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Enhancement of cationic polyacrylamide conditioning of sewage sludge with modified coal fly ash

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ABSTRACT

To improve the efficiency of sewage sludge conditioning, modified coal fly ash (MCFA) was introduced into the sludge conditioning with cationic polyacrylamide (CPAM). Specific resistance to filtration (SRF), net sludge solid yield (Y_N), modified filter cake moisture (FCM_m), and time to filter (TTF) were analyzed to evaluate the sludge filterability and dewaterability. Results showed that the MCFA addition significantly promoted the sludge filterability and dewaterability, compared with the single CPAM conditioning. There was a synergistic effect between the MCFA and CPAM conditioning. The suitable dosages of the CPAM and MCFA were 1.3 g kg^{-1} and 60% DS for the experimented sewage sludge, respectively. Under the suitable conditions of dual conditioning, the Y_N of sludge conditioned increased by 383%, and the TTF reduced by 427 s, compared with that of raw sludge; the FCM_m of sludge conditioned was 82.9%. The change in zeta potential and floc size of sludge particles after conditioning suggested that the dual conditioning improved the sludge filterability and dewaterability mainly because of the interactions between sludge and MCFA, CPAM.

Keywords: Sludge conditioning; Modified coal fly ash; Flocculation; Skeleton builder; Compressibility

1. Introduction

Water content in excess sewage sludge is more than 99%, therefore, handling and disposal of the excess sludge lead to a rather high cost in wastewater treatment plants (WWTPs) [1], which amounts to approximately 50% of the total operating cost of whole WWTPs [2]. It is economically valuable to reduce sludge volume by dewatering. Polymers have been practically used as chemical conditioners for flocculating the sludge particles and improving the sludge dewaterability before mechanical dehydration for decades, and polymer dosage significantly influences the sludge dewatering efficiency. However, a high polymer dosage results in a high cost for sludge management [3]. At present, cationic polyacrylamides (CPAM) are the most commonly used sludge conditioner in WWTPs. Nevertheless, the sludge is unable to be dewatered as desired at an acceptable polymer dosage [4].

Some materials with inert properties derived from industrial or agricultural wastes can be applied as physical conditioners, which are more inexpensive than the chemical conditioners. The physical conditioners as skeleton builders have been employed to decrease the compressibility of the sludge cake, including fly ash [5,6], fine coal [7], hydrated lime [8], quicklime [9], cement kiln dust, bagasse [10], wood chips and wheat dregs [11], gypsum [12,13], phosphogypsum [14,15], lime [16,17], lignite [18,19], rice husk [20,21], sawdust [22], and cinder [23], etc. When these skeleton

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builders were added into the sewage sludge, a permeable and rigid lattice structure of sludge cake could be formed to remain channels for water transmission under high pressure [10], further to improve the filterability of sludge cake. As a result, the polymer dosage for sludge flocculation could significantly reduce. Moreover, the physical conditioners show the advantages of increasing solid content of sludge cake and enhancing cake detachment from filter media [24].

In our previous study [25], it was demonstrated that the modified coal fly ash (MCFA) with sulfuric acid was effective for excess sludge conditioning. However, the MCFA dosage was high when the excess sludge was conditioned by the MCFA alone, which might lead to an increased volume of dewatered sludge and a higher cost of subsequent processing. In this study, the MCFA was combined with CPAM to condition the sewage sludge. The conditioning and dewatering behaviors of excess sludge with dual conditioning were investigated.

2. Materials and methods

2.1. Sewage sludge sample

The sewage sludge was obtained from the inlet of sludge thickening tank from one local WWTP in Changsha, Hunan Province, China. The sludge samples were stored in a refrigerator at 4°C after collection, to minimize microbial activity. The sludge samples were kept in a water bath at a temperature of 20°C ± 2°C for 30 min before experiments. The characteristics of sludge samples are presented in Table 1.

Table 1
Properties of raw sewage sludge

Parameter	Value
Total suspended solids (g L^{-1})	11.63–12.14
Volatile suspended solids (g L^{-1})	7.66–8.23
pH	6.4–6.8
Water content (%)	98.7–99.0
Filter cake moisture (%)	95.0–96.8
Specific resistance of filtration (m kg^{-1})	1.785×10^{13}–2.036×10^{13}
Compressibility	0.99–1.00

2.2. Conditioners

Coal fly ash was taken from one thermal power station in Zhuzhou, Hunan Province, China. The MCFA was prepared according to the literature [25]. The dried coal fly ash was soaked in a sulfuric acid solution of 4 mol L^{-1} at room temperature for 3 h, and the ratio of acid to coal fly ash was 5:1 mL g^{-1}. During soaking, the mixture was stirred with a speed of 30 rpm. After filtration of the mixture, the treated coal fly ash was dried at 105°C ± 2°C to a constant weight, milled and sieved with 120 meshes. The chemical conditioner CPAM (Praestol 851BC) is produced from Ashland Inc., Germany, which have a molecular weight of 1.2×10^8. The CPAM was completely dissolved in distilled water with a concentration of 0.1% (w/w), and the CPAM solution was freshly prepared every 24 h. All the chemicals used in this study were analytic grade, and the water used was distilled water.

2.3. Sewage sludge conditioning and filtration dewatering

The MCFA was first added into 100 mL sewage sludge in a beaker of 200 mL, and the mixture was mixed at 250 rpm for 30 s to ensure the MCFA dispersion. The CPAM solution was then added into the mixture and the mixture was stirred at 250 rpm for 30 s, and followed a slow agitation at 30 rpm for 2 min to promote flocculation. The conditioned sludge was poured into a Buchner funnel to be filtered. A standard Buchner funnel apparatus was used for vacuum filtration. If there were no special instruction, the Buchner test was carried out in a Buchner funnel with a diameter of 9 cm under 0.03 MPa vacuum pressure for 10 min. The specific resistance to filtration (SRF) was considered as the key index to evaluate the filterability of sewage sludge. The SRF (m kg^{-1}) is calculated by Eq. (1):

$$\mathrm{SRF} = \frac{2PA^2b}{\mu\omega} \tag{1}$$

where P is the filtration pressure (N m^{-2}), A is the filter area (m^2), b is the slope of filtrate discharge curve (t/V versus V) (s m^{-6}), μ is the filtrate viscosity (N s^{-1} m^{-2}), and ω is the cake solid weight per unit filtrate volume (kg m^{-3}).

However, the SRF was only used as a criterion to compare sludge conditioning effectiveness when the sludge solids remained relatively constant, independent of conditioner dosage [10]. When the added conditioners significantly influenced the amount of conditioned sludge solids, which contained the original sludge solids and the added conditioner solids, the sludge solid yield (Y) should be used for better description of the sludge filterability [26]. Y was related mathematically to SRF and could be calculated directly from the Buchner test [27]. The net sludge solid yield (Y_N, kg m^{-2} h^{-1}) was expressed as Eq. (2) [10]:

$$Y_N = F \times \left(\frac{2P\omega}{\mu \times t} \times \frac{1}{\mathrm{SRF}} \right)^{1/2} \tag{2}$$

where t is the filtration time (s) and F is a correction factor as Eq. (3):

$$F = \frac{\mathrm{SS}_{\mathrm{original}}}{\mathrm{SS}_{\mathrm{original}} + \mathrm{SS}_{\mathrm{conditioner}}} \tag{3}$$

where $\mathrm{SS}_{\mathrm{original}}$ is the original sludge solids (g L^{-1}) and $\mathrm{SS}_{\mathrm{conditioner}}$ is the conditioner solids (g L^{-1}).

Time to filter (TTF) is defined as the time when the filtrate volume increases to half of the volume of total sludge [28].

The SRF, Y_N, and TTF have been used as the main indexes for evaluating sludge dewatering, but they mainly express the sludge filterability. There is no evident link between the sludge filterability and cake moisture content of dewatered sludge. It is possible that the sewage sludge possesses good filterability, but the filter cake contains a high amount of residual water. Therefore, filter cake moisture (FCM) was used to directly evaluate the sludge dewaterability. After the sewage sludge was filtrated in a Buchner funnel under 0.03 MPa vacuum pressure for 10 min, the filter cake was dried in an oven at 105°C ± 2°C to determine the moisture content. In order to eliminate the influence of MCFA addition on the sludge solids, modified filter cake moisture ($\mathrm{FCM_m}$) of dewatered sludge was proposed as Eq. (4):

$$\mathrm{FCM_m} = \frac{W_{\mathrm{wet}} - W_{\mathrm{dry}}}{W_{\mathrm{wet}} - W_{\mathrm{MCFA}}} \times 100\% \tag{4}$$

where W_{wet} is the weight of wet filter cake (g), W_{dry} is the filter cake weight after drying at 105°C ± 2°C to a constant (g), and W_{MCFA} is the weight of added MCFA solids (g).

Some researchers [29,13] found that the sludge conditioning improved the sludge dewatering effectiveness by altering sludge compressibility. The sewage sludge contained a large number of fine particles [30]. These particles were easily deformed under high pressure during the filtration, and the channels and pores in sludge cake would be blocked, resulting in a reduction of filtration rate. As a result, the sludge filter cake held more water in the solid fraction. Therefore, not only the SRF, but also the sludge cake compressibility should decrease for a successful sludge conditioning. Coefficient of compressibility (s) showed a well-known empirical relation between the SRF under different pressures and the reference filtration pressure, as Eq. (5) [8,13]:

$$\frac{\mathrm{SRF}_i}{\mathrm{SRF}_0} = \left(\frac{P_i}{P_0}\right)^S \tag{5}$$

where P_i and P_0 refer to the applied pressure and reference pressure, respectively. SRF_i and SRF_0 are the SRF values corresponding to the pressures.

Parameter s can be obtained from a log–log plot of $\mathrm{SRF}_i/\mathrm{SRF}_0$ against the corresponding pressure ratio. The easier the filter cake is compressed, the larger the s value is. A nearly incompressible cake has a s value closed to zero, while the s value of highly compressible sludge is equal or higher than 1.

After sludge settlement for 15 min, the sludge supernatant was obtained. The zeta potential of sludge supernatant was measured with a Zetasizer Nano Instrument (ZEN3600, England).

Each experiment was performed in triplicate. The data shown in following sections were the average values with standard deviations.

3. Results and discussion

3.1. Single conditioning

3.1.1. Single CPAM conditioning

Fig. 1(a) displays the effect of CPAM dosage on sludge SRF. It was found that the sludge SRF decreased with increasing the CPAM dosage. The SRF decreased significantly in a CPAM dosage range from 0.7 to 1.5 g $\mathrm{kg^{-1}}$, while the sludge SRF decrease became insignificant when the CPAM dosage was higher than 1.5 g $\mathrm{kg^{-1}}$. Compared with the SRF of the raw sludge (1.89×10^{13} m $\mathrm{kg^{-1}}$), the SRF reduction was above 80% and the corresponding sludge SRF was 2.91×10^{12} m $\mathrm{kg^{-1}}$ with a CPAM dosage of 1.5 g $\mathrm{kg^{-1}}$.

The TTF and $\mathrm{FCM_m}$ of conditioned sludge at different CPAM dosages are shown in Fig. 1(b). The TTF decreased with increasing the CPAM dosage, which was corresponding to that of the sludge SRF change. There was a sharp TTF decline in the CPAM dosage range of 0.7–1.5 g $\mathrm{kg^{-1}}$, and the decrease was slight with a CPAM dosage higher than 1.5 g $\mathrm{kg^{-1}}$, indicating that the further increase of CPAM dosage was of little help to accelerating sludge filtration. From the change of the $\mathrm{FCM_m}$ in Fig. 1(b), it could be observed that the $\mathrm{FCM_m}$ gradually decreased from 89.28% to 85.42 % with increasing the CPAM dosage from 0.7 to 2.3 g $\mathrm{kg^{-1}}$. The $\mathrm{FCM_m}$ of conditioned sludge reduced by about 13.5% compared with that of raw sludge, however, the $\mathrm{FCM_m}$ was still higher than 85% after Buchner filtration at a CPAM dosage of 2.3 g $\mathrm{kg^{-1}}$. When the sewage sludge was conditioned with CPAM alone, the sewage sludge dewaterability was greatly improved. The larger the CPAM dosage was, the more effective the sludge conditioning was.

Results of compressibility tests for sludge conditioned with CPAM are shown in Fig. 2. The raw sludge was very

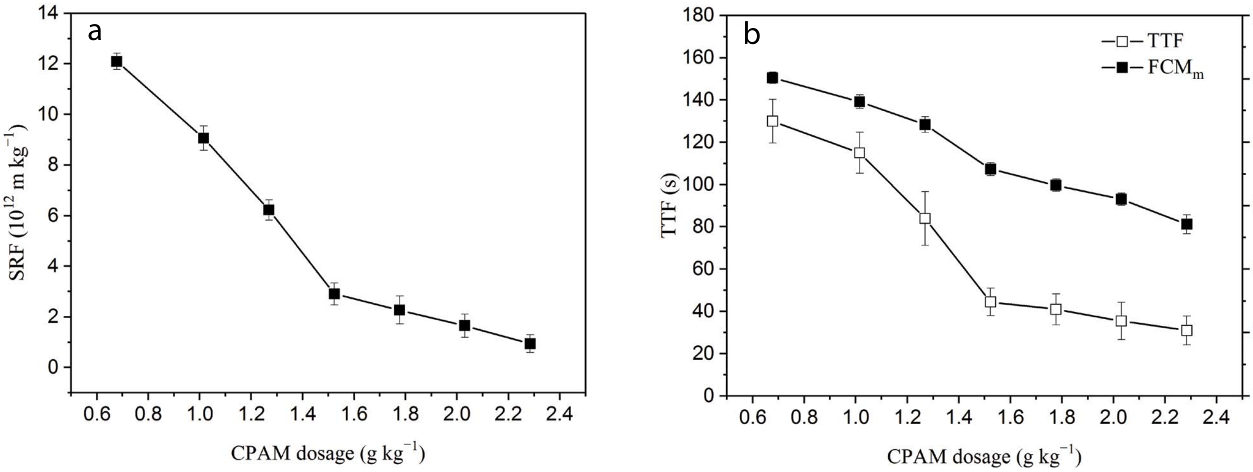

Fig. 1. Effect of CPAM dosage on characteristics of conditioned sludge, (a) SRF, and (b) TTF and $\mathrm{FCM_m}$.

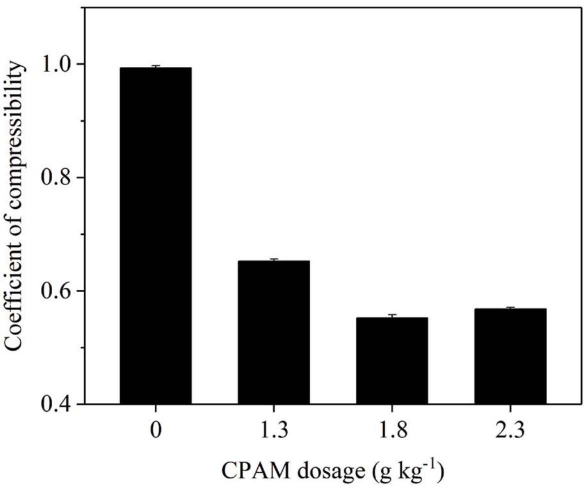

Fig. 2. Compressibility of sludge conditioned with CPAM.

compressible with an *s* value of 0.99. After the CPAM conditioning, the sludge compressibility reduced. With increasing the CPAM dosage from 1.3 to 2.3 g kg^{-1}, the *s* value first decreased and then increased. The minimum was achieved at a CPAM dosage of 1.8 g kg^{-1}, and further increase of the CPAM dosage resulted in a slight increase of *s* value, which might be attributed to the increase of sludge viscosity [31]. Johnson et al. pointed out that a more viscous sludge supernatant would lead to an increased resistance to water release [32]. In the underdose range of CPAM, the viscosity of supernatant decreased due to the decrease of fine particle concentration [33,34], therefore, the sludge compressibility decreased and sludge filterability was improved. In the overdose range of the CPAM, however, the viscosity increased because of the excess polymers or the saturation adsorption of polymers [35], as a result, the sludge compressibility might increase and the sludge dewaterability became worse. Therefore, only through increasing the CPAM dosage a satisfactory effect to improve the sludge dewatering could not be achieved. On the other hand, the excess CPAM significantly increased the expenditure of sludge dehydration.

3.1.2 Single MCFA conditioning

Rebhun et al. [26] demonstrated that Y could better express the sludge filterability in case of sludge conditioned by large amount of conditioner solids. In this study, the Y_N was adopted as the index to evaluate the sludge filterability for MCFA conditioning. Fig. 3(a) shows the Y_N changed with the change of MCFA dosages. The MCFA dosage range of 20%–80% DS was examined, which was expressed as a ratio between the added MCFA and the dry sludge solids. According to Fig. 3(a), the Y_N significantly increased with increasing the MCFA dosage from 40% to 60% DS, while the Y_N slightly increased when the MCFA dosage was lower than 40% or higher than 60% DS.

The TTF and FCM$_m$ change with MCFA dosage are given in Fig. 3(b). Both the TTF and FCM$_m$ decreased with increasing the MCFA dosage, but the decrease trends became inconspicuous in the dosage range of 60%–80% DS. The minimum of TTF and FCM$_m$ was 29 s and 83.9%, respectively, which was achieved at a MCFA dosage of 80% DS. It was evident that the single MCFA conditioning showed significant effect on the improvement of sludge filterability. The MCFA could neutralize the negative charge of sludge particles and provide more water transmitting passages as skeleton builder [25].

Fig. 4 shows the results of compressibility of sludge conditioned with MCFA. The larger the MCFA dosage was, the more incompressible the conditioned sludge was. The s value reduced to 0.58 at a MCFA dose of 80% DS. The decrease of sludge compressibility could be attributed to the function of MCFA. The MCFA particles have the rough surface and rigid lattice structural frame [25], and acted as skeleton builders in the filter cake, which altered the sludge compressibility. And more channels and pores were formed because of different particle size distributions, which improved the water transmitting and release.

3.2. Dual CPAM and MCFA conditioning

To achieve satisfactory conditioning effectiveness, the conditioner dosage will be relatively large when using single CPAM or MCFA. High CPAM dosage will cause high operation cost, and high MCFA dosage will lead to significant

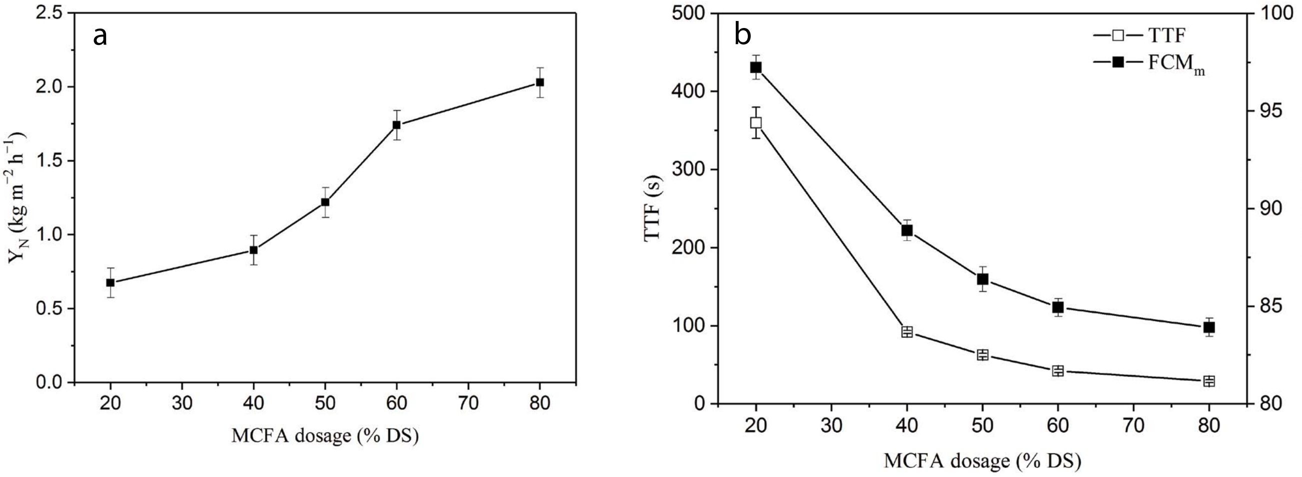

Fig. 3. Effect of MCFA dosage on characteristics of conditioned sludge, (a) Y_N, and (b) TTF and FCM$_m$.

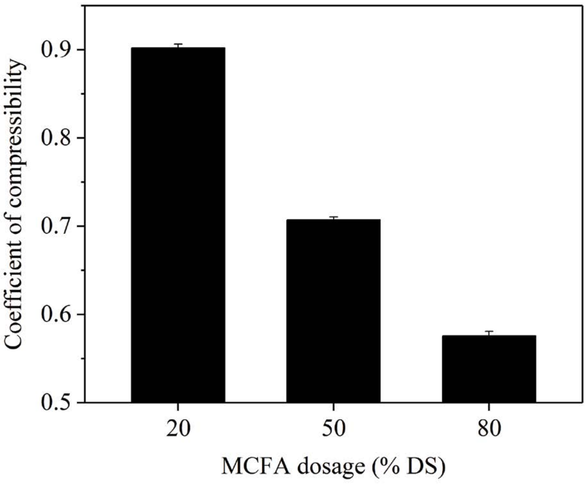

Fig. 4. Compressibility of sludge conditioned with MCFA.

increase in the total volume of dewatered sludge and the cost of subsequent sludge processing. Therefore, the combined sludge conditioning with MCFA and CPAM was investigated.

3.2.1. *Effect of MCFA dosage*

Fig. 5(a) shows that the Y_N change concerning different MCFA dosages, and the CPAM dosage was chosen as 1.3, 1.8, and 2.3 g kg^{-1} based on a relative good conditioning effectiveness (Fig. 1). The performance of dual conditioning presented distinct characteristics at different CPAM dosages. At a CPAM dosage of 1.3 g kg^{-1}, the Y_N increased with increasing the MCFA addition from 0 to 60% DS, while further increment of the MCFA dosage caused the deterioration in dewaterability. The suitable MCFA addition was 60% DS, and the corresponding Y_N was 4.33 kg m^{-2} h^{-1}. At a CPAM dosage of 1.8 g kg^{-1}, the Y_N was 2.33 kg m^{-2} h^{-1} without the MCFA addition. While combined with a MCFA dosage of 20% DS, the Y_N rapidly increased to the maximum of 4.56 kg m^{-2} h^{-1}; there was no significant Y_N change as the MCFA dosages increased from 20% to 60% DS; however, a marked Y_N reduction was observed when the MCFA addition was higher than 60% DS. At a CPAM dosage of 2.3 g kg^{-1}, the Y_N fluctuated between 3.0 and 3.5 kg m^{-2} h^{-1} within the whole MCFA dosage range of 0%–80% DS, and the MCFA addition didn't show obvious improvement of the sludge filterability. The sludge filterability might be significantly affected by the overdosed CPAM, which could induce the clogging in the filter cake [36]. At the same time, the overdosed CPAM might lead to the conversion of sludge floc charge and weakening the flocculation between the sludge particles. Blocking the filter cake and weakening the flocculation might cause more water wrapped by flocs, which could offset the enhancement of sludge filterability and dewaterability from the synergistic effect with dual CPAM and MCFA addition.

Fig. 5(b) shows the TTF change with various MCFA dosages. The TTF change trends at three different CPAM dosages were similar. The TTF first decreased to a minimum value, and then slightly increased with the further increase in MCFA dosage. The minimum TTF appeared at a MCFA dosage of 60%, 50%, and 40% DS, when the CPAM dosage was 1.3, 1.8, and 2.3 g kg^{-1}, respectively. Lower CPAM dosage needed an increase of MCFA dosage for achieving the minimum TTF, showing the synergistic effect between the CPAM and MCFA. With the overdosage of CPAM and MCFA, larger flocs could be formed, and some free water might be wrapped by the flocs again, resulting in a reduction of filtration rate.

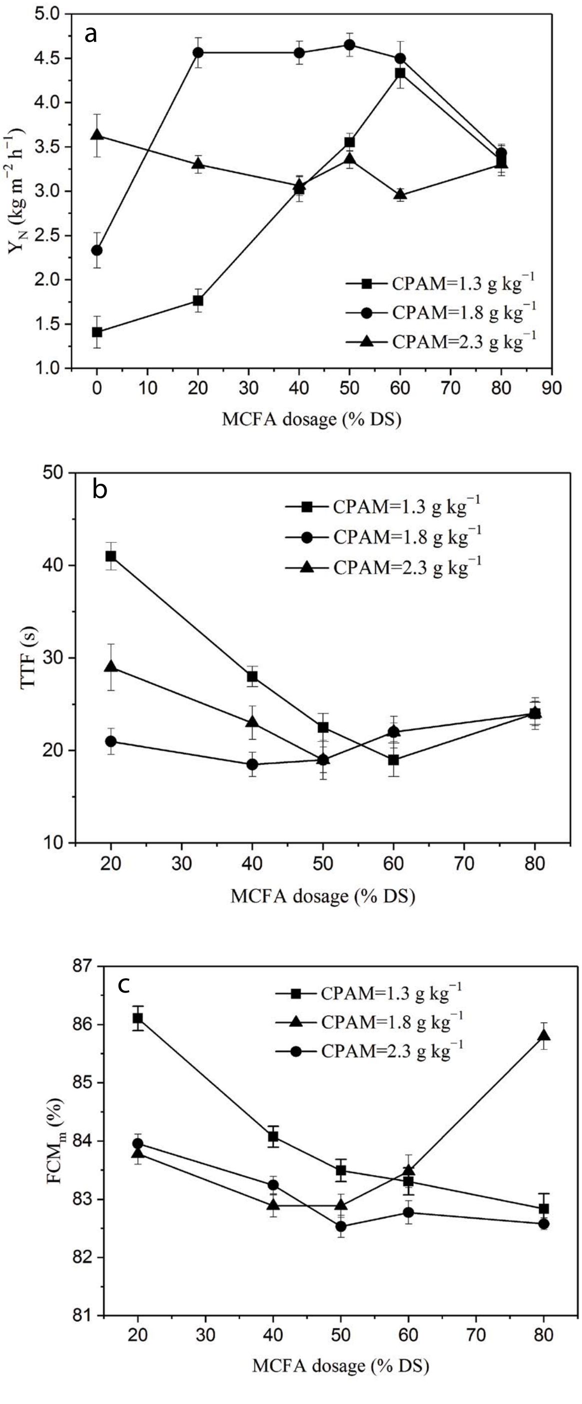

Fig. 5. Effect of MCFA addition on sludge conditioning with various CPAM dosages, (a) Y_N, (b) TTF, and (c) FCM$_m$.

Fig. 5(c) displays the FCM$_m$ change with various MCFA dosages. The FCM$_m$ change trends at the CPAM dosages of 1.3 and 1.8 g kg^{-1} were similar, and the FCM$_m$ decreased as the MCFA dosages increased from 20% to 80% DS. However, at a CPAM dosage of 2.3 g kg^{-1}, the FCM$_m$ first decreased and then increased when the MCFA dosage was higher than 50% DS. Fig. 5(c) illustrates that the lower FCM$_m$ was achieved at a higher CPAM dosage except the case of MCFA dosage higher than 50% DS at a CPAM dosage of 2.3 g kg^{-1}. The MCFA could neutralize part of the electric charge of sludge particles and change the structure of sludge aggregates. The CPAM could also neutralize part of the electric charge of sludge particles and agglomerate the dispersive sludge particles by flocculation. Both conditioners could promote the floc growth. However, at a higher CPAM dose, the larger flocs wrapped more water, resulting in an increase of sludge cake moisture content.

3.2.2. Effect of CPAM dosage

The effect of CPAM dosage on the sludge dewaterability at a MCFA dosage of 60% DS is shown in Fig. 6(a). For the sludge conditioning with single CPAM addition, the Y_N increased with increasing the CPAM dosage. A slight Y_N increase in a CPAM dosage range of 0.7–1.3 g kg^{-1} was observed, and then the Y_N obviously increased when the CPAM dosage was higher than 1.3 g kg^{-1}. When the CPAM and MCFA conditioning was combined at a MCFA dosage of 60% DS, an evident Y_N increase was observed as the CPAM dosage increased from 0.7 to 1.3 g kg^{-1}, and there was a tiny Y_N increase in the CPAM dosage range of 1.3–1.8 g kg^{-1}, while the Y_N distinctly reduced when the CPAM dosage exceeded 1.8 g kg^{-1}. The suitable CPAM dosage should be in the range of 1.3 to 1.8 g kg^{-1}, and the Y_N correspondingly increased by 86%–192%, compared with the single CPAM conditioning. The overdosage of CPAM led to a dramatic reduction of sludge conditioning effectiveness.

The influence of CPAM dosage on TTF and FCM$_m$ is shown in Fig. 6(b). With a MCFA dosage of 60% DS, the sludge conditioning performances displayed that both the TTF and FCM$_m$ decreased with increasing the CPAM dosage from 0.7 to 1.3 g kg^{-1}; the TTF significantly increased, while the FCM$_m$ showed insignificant change with increasing the CPAM dosage from 1.3 to 2.3 g kg^{-1}. Combined with a MCFA addition of 60% DS, 1.0 g kg^{-1} CPAM dosage led to a FCM$_m$ of 85.3% and a TTF of 20 s. When the FCM$_m$ decreased to 85.4% and the TTF reduced to 30 s with the single CPAM conditioning, a CPAM dosage of 2.3 g kg^{-1} was needed (see Fig. 1(b)). More than half of CPAM could be saved with dual conditioning. Considering the Y_N, TTF, and FCM$_m$, the suitable CPAM dosage was chosen as 1.3 g kg^{-1} at a MCFA addition of 60% DS.

3.2.3. Effect of optimum dual conditioning

The Y_N, TTF, and FCM$_m$ for the raw sludge and conditioned sludge with the addition of 60% DS MCFA, 1.3 g kg^{-1} CPAM, and dual conditioners (60% DS MCFA and 1.3 g kg^{-1} CPAM) are shown in Table 2. The raw sludge showed a poor filterability and dewaterability. After sludge conditioning, the properties of conditioned sludge significantly changed, the Y_N increased, and the TTF and FCM$_m$ decreased. For single MCFA and CPAM conditioning, the Y_N respectively increased by 66% and 105%, compared with that of the raw sludge. The Y_N of sludge conditioned by dual conditioners increased by 383%, correspondingly, the TTF reduced by 427 s and reached 19 s, compared with that of raw sludge. The FCM$_m$ of sludge conditioned by 1.3 g kg^{-1} CPAM without and with 60% DS MCFA was 88.6% and 82.9%, respectively, and the FCM$_m$ decreased by 5.7% with dual conditioning. After dual conditioning and vacuum filtration, the volume of dewatered sludge accounted for only about 7% of the raw sludge volume. It was evidenced that the sludge filtration rate could significantly increase due to the flocculation of CPAM and the skeleton building of MCFA in sludge cake formation stage [18]. The dual conditioning could also be beneficial to the sludge dewatering in cake compression stage [18], because a filter cake with more pores or channels for water transmission could be formed due to the even distribution of rigid MCFA particles.

Compressibility test for sludge conditioned with optimum dual doses was also investigated. When the sludge was

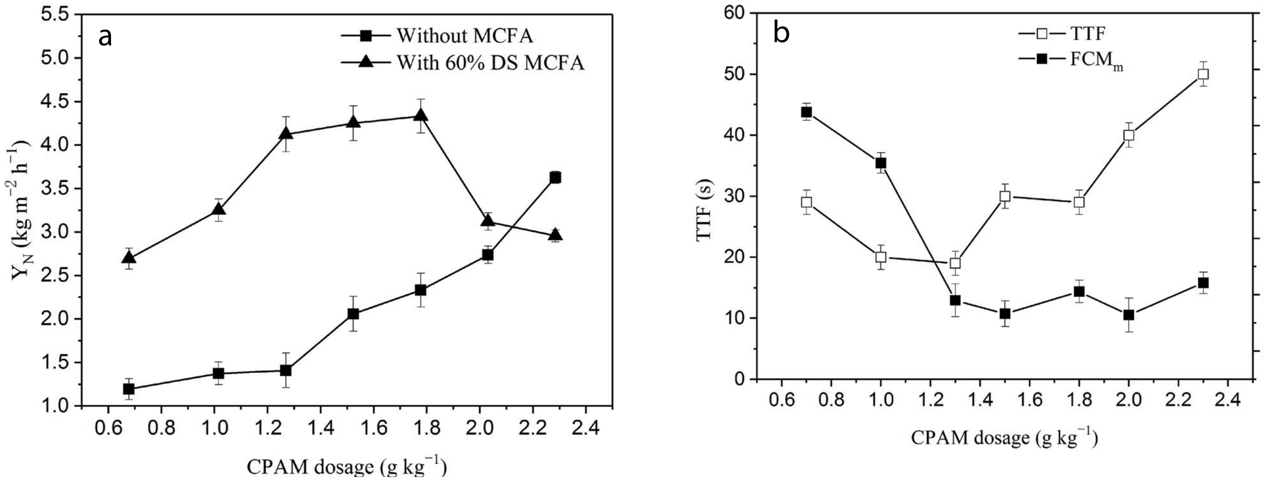

Fig. 6. Effect of CPAM dosage combined with a 60% DS MCFA dosage on sludge dewaterability, (a) Y_N, and (b) TTF and FCM$_m$.

Table 2
Sludge filterability and dewaterability with various conditioners

Samples	Y_N (kg m^{-2} h^{-1})	TTF (s)	FCM$_m$ (%)
Raw sludge	0.85	446	96.0
Sludge conditioned with single CPAM (1.3 g kg^{-1})	1.41	75	88.6
Sludge conditioned with single MCFA (60% DS)	1.74	42	84.9
Sludge with dual conditioning (MCFA of 60% DS + CPAM of 1.3 g kg^{-1})	4.11	19	82.9

conditioned with dual conditioner (MCFA dosage of 60% DS and CPAM dosage of 1.3 g kg^{-1}), the sludge compressibility significantly reduced with an s value of 0.62. Compared with the raw sludge (s = 0.99). By the Buchner test and filter press, the raw sludge was transformed into impermeable filter cake because of a large number of fine sludge particles, while the conditioned sludge with CPAM and MCFA could be transformed into permeable filter cake with channels and pores during unrestricted cake growth. It was also noted that, the cake formed by sludge particles could experience an expansion or spongy rebound, when the filter press was opened [8]. The conditioned sludge with the dual conditioners (MCFA and CPAM) would maintain its compressed shape. The relatively incompressible MCFA particles more effectively maintain the channels or pores in sludge filter cake. Therefore, the compressibility of sludge conditioned by CPAM and MCFA reduced.

3.3. Interactions between sludge and MCFA and CPAM

3.3.1. Charge interactions

Table 3 lists the zeta potential of sludge with and without conditioning. It could be seen that sludge particles carried negative charge, and the negative charge of sludge was neutralized by conditioners after conditioning. The results testified that there were interactions between the sludge particles and conditioners. When the MFCA was added in the sludge, because there were silicon and aluminum active sites with positive charge emerged on the MCFA surface [37], the positive charge of MCFA microspheres counteracted the negative charge of sludge particles, and the zeta potential increased form −16.7 to −12.6 mV. The CPAM, as a kind of cationic polyelectrolyte, carries a great quantity of positive charge and presents a strong charge neutralization ability. The zeta potential after CPAM conditioning was −9.1 mV. In dual conditioning (MCFA and CPAM), the negative charge of sludge particles was first counteracted by the positive charge from MCFA, and the stability of sludge particles was destroyed; after the addition of CPAM, the sludge system with negative charge was completely destroyed and showed an isoelectric point. The zeta potential of dual conditioned sludge increased to zero (see Table 3).

Table 3
Zeta potential of sludge particles with different conditionings

Samples	Zeta potential (mV)
Raw sludge	−16.7
Sludge conditioned with single CPAM (1.3 g kg^{-1})	−12.6
Sludge conditioned with single MCFA (60% DS)	−9.1
Sludge with dual conditioning (MCFA of 60% DS + CPAM of 1.3 g kg^{-1})	0

3.3.2. Flocculation interactions

In dual conditioning, when sludge was preconditioned with MCFA, followed with CPAM, the sludge particles could be adsorbed by MCFA microspheres to form conglomerates, due to charge interactions between sludge and MCFA. And then, these conglomerates gathered together to form flocs under the influence of CPAM. The flocs formed in dual conditioning were different from in single CPAM conditioning. With the single CPAM conditioning, the flocculation came into being between sludge particles, and particle-particle bridging led to conglomerate formation [38]. While, in dual conditioning, the MCFA solids acted as cores of floc framework, and the flocs containing MCFA microspheres were strong and insensitive to shearing force in flocculation process, and the conglomerate-conglomerate bridging resulted from the CPAM addition occurred instead of particle-particle bridging. Therefore, the floc size with the dual conditioning was much larger than that with the single CPAM conditioning as the same dosage (see Fig. 7). Although the larger-size flocs could be formed under higher CPAM dosage, the flocs formed in this way might be loose, which were weakly bound together and sensitive to shearing conditions caused by continuous stirring, and part of the polymer chains might remain free in the suspension [39,40]. As a result, these flocs were deformed easily under high pressure in filtration process, which could increase the filter cake compressibility and reduce the cake permeability. The explanation could be supported by the results of compressibility tests for sludge conditioned with CPAM (Fig. 2), that the s value increased when the CPAM dosage increased from 1.8 to 2.3 g kg^{-1}.

Moreover, due to the MCFA particles were rigid and ball-shaped with rough surface [25], which could be as skeleton builder or filter aid, formed a permeable and more rigid lattice structure, which can remain the sludge filter cake porous under high pressure during mechanical dewatering, which might result in the formation of channels and pores in the filter cake. Therefore, the sludge filtering speeded up, and the water kept by the sludge cake could be easily released.

According to above analyses, MCFA not only was as skeleton builder or filter aid as physical conditioners to reduce the sludge compressibility by forming rigid structures of sludge filter cake, but also interacted with sludge particles directly

Fig. 7. Images of sludge conditioned by single CPAM (a) and dual conditioners (b).

by neutralizing charge of sludge particles and promoted flocculation effectiveness of CPAM. Therefore, the MCFA is promising to introduce into sewage sludge conditioning combined with CPAM, which can improve sludge dewatering. Meanwhile, the MCFA introduction can reduce the sludge conditioning cost through reducing the CPAM dosage.

4. Conclusions

When the MCFA and CPAM were dually applied for sewage sludge conditioning, a less CPAM addition was demanded and a better conditioning effectiveness was achieved. Compared with the single CPAM conditioning, floc size enlarged, filtration resistance reduced, filtration velocity increased, and filter cake moisture decreased during filtration dewatering with dual conditioning. Both the MCFA and CPAM dosage were the key factors to improve the sludge conditioning efficiency. The mechanisms of MCFA for improving sludge CPAM conditioning were the interactions between sludge and MCFA and CPAM. The MCFA acted as skeleton builder or filter aid to reduce the sludge compressibility by forming rigid sludge filter cake structure, and interacted with sludge directly by neutralizing charge of sludge particles and promoting flocculation of CPAM. Meanwhile, the MCFA introduction greatly decreased the CPAM dosage, thus the cost of sludge conditioning and dewatering decreased.

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