normally composes three steps: thickening, conditioning, and mechanic dewatering. Thickening, the first step of sludge dewatering, increases the dry weight of bio-sludge to 3% or higher, i.e., reduces the sludge volume by more than 70%. Obviously, thickening is the single most effective step for volume reduction and its efficiency determines the effects and costs of all following treatments and disposals. Thickening can be achieved by gravitational settling or via mechanical solid–liquid separation such as centrifuging. Since gravitation settling requires no energy input and little maintenance, it is widely adopted worldwide. However, the high viscosity and poor settleability of bio-sludge make gravitational thickening very slow, and a minimum retention time of

12 h is required (design code, Yasuhiko and Kazuhiro 1999). Therefore, sometimes polyelectrolyte(s) are added to accelerate the process. However, addition of polyelectrolyte(s) increased the cost and might interfere with following treatments. This paper proposes an ultrasonic process to enhance the gravitational thickening of bio-sludge.

Ultrasound waves, when entering bio-sludge, produce a kind of sponge effects and facilitate the migration of moisture through natural channels or other channels created by wave propagation (Yin et al. 2004). When ultrasonic power is beyond certain threshold, a phenomenon called "acoustic cavitation" can be observed, which causes powerful streaming, agitation, extreme local heating, and interface instabilities (Suslick 1990). Such effects significantly changed the structures and properties of bio-sludge (Chu et al. 2001). Sonication has been proven to be effective in accelerating sludge disintegration (Chu et al. 2001; Gonze et al. 2003; Bougrier et al. 2006); and enhancing sludge biodegradability (Tiehm et al. 2001; Nickel and Neis 2007).

In some cases, sonication was reported to improve the dewaterability of bio-sludge by changing the supernatant EPS (Yin et al. 2004, 2006), particle size, and decreasing the sludge-specific resistance of filtration (Yin et al. 2006; Na et al. 2007; Nickel and Neis 2007). The sludge capillary suction time and the bound water content were reduced by more than 50% with appropriate sonication (Bien and Wolny 1997; Kim and Kim 2003; Yin et al. 2006). Sonication improved the solid/liquid separation in cake filtration processes via accelerating the agglomeration process (de Sarabia et al. 2000), and also enhanced the water removal effect of three types of digested sludge (Janu[illegible] and Lidia 1997; Na et al. 2007).

However, adverse effects of sonication on sludge dewaterability were also reported (Wang et al. 2005; Dewil et al. 2006). Intensive sonication increased the capillary suction time and polymer consumption (Wang 2006; Na et al. 2007; Feng et al. 2009). Such controversial conclusions might be caused by the great variations in sludge sources and characteristics, ultrasound power level, treatment time and energy input, and polymer used. In summary, some researches showed that low-frequency ultrasound put the sludge particles together and made them easier to be dewatered (Yin et al. 2004), but the actual effects depend strongly on the kind of sludge and polyelectrolyte and on the sonication conditions (Yin et al. 2004; Feng et al. 2009). These changes of bio-sludge properties might also be used to accelerate gravitational thickening and/or to reduce the consumption of polyelectrolyte.

This paper studied the influences of sonication operational parameters such as ultrasound frequency, power density, and sonication duration on bio-sludge before thickening, to investigate the feasibility of sonication on accelerating the bio-sludge gravitational thickening and/or to reducing polyelectrolyte dosage. Since no reference was available on ultrasonic enhancement of sludge thickening, the experiments were designed following reports on ultrasonic enhancement of mechanical dewatering (Kim and Kim 2003; Dewil et al. 2006; Na et al. 2007; Feng et al. 2009). This work was done in Changsha, China within 2008–2009.

Materials and methods

Bio-sludge

Bio-sludge was collected from a municipal wastewater treatment plant that uses the conventional activated sludge process. The bio-sludge had a water content of 99.3% (Table 1) and was highly resistant to dewatering. The wastewater treatment plant adopted gravitational thickening assisted with polyacrylamide (PAM) as the first step of dewatering. The goal of gravitational thickening was to increase the water content of sludge dry weight (DS) to 3%, which was the most important design criterion for gravitational thickening tanks (design code). The collected bio-sludge was stored at 4°C before used.

Polyelectrolyte

Cationic PAM was the most widely used polyelectrolyte in sludge conditioning and this study also used a type of cationic PAM (DS112, Baoding Yisheng). The PAM had a molecule weight of around 1.2×10^7. Stock solution (0.5%) was prepared by completely dissolving the powdered PAM in distilled water for 24 h prior to be used. Before each experimental run, certain amount of stock solution was added to the bio-sludge and mixed at 120 rpm for 1 min.

Table 1 Bio-sludge characteristics

Water content	DS	pH	SCOD	Organic content
99.3%	6,750 mg/L	6.36	215 mg/L	81.2%

Settling tank

The glass settling tank used for sludge gravitational thickening (schematic diagram see supporting information) was designed after configurations of the actual one in the wastewater treatment plant. The working volume was 1.0 L and the slope of the bottom was around 1:1. The small size of the tank might cause certain "side-wall effect" that might interfere with accurate measurement of sludge settlability.

Sonication

Three ultrasonic cell-devices were used: one with 25 kHz frequency (Kunshan Ultrasonics, China), one with 40 kHz frequency (Kunshan Ultrasonics, China), and one with 150 kHz frequency (home-made). For each experimental run, 1 L of sludge was treated in the ultrasonic device. The sonication time varied from 7 to 120 s and the power density was from 0.1 to 1.0 W/mL. The ranges were chosen following the literature reports. Although sonication could increase the sludge temperature and lower the sludge pH (Li et al. 2009), insignificant changes were observed in both temperature and pH due to the short sonication time. Therefore, neither sludge temperature nor pH was adjusted. Each treatment was repeated in triplicate and average values were reported.

Analytic methods

The sludge water content, DS, organic content, and supernatant organic content (SCOD) were measured according to the standard methods (Andrew and Mary 1998). The pH was measured using a Hach pH meter. The dissolved oxygen level was measured using a Hach DO meter.

Results and discussion

Bio-sludge settling without sonication

The bio-sludge contained 81.2% of organics, which was mainly biomass and extracellular polymeric substances (EPS), and was very hard to be dewatered. The gravitational settling was very slow and 24 h was needed to achieve 3% DS (Fig. 1a). Meanwhile, the SCOD kept rising during bio-sludge settling (Fig. 1b). The dissolved oxygen level in bio-sludge dropped to below 0.5 mg/L after 0.5 h, which maintains anaerobic condition in the settling time. With plenty of bacteria in the bio-sludge, anaerobic fermentation occurred and released partial organics into the supernatant. Rapid increase of SCOD after 12 h might also deteriorate the bio-sludge settling since high organic content in the supernatant would increase the sludge viscosity. But the dominating reason for slow settling after 6 h should be the increased sludge DS (higher than 2%).

Such a long retention time was economically infeasible. For a wastewater treatment plant with capacity of 100,000 m^3/d, the volume of bio-sludge would be ~20,000 m^3/d, and a 20,000 m^3 tank would be required for gravitational thickening. Therefore, PAM addition was necessary to accelerate the bio-sludge settling. Adding cationic polymers can change the form of water in sludge and increase the velocity of dewatering process; the

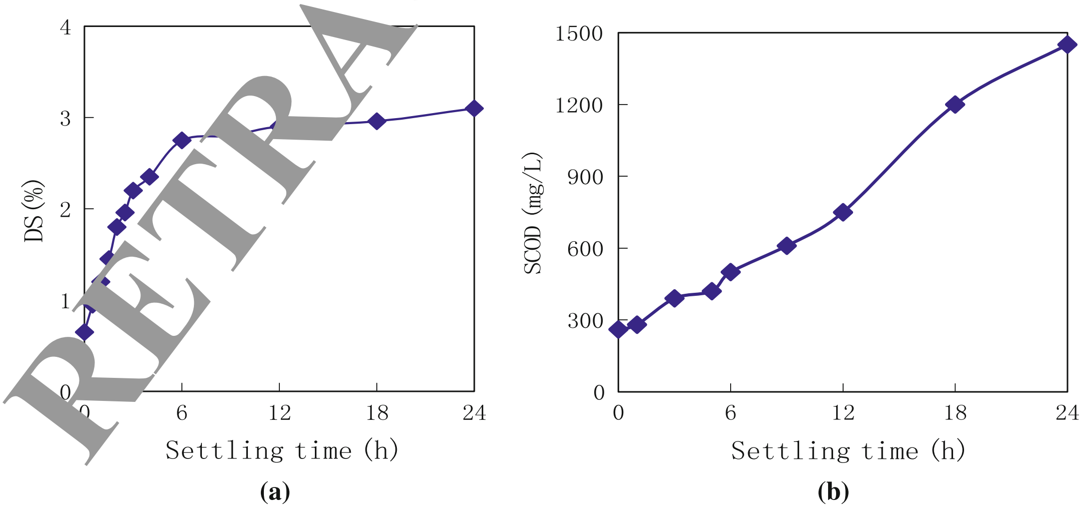

Fig. 1 Bio-sludge gravitational thickening, **a** sludge dry weight **b** supernatant organic content

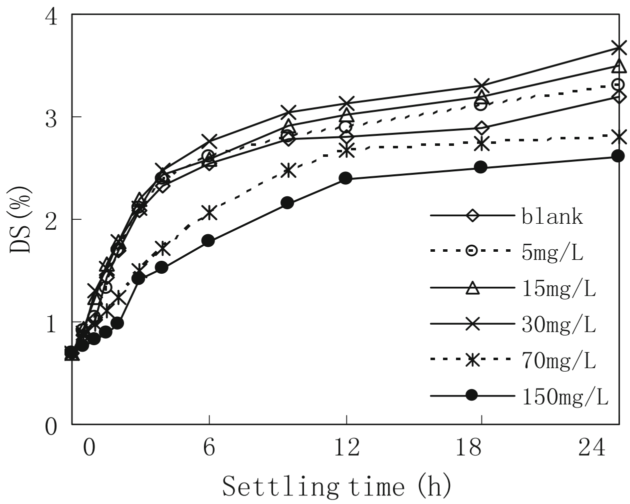

Fig. 2 Impact of PAM addition on bio-sludge gravitational thickening

optimum dose depended on sludge properties and normally ranged from 0.1 to 0.5% of sludge DS. In this study, the optimal PAM dose was 30 mg/L (Fig. 2). When 30 mg/L PAM was added, 12 h was enough to increase sludge DS to 3.17% and reduce sludge volume by 80%. Comparing to the blank (Fig. 1), the settling time was 50% less and, correspondingly, the settling tank size could be cut by 50%. Further increase of PAM dose worsened the sludge settling.

Bio-sludge sonication

Sonication was then applied to the bio-sludge. The effects of sonication on sludge dewaterability depended strongly on the sonication conditions (Tiehm et al. 2001; Yin et al. 2004; Wang et al. 2005; Dewil et al. 2006). The three most important parameters in sonication are power density, sonication time, and sound frequency (Hua and Hoffmann 1997). Following section examined the three parameters in details.

Impact of sound frequency

Higher frequencies benefited free-radical reactions while lower frequencies provided stronger mechanical effects (Hua and Hoffmann 1997). Low frequencies were normally used for sludge sonication (Schlafer et al. 2002; Bougrier et al. 2006) and Wang et al. (2005) demonstrated that free-radical reaction had little influence on bio-sludge. Three ultrasound frequencies, 25, 40, and 150 kHz, were examined in this study and the low frequency of 25 kHz was better than the other two frequencies, but the difference was insignificant. After 12 h gravitational settling, the bio-sludge was concentrated to 3.14, 3.09, and 2.89% DS after sonication by ultrasound at 25, 40, and 120 kHz, respectively. Therefore, the sludge settleability was mainly impacted by the sound intensity and duration while frequency was less important.

Impact of ultrasonic power density

Ultrasonic power density must be higher than certain threshold to cause acoustic cavitation and the level of power density determines the intensity of acoustic cavitation (Suslick 1990). Too strong sonication would significantly reduce the sludge size (Chu et al. 2001); smaller flocs might adsorb more water and, hence, deteriorated the sludge dewatering (Wang et al. 2006). Similar effects were observed in this study (Fig. 3). Power density of 0.1 W/mL showed little improvement of bio-sludge thickening and ∼20 h was needed to achieve 3% DS. Power densities of 0.15 and 0.25 W/mL were much better; under both conditions, the settling time needed to achieve 3% DS was shortened to 10 h, a 50% cut comparing to that of the blank. Further increase of power density actually deteriorated the bio-sludge settleability. When 1.0 W/mL ultrasound was applied, the bio-sludge DS was only 2.4% after 24 h thickening. Though 0.25 W/ml was slightly better than 0.15 W/mL, the energy consumption was 60% higher. Therefore, the power density level of 0.15 W/mL was selected.

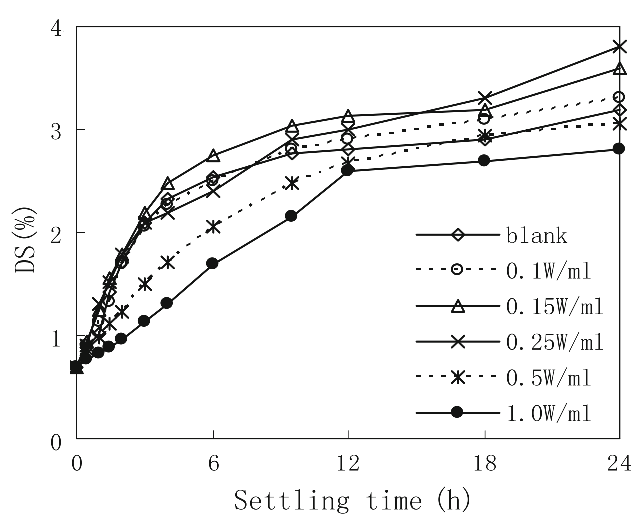

Fig. 3 Impact of sonication power density on bio-sludge gravitational thickening, 15 s, 25 kHz

Impact of sonication time

Yin et al. (2006) reported sonication duration of 2–4 min was the best. However, it was found that much shorter time was enough and sonication longer than 30 s even slowed down sludge thickening (Fig. 4). This particular contradictory result might because of different sludge characteristics. Bio-sludge used in this study was obtained from a wastewater treatment plant that treated urban sewage using the conventional activated sludge method, and had a DS of ~6,750 mg/L. Sludge used by Yin et al. (2006) was obtained from a wastewater treatment facility that treated petrochemical wastewater and had a DS of 20,000–40,000 mg/L. The bio-sludge settling improved with the increasing sonication time from 3 to 15 s. However, the thickening improvement from 7 to 15 s was insignificant while the energy consumption doubled.

The microphotographs of floc structure obtained before/after sonication showed that sonication could change the floc structure, and the change varied with the energy input (Fig. 5). In low frequency (25 kHz) and power density (0.15 W/mL), sludge floc structure changed significantly during sonication. With short sonication (3 and 7 s) the sludge floc density increased, the volume decreased and the floc structure became more compacted. With sonication of 15 s, although the structure of sludge became unconsolidated, the frame of sludge still remained. After 30 s sonication, the floc volume decreased sharply; sonication of 1 min faded floc core, lowered floc size, and destructed the sludge frame. With sonication of 2 min, particles in floc became more and more loose and the frame of sludge was thoroughly broken down.

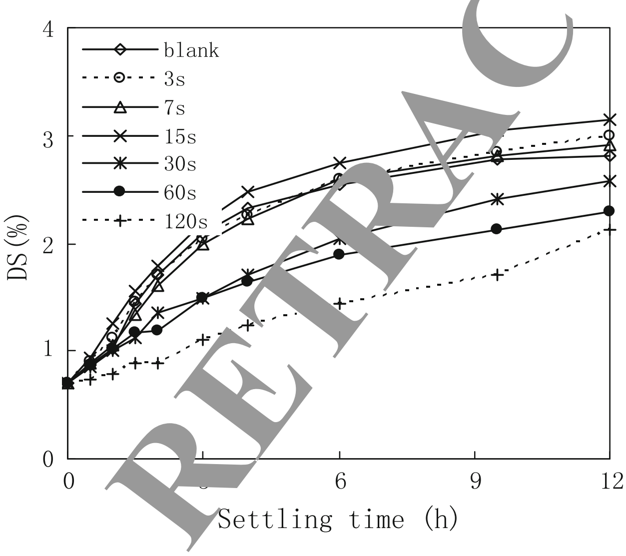

Fig. 4 Impact of sonication duration on bio-sludge gravitational thickening, 0.15 W/ml, 25 kHz

Clearly, short sonication was beneficial for striking the sludge floc. Therefore, a sonication time of 7 s is suggested.

Discussions on bio-sludge sonication

Comparing findings in Figs. 1, 2, 3, and 4, there were three ways to achieve the design goal of gravitational thickening (3% DS): settling for 24 h, adding PAM and treated by weak sonication.

Generally, low power density and short time were preferred for sludge dewatering (Chu et al. 2001). Feng et al. (2009) reported that ultrasonic energy input below 4,400 kJ/kg DS was beneficial to sludge dewatering and the optimum value was 800 kJ/kg DS. Na et al. (2007) found the upper limit to be 2,000 kJ/L, beyond which the sludge capillary suction time significantly increased. Yin et al. (2006) suggested a power intensity of 400 W/m^2 and duration of 2–4 min for enhancing sludge dewaterability; the energy consumption was unavailable since detailed information about the reactor was unknown. In this study, the ultrasonic energy dose was 0.5–18 kJ/L or 75–2,670 kJ/kg DS. It was found that energy dose higher than 680 kJ/kg DS was too strong for sludge settling and the best energy dose was 155 kJ/kg DS, both values were much lower than those reported in literatures (2,000–45,000 kJ/kg DS). The energy dose data could not be compared directly since very different types of sludge and sonication devices were used in different studies. The sludge DS and sonication duration were unknown in Feng's study (Feng et al. 2009), while digested sludge was used in Na's study (Na et al. 2007). Furthermore, it was suspected that the huge gap between energy dose in this study and the literature values was because of different purposes pursued. This study targeted at enhancing the gravitational thickening of sludge, while other studies aimed at improving the mechanical dewaterability of sludge. The sludge settleability and dewaterability, though closely related to each other, depended on different properties (Mikkelsen 2001).

The SCOD increase (Fig. 6) indicated that sonication might damage the integrity of sludge floc and released partial intracellular materials, which then could alter the compatibility in liquid–solid separation of sludge (Emir and Erdincler 2006).

Researches found that EPS concentration is the one of the most important factors affecting the sludge's dewaterability. EPS are highly hydrated and high EPS concentrations increase the sludge viscosity and decrease its dewaterability (Wang 2006). Keiding and Nielsen (1997)

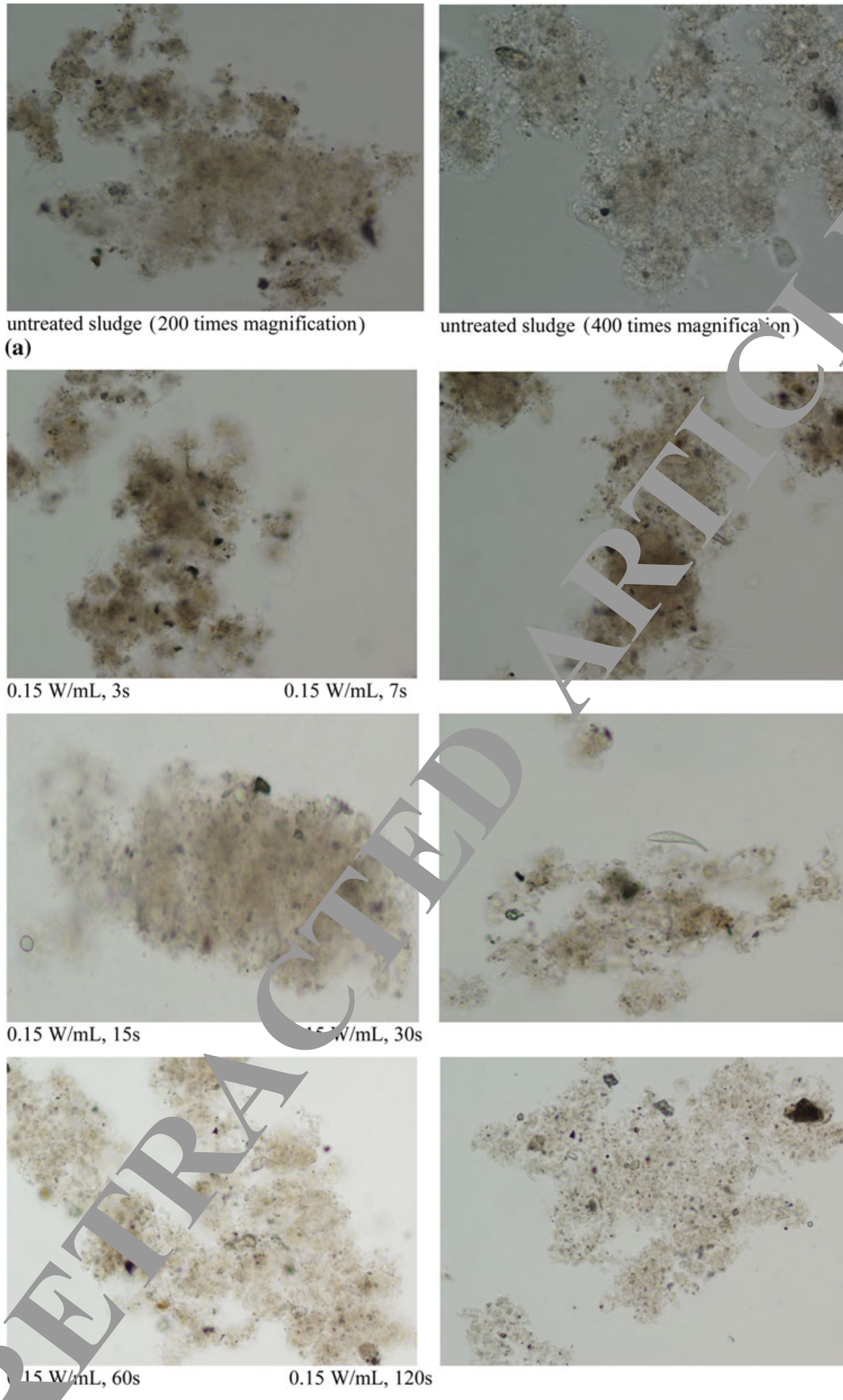

Fig. 5 Microphotographs of floc structure, 0.15 W/mL, 25 kHz. **a** Floc structure in untreated sludge, **b** floc structure changes during sonication (magnification ×400)

proposed that EPS components were bound by very weak forces and it was very important to the colloidal stability of the floc. The SCOD increased either from EPS release or cellular materials release. With powerful sonication, the sludge floc was disrupted, the size was diminished, and EPS and cellular materials were released, resulting in rapid increase of SCOD to 2,000 mg/L or higher (Chu et al. 2001), but weak sonication used in this study was unlikely to break the bacterial cells and release the cellular materials (Zhang et al. 2007). Therefore, majority SCOD increase from EPS release was proposed in this study. Feng et al. (2009) found that the sludge capillary suction time was relatively stable and low (<100 s) when the supernatant EPS was below 500 mg/L, increased to 200–320 s when the supernatant EPS was 600–900 mg/L, and then jumped to 680 s when the supernatant EPS was more than 900 mg/L. Correspondingly, it was found that when the SCOD increase was lower than 300 mg/L, the sludge settleability was good; when the SCOD increase was more than 600 mg/L, the sludge settleability significantly deteriorated.

The SCOD increased more rapidly with sonication power/time increase when the power/time was low and slowed when the sonication power/time was beyond certain limits (Fig. 6). The same phenomenon was reported by Wang et al. (2005). Studies showed that for bio-sludge disintegration, sonication with high density and short duration was more effective than sonication with low density and long duration at the same energy dose (Zhang et al. 2007). In this study, SCOD increase was more sensitive to the power density than to sonication time (Fig. 6). Correspondingly, the bio-sludge settling was more sensitive to power density (Figs. 3 and 4) and the workable power density range was very narrow (0.1–0.25 W/mL).

Ca^{2+} and Mg^{2+} are the most important cations for EPS, which have bridging adsorption action and can greatly affect the structure of EPS. The concentration changes of Ca and Mg in supernatant during sonication were studied in Fig. 7. In the first 7 s of sonication, both concentrations in supernatant decreased sharply, since lower power density sonication released the cations of Ca^{2+} and Mg^{2+}, which were beneficial for bridging adsorption of EPS and the flocs became more compacted; with further sonication, the structure of EPS was broken. Regardless of the release of the protein and polysaccharide in EPS, the concentration of Ca in supernatant decreased because the released organic matters would absorb Ca^{2+} till the absorption reached equilibrium. Sonication with 120 s lowered the particle size. The small sludge particles with negative charges would absorb the cation of Ca^{2+}, which resulted in the great decrease of Ca^{2+} in supernatant. For Mg, the concentration in supernatant was the lowest when sonication for 7 s; with further sonication, the concentration increased, since further sonication broke EPS and the sludge structure was loose, resulting in the release of Mg in liquid phase. The release of Mg was higher than that of Ca (Wang 2006), which could explain that the concentration of Mg in supernatant was high after sonication.

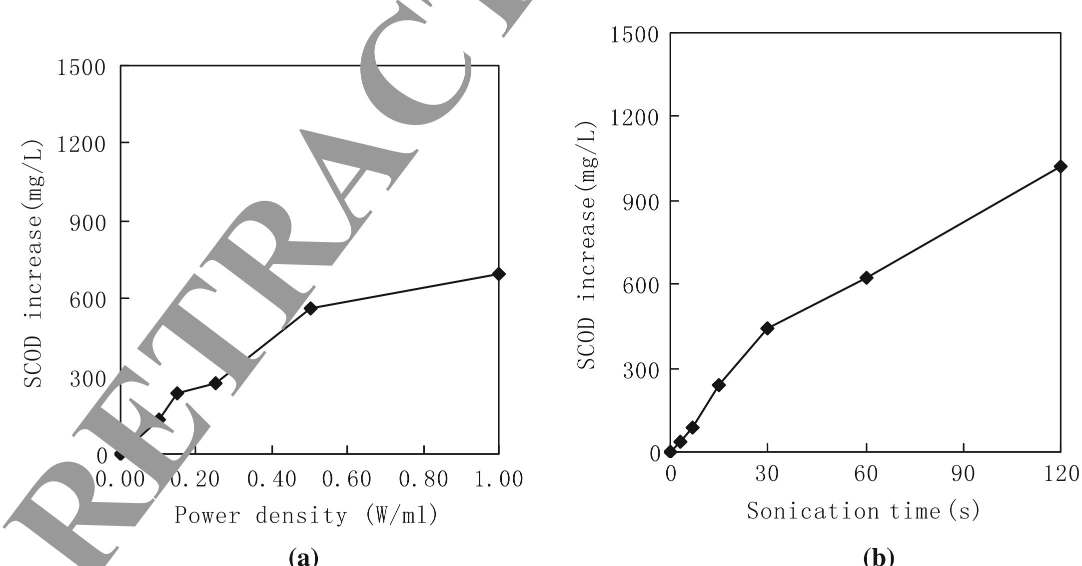

Fig. 6 Bio-sludge SCOD increase during sonication, **a** 15 s, 25 kHz **b** 0.15 W/mL, 25 kHz

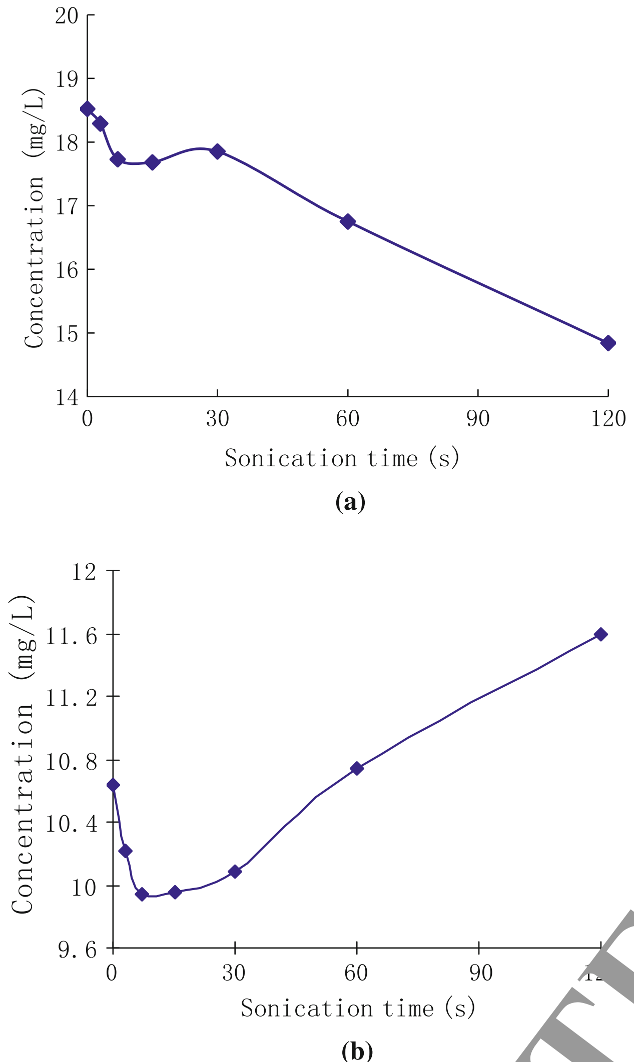

Fig. 7 Concentration increase of Ca and Mg in supernatant during sonication, 0.15 W/mL, 25 kHz. **a** Concentration increase of Ca in supernatant, **b** concentration increase of Mg in supernatant

Therefore, sonication could change the binding of EPS and released EPS into the supernatant; weak sonication was beneficial for sludge thickening.

Though sonication accelerated the bio-sludge settling, it did not increase the final sludge DS after thickening (Figs. 2, 3, and 4). There are four categories of water in bio-sludge: free water, interstitial water, surface water, and chemically bound water (Kopp and Dichtl 2001). Thickening removes free water, which is not associated with the particles. Feng et al. (2009) examined the sludge water distribution during sonication, and found that change of free water was negligible when energy dose was below 17,600 kJ/kg DS. Therefore, sonication at low energy dose

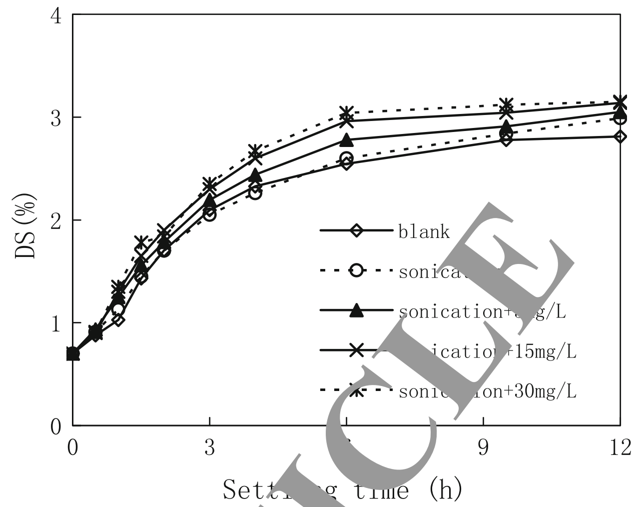

Fig. 8 Combinations of sonication and PAM for bio-sludge thickening, 0.15 W/mL, 7 s, 25 kHz

did not change the final water content in the thickened bio-sludge.

Bio-sludge with sonication and PAM addition

Results in above-mentioned sections showed that the bio-sludge needed 24 h for gravitational settling to achieve 3% DS, the process could be shorted by half to 12 via weak sonication (energy dose <680 kJ/kg DS) or via adding 30 mg/L of PAM. The combination of sonication and PAM on the bio-sludge thickening were further examined. The aim was to examine whether it was possible to further shorten the settling time or increase the dry weight concentration. Obviously, combination of weak sonication with polyelectrolyte coagulant significantly cut the settling time needed for 3% DS to 6 h (Fig. 8) and 15 mg/L PAM was sufficient for bio-sludge coagulation with the aid of sonication. Such beneficial effects of sonication combined with polyelectrolyte have been reported before; researches showed that the combination enhanced the sludge dewatering/filtration and saved polyelectrolyte (Bien and Wolny 1997; Na et al. 2007; Feng et al. 2009). Application of ultrasonic field was believed to change the inner structure of polyelectrolyte, which then intensified the polyelectrolyte activity on sewage sludge (Yin et al. 2004). Similar to the findings in the last section, combination of sonication and PAM did not improve the final sludge DS due to the stable distribution of free water (Feng et al. 2009).

Conclusion

Large amount of waste bio-sludge is generated from the wastewater treatment processes. With a water content of 99.2–99.8%, the first step is thickening, which is the single most effective step in sludge volume reduction and its efficiency determines the overall effect of sludge handling. Gravitational settling is a low-cost method for thickening but the process is very slow due to the ultra-compactability of bio-sludge. This paper used weak sonication to enhance this process. Very low energy (155 kJ/kg DS) was sufficient to shorten settling time from 24 to 12 h, which equaled the effect of adding 30 mg/L polyacrylamide, a common polyelectrolyte for sludge treatment. The optimum conditions were: 0.15 W/mL, 7 s, and 25 kHz. Ultrasound energy dose higher than 680 kJ/kg DS deteriorated the bio-sludge settling by release too much loosely bound extracellular polymeric substances into supernatant. Another way to use sonication was to combine it with 15 mg/L polyacrylamide; such a hybrid treatment further reduced the settling time to 6 h. With all the treatments, the final water content of the thickened sludge did not change much due to the stable free water distribution in sludge floc. The ultrasonic energy dose used in this study was one order lower than that needed for sludge conditioning. The minimum energy consumption made weak sonication highly attractive since it significantly reduced/eliminated the need for expensive polyacrylamide or shorten the thickening time by 50% or more. However, cautions must be taken to apply these findings to bio-sludge thickening in general since the changes of sludge thickening were very sensitive to sludge properties, polyelectrolyte, and sonication conditions.

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