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Study of sludge moisture distribution and dewatering characteristic after cationic polyacrylamide (C-PAM) conditioning

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ABSTRACT

Dewatering is a key step in sludge handling, and flocculant conditioning is the commonest way to improve the sludge dewatering. The sludge dewatering performance is largely affected by the sludge moisture distribution. But changes of sludge moisture distribution by flocculants were unclear and literature findings were controversial to each other. This paper investigated the changes of sludge moisture distribution and sludge dewatering characteristics after flocculant conditioning, and the flocculant used was cationic polyacrylamide (C-PAM). Results showed that C-PAM conditioning effectively changed the sludge moisture distribution, sludge viscosity, specific resistance of filtration (SRF), particle size, extracellular polymeric substances (EPS) concentration, and filtrate liquid viscosity. Especially, free water was increased by C-PAM conditioning and the highest value reached 95.04%. On the other hand, the interstitial water content was decreased by C-PAM conditioning. The optimal dosage was 3 mg g^{-1} TS considering both effects and cost. After C-PAM conditioning, the mean sludge particle size increased to 219.1 μm, the sludge SRF reduced by 87%, and the supernatant EPS decreased. Specifically, the filtrate liquid viscosity could also determine the optimal dosage of C-PAM and an equation was proposed for the correlation between filtrate viscosity and C-PAM dosage.

Keywords: Sludge moisture distribution; SRF; Coagulation; Extracellular polymeric substance

1. Introduction

Excess sludge is the unavoidable byproduct of biological wastewater treatment. Each year, more than 100 million tons of excess sludge (dry weight) is generated worldwide. The sludge treatment accounts for more than 60% of total cost in municipal wastewater treatment plants [1]. The excess sludge contains around 99% of water. Therefore, dewatering is the most important step in sludge handling to reduce the sludge volume. Typical sludge dewatering process involves chemical conditioning and mechanical dewatering. The chemical conditioning of sludge before dewatering is necessary to increase the processing effi-

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ciency of dewatering device through enlarging the floc size and compressing the floc interior [2]. The chemicals used to improve the sludge dewaterability include alum, iron(III) chloride, iron(II) sulfate, and polyelectrolyte [3]. Polyacrylamides (PAMs) are the primary choice for sludge conditioning, especially the cationic polyacrylamide (C-PAM) [4,5]. Improvements in the sludge dewaterability and reductions in the sludge volume are ascribed to changes in sludge physical characteristics, such as floc size, density, fractal dimension, and rheological properties [6–8], which are brought about by polymer conditioning.

Usually the sludge moisture can be divided into four categories [9,10]:

(1) Free water, which is not bound to the particles.
(2) Interstitial water, which is bound by capillary forces between sludge flocs.
(3) Surface water, which is bound by adhesive forces.
(4) Bound water.

The last two categories (surface water and bound water) can be grouped as bounding water. Free water is the easiest to be removed while bounding water is the hardest one. It is necessary to measure the sludge water distribution to predict the dewaterability of sludge. There are some literatures trying to explore the possible correlation between the water distribution within the sludge and the sludge dewatering performances, but no clear conclusion could be drawn. Smollen [11] found that sludge water distribution had no correlation with its capillary suction time, an index of dewaterability. Robinson and Knocke [12] reported that the relationship between sludge water distribution and its specific resistance of filtration (SRF) was vague.

Specifically, there have been some researches about the changes of sludge moisture distribution after flocculant conditioning. However, the conclusions of scientific literatures in this field reveal certain discrepancies because of controversial data and definitions [13]. Kopp and Dicht [9] reported that polymer conditioning increased the velocity of sludge water release, but the free water content was not influenced by this process. As to the bound water, Katsiris and Kouzeli-Katsirit [13] reported decreasing bound water content with increasing polymer dosage. Smollen [11] had a reverse conclusion that the bound water content increased after polymer addition due to the adsorption of water molecules onto the polymer molecules. Wu et al. [14] suggested that the bound water of alum sludge decreased firstly and then increased with the polymer dosage. Chu and Lee [15] reported a similar trend as Wu et al. Still, some argued that bound water was not changed by conditioning [16]. The comparison was based on results from different publications, so the referential value was weakened due to great differences in experimental conditions and materials [17], and different classifications of the sludge moisture distribution.

This work investigated the effects of C-PAM conditioning on the status of moisture distribution and dewatering characteristics of sludge. The purpose was to better understand the specific process of C-PAM conditioning, and make it play a more effective role in sludge dewatering. The specific resistance to filtration (SRF), viscosity (the sludge viscosity and filtrate viscosity), sludge particle size, and extracellular polymeric substance (EPS) concentration were also investigated. The mechanism behind the changes observed in sludge moisture distribution was also discussed. With the help of experiments, it is possible to determine the polymer demand for sludge conditioning. The results of this study will improve the current understanding on sludge conditioning and dewatering.

2. Materials and methods

2.1. Materials

Excess sludge was collected from a pilot wastewater treatment tank in the lab. The sludge total solids content (TS) was around 5,780 mg/L, the total chemical oxygen demand (TCOD) was around 6,910 mg/L, the volatile solids content (VS) was around 4,580 mg/L, the supernatant chemical oxygen demand (SCOD) was around 141 mg/L, the pH was around 7.4, and the temperature was 19–26℃. It was concentrated to TS of 1.5% through thickening.

C-PAMs are the commonest flocculant used for sludge conditioning in China. In this work, the used C-PAM had a cation concentration of 20% and a molecule weight of 8–15 million (Futong Chemicals, Tianjin, China). Polymer solution (0.1% w/w) in stock was made. Before chemical conditioning, the stock solution was diluted with distilled water to the final designed concentration.

2.2. Experimental

For each experimental run, 100 ml of sludge was conditioned. The sludge and C-PAM solution was careful mixed to homogenize the sludge with C-PAM in a 250 ml beaker. The procedure was as following: 120 r min^{-1} for 10 min and then 40 r min^{-1} for 30 min, which was a procedure in a local wastewater treatment plant. Sludge dewatering was achieved by vacuum filtration.

2.3. Analysis

Drying test was applied to determine sludge moisture distribution [18]. This technique assumes that the rate of water evaporation depends on the type of bond between the water and solid particles. Some sludge sample was introduced to the balance dish. The dish was dried in an air dry oven with a temperature of 30℃ and at a controlled humidity by sparging the oven with 400 ml min^{-1} of compressed dry air [17]. The sludge mass was recorded at 10 min intervals at earlier stage, and later it was recorded at 5 min intervals. When there was no change in sludge mass, the sludge sample was heated at 105℃ for 12 h. By this method, a typical drying curve could be gained (Fig. 1).

The EPS content of sludge supernatant was determined spectrophotometrically with a double beam UV–visible spectrophotometer. Proteins were determined by the modified Lowry method [19]. Polysaccharides were measured by the anthrone method [20]. Viscosity was determined using a rotational viscosity meter (NDJ-5S, China). Sludge SRF was measured following the method of Feng et al. [3]. The pH was measured using a Hach pH meter. The sludge size distribution was measured with a laser diffraction particle size analysis (Mastersizer 2000, Malvern Instruments, UK). The sludge water content, TS, VS, and TCOD were measured according to the standard methods given in APHA [21]. All the reported values were the average of three or more repetitive experimental data.

3. Results and discussion

3.1. Sludge moisture distribution after C-PAM conditioning

The sludge water content after vacuum dewatering was 90.4, 88, 86.7, 85.1, 84.9, and 86% for the blank, 1, 2, 3, 4, and 5 mg C-PAM g^{-1} TS samples, respectively. Fig. 2 reports the changes of sludge moisture distribution before and after C-PAM conditioning. Almost 99% of moisture existed as free and interstitial water in the raw sludge. These two types of water are easy to be removed during dewatering. Fig. 2(a) shows that the sludge water distribution had significant changes after C-PAM conditioning. Compared to the raw sludge, the proportion of free water, interstitial water, surface water, and bounding water all had significant changes.

Fig. 2(b) and (c) shows in details the changes of free water and interstitial water distributions in sludge after C-PAM conditioning. Clearly, after C-PAM conditioning, the free water content of sludge increased and the interstitial water content decreased. Comparing Fig. 2(b) and (c), it suggested that the changes of free water and interstitial water were in the opposite trend. With the increase of C-PAM dosage, the free water content increased firstly and then decreased, and the interstitial water decreased firstly and then increased. When the dosage of C-PAM was 4 mg g^{-1} TS, free water content reached the highest level of 95.01%, which was a significant change. The increase of free water by chemical conditioning was also reported by Robinson and Knocke [12] and Colin and Gazbar [22], but Kopp and Dicht [9] and Tsang and Vesilind [16] reported no significant change in free water content by chemical conditioning, which might

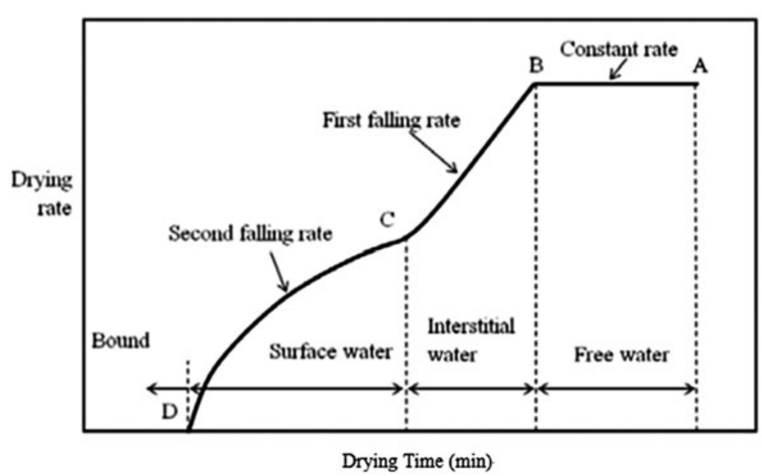

Fig. 1. Typical sludge drying curve.

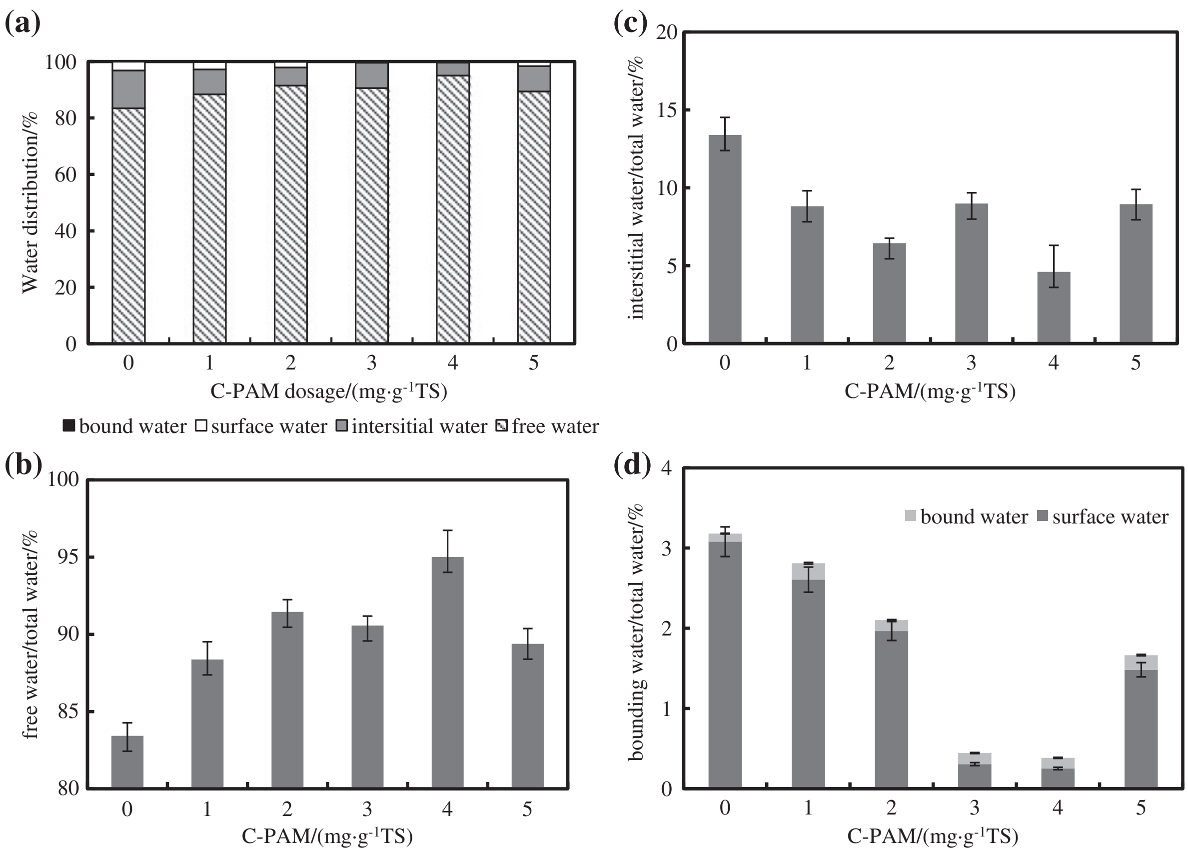

Fig. 2. The sludge water distribution after C-PAM conditioning.

be because they used different coagulants and different sludges.

The changes of bounding water (including surface water and bound water) distribution in sludge after C-PAM conditioning were shown in Fig. 2(d). As the most difficult part to be removed during dewatering, reducing bounding water ratio had significant meaning for sludge dewatering. Clearly, the bounding water decreased firstly and then increased with the C-PAM dosage increase. Specially, when the dosage of C-PAM increased from 0 to 4 mg g^{-1} TS, the bounding water content decreased from 3.18 to 0.38%; oppositely, from 4 to 5 mg g^{-1} TS, the bounding water content increased from 0.38 to 1.67%. When the dosage of C-PAM was 3 and 4 mg g^{-1} TS, the bounding water ratio reached the lowest level of 0.44 and 0.38%, respectively. In the study of Katsiris and Kouzeli-Katsiri [13], all chemical processes resulted in the reduction of the bound water and the specific resistance, which was somehow different with results in Fig. 2. The reason might be that they used different coagulants ($FeCl_3$, $AlCl_3$, $FeSO_4$, and polyelectrolytes).

Conventionally, C-PAM was used to aggregate sludge particles through charge neutralization and inter-particle bridging [2,23,24]. C-PAM acted as either coagulant by reducing the zeta potential of the solid particles or flocculant through the bridging effect to form proper-sized flocs [25]. So sludge structure was more compact and rigid. When the dosage of C-PAM was from 0 to 4 mg g^{-1} TS, bounding water decreased for the replacement of water molecules on the solid surface by the polymer molecules at lower dose regimes [13,16]. Katsiris and Kouzeli-Katsiri [13] proposed that the state where bound water has reached its minimum value corresponded to optimum surface coverage of the particle by the coagulant. When the dosage of C-PAM was from 4 to 5 mg g^{-1} TS, according to Smollen [11], the excess polymer molecules attached onto the particle surface could absorb moisture from bulk water phase in overdosed regimes, so much more bound water content was found. Therefore, the 3–4 mg g^{-1} TS dosage was preferred.

3.2. *Changes of sludge dewatering characteristics after C-PAM conditioning*

The sludge SRF and viscosity (including sludge viscosity and filtrate viscosity) were monitored to assess the dewaterability of the C-PAM conditioned sludge. The results were summarized in Fig. 3.

Both sludge viscosity and SRF decreased after C-PAM conditioning. When the C-PAM dosage was from 0 to 3 mg g^{-1} TS, the sludge SRF decreased significantly; when the C-PAM dosage was more than 4 mg g^{-1} TS, SRF did not change much with further increase in polymer dosage. The results suggested that 3 or 4 mg g^{-1} TS was the ideal dosage of C-PAM. The sludge viscosity decreased with the C-PAM dosage increase, while the sludge filtrate viscosity decreased firstly and then increased. When the dosage of C-PAM was 3 or 4 mg g^{-1} TS, sludge filtrate viscosity remained at very low levels. The correlation between C-PAM dosage and sludge filtrate viscosity could be described as:

$$y = 1.7375\,x^2 - 11.033\,x + 73.096 \quad (1)$$

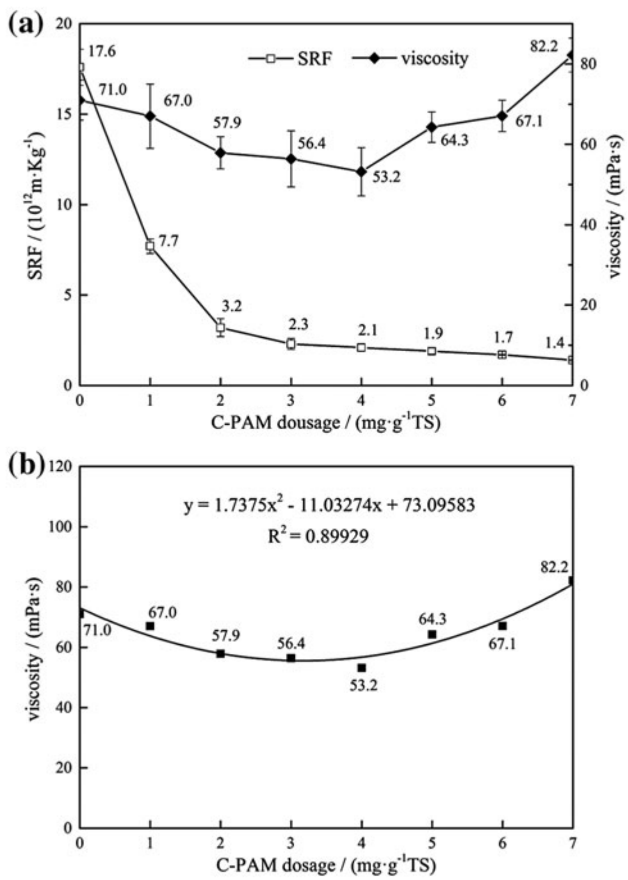

Fig. 3. Sludge SRF and sludge filtrate viscosity after C-PAM conditioning: (a) sludge SRF and sludge filtrate viscosity and (b) correlation between C-PAM dosage and sludge filtrate viscosity.

in which y = sludge filtrate viscosity, x = C-PAM dosage, and the $R^2 = 0.9$.

The mechanism of applying coagulation/flocculation technology was generally to aggregate small particles into larger ones and to remove the colloidal matter present in the wastewater [26]. The dewaterability of sludge was determined in terms of filterability and compactibility, which were improved by the increase in floc size and strength, so sludge had a better dewaterability [27].

According to Einstein viscosity formula [28], sludge filtrate viscosity was mainly dependent on the concentration of suspended particles and residual C-PAM. With the dosage of C-PAM increasing, sludge particles gathered mutually, so the concentration of suspended particles decreased, so did the sludge filtrate viscosity. When the dosage of C-PAM was 3 or 4 mg g^{-1} TS, the flocculation effect of C-PAM was ideal, and the sludge filtrate viscosity remained at very low levels. In the overdosed regime, high concentration of residual C-PAM led to an increase of sludge filtrate viscosity.

In conclusion, the ideal dosage of C-PAM was 3 or 4 mg g^{-1} TS, but considering the cost, the optimal dosage of C-PAM was 3 mg g^{-1} TS.

3.3. *Changes of sludge particle size and sludge supernatant EPS after C-PAM conditioning*

The variations of particle size distribution of sludge flocs were given in Fig. 4. The floc size increased obviously after C-PAM conditioning. When the dosage of C-PAM was 3 mg g^{-1} TS, the mean volume diameter of sludge flocs reached the largest value of 219.09 μm.

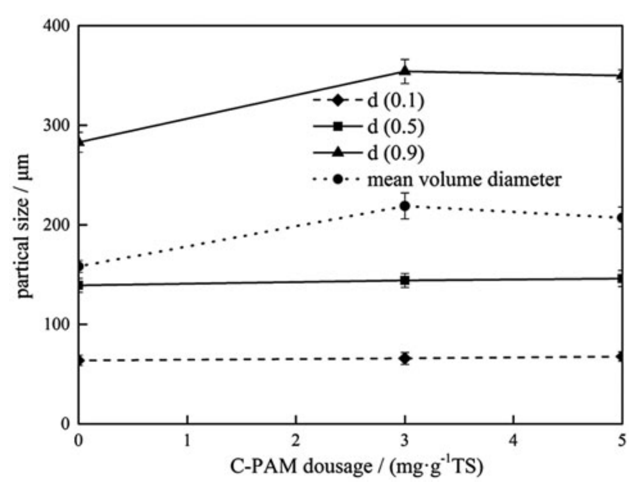

Fig. 4. Particle size distribution (based on volume) of sludge after C-PAM conditioning.

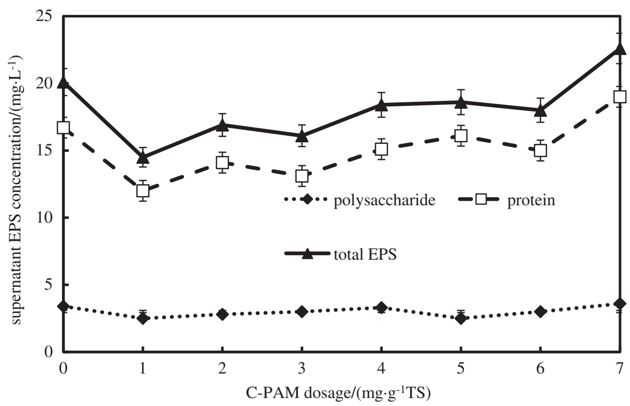

Fig. 5. Supernatant EPS concentration after C-PAM conditioning.

The increase of flocs size meant that the sludge interstitial water was squeezed out through inter-particles squeezing due to more compacting structure, leading to free water increase. When the dosage of C-PAM was more than 3 mg g^{-1} TS, there was an extremely slow decrease on the particle size. At this time, there were much more cations with the increase of C-PAM dosage. Then the sludge had a certain degree of loose for the repulsion between sludge particles. Loose structure of sludge absorbed part of free water into interstitial water, so the free water content decreased and interstitial water content increased on the contrary. These changes might explain the changes of moisture distribution with C-PAM dosages (Fig. 2).

EPS is a key component of sludge flocs and significantly influence the sludge dewatering performance. The effects of C-PAM on EPS concentration in the sludge supernatant were examined and the results were expressed in Fig. 5. The initial EPS proteins and polysaccharides in the supernatant of raw sludge were at concentrations of 16.7 and 3.4 mg L^{-1}, respectively. After conditioning with C-PAM, the soluble EPS had a slight drop firstly, then increased slightly when the dosage of C-PAM was more than 6 mg g^{-1} TS.

After conditioning with C-PAM, the soluble EPS were more difficult to be extracted [29,30]. This result was consistent with particle size analysis and sludge moisture distribution, for the sludge flocs were compressed and became smaller and more compact after C-PAM conditioning. Besides, with the action of C-PAM, the soluble microbial products combined with the sludge flocs, then transferred from the aqueous phase to the solid phase, so the soluble EPS decreased accordingly. In overdosed regimes, excessive cations made colloidal particles become stable and scattered again, so it was easier to extract the soluble EPS, leading to a slight increase in the supernatant EPS concentration.

4. Conclusions

This paper studied the sludge moisture distribution and dewatering characteristic changes after C-PAM conditioning, and following conclusions could be drawn:

(1) The sludge moisture distribution changed significantly after flocculation conditioning. In general, the free water increased, the interstitial water decreased, while the bound water might increase or decrease depending on the C-PAM dosage.
(2) The optimal conditioning of C-PAM was 3 mg g^{-1} TS. After C-PAM conditioning, the floc size obviously increased, and the supernatant EPS concentration decreased firstly and then increased.
(3) The filtrate liquid viscosity also could be used to determine the optimal dosage of C-PAM.

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