EXPERIMENTAL STUDY ON FLOCCULATION DEHYDRATION OF DREDGED SEDIMENT

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Abstract. Focusing on the problems of high-water content, strong compressibility and difficult dehydration of dredged sediment, this paper used polymer flocculants to conduct sediment-water separation tests. We found that the cationic polyacrylamide has the best flocculation effect on the sediment-water separation, and the optimal dosage of polyaluminum ferric chloride, anionic polyacrylamide and cationic polyacrylamide were 5 g/L, 2 g/L and 1 g/L respectively. The zeta potential decreased with increasing the dosages of polyaluminum ferric chloride and cationic polyacrylamide and increased with increasing the dosage of anionic polyacrylamide. And it is also concluded that cationic polyacrylamide has the most obvious effect on the increase in sediment particle size, followed by anionic polyacrylamide and polyaluminum ferric chloride. The water content in each part of the flocculated sediment varies greatly, the lowest is in the bottom, followed by the middle, and the highest is in the upper.
Keywords: *dredged sediment, precipitate, flocculant, zeta potential, particle size, SEM*

Introduction

With sediment accumulating at the bottom of the river channel, sediment deposition not only affects the normal navigation function of the river but also has a negative impact on the environment. It may also have a negative impact on the lives and production of surrounding residents. Dredged sediment is produced in large quantities every year in China, and its poor mechanical properties, such as high water content, macro-void ratio, large compressibility, and low strength, seriously restrict its treatment, disposal and utilization (Wang et al., 2020a; Hu et al., 2023). Dredged sediment has a high water content and a large volume, which is not conducive to transport. Even though dredged sediment is disposed of in the spoil ground, it still has a high water content with poor mechanical properties after several years. Dewatering can reduce the dredged sediment volume for easy transportation, and even can reduce the area occupied by the sediment, dewatering is the key link in its disposal and utilization (Wu et al., 2018, 2019; Liu et al., 2020; Cao et al., 2021; Wang et al., 2022b).

There are many methods to dehydrate and reduce the dredged sediment, and flocculants are a widely used method to dewater the sediment (Wu et al., 2015; Chen et al., 2020; Karadoğan et al., 2020). Sui et al. (2017) reported that the flocculation effect of anionic polyacrylamide (APAM) for iron tailings is related not only to pH but also to temperature. Yu et al. (2020) analyzed the effects of the composite flocculant in comparison with PACl on coagulation efficiencies and membrane fouling in the coagulation-ultrafiltration process and found that the composite flocculant improved the

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coagulation efficiency. Zhu et.al. (2023) found the dosage of anionic polyacrylamide (APAM) can affect the dewatering effect of unclassified tailings, and ultrasound action can reduce the optimal dosage for unclassified tailings. To obtain better dehydration depth and higher resource utilization efficiency, flocculants are also used in combination with other methods (Kasmi et al., 2016; Wu et al., 2022).

Flocculants are feasible for dredged sludge, and they are economical and easy to operate. This paper analyzed the flocculation dehydration process of dredged sediment, studied the dredged sediment properties after flocculation, and the results in this paper are very important for the dehydration of dredged sediment.

Materials and methods

Materials

The dredged sediment is from Huainan City, Anhui Province, China. The sediment is dark and smelly, and the particle size distribution is shown in *Fig. 1*. It was found that the clay particles (≤ 0.005 mm) accounted for 37.2%, while the powder particles (0.005-0.075 mm) accounted for 58.6%, and the sand particles (> 0.075 mm) accounted for 4.2%. The particles of the sediment are mainly composed of clay and silt particles, among which the clay particles have a greater impact on the engineering properties. Polyaluminum ferric chloride (PAFC), APAM, and cationic polyacrylamide (CPAM) were used for the test as shown in *Fig. 2*.

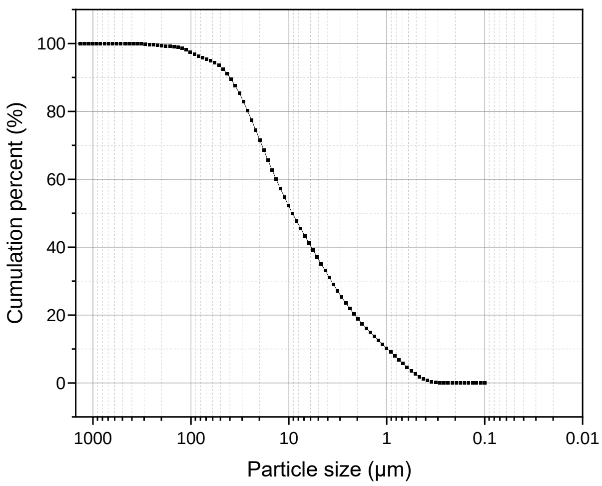

Figure 1. *Size distribution of sediment particles*

Through XRF analysis of the dredged sediment, it can be seen that the main oxide composition is SiO_2 (68.8%), followed by Al_2O_3 (17.0%), and Fe_2O_3 (6.7%) (*Table 1*).

Methods

(1) Flocculation precipitation test: We placed 1 g, 2 g and 3 g APAM and CPAM into a 1000 mL cylinder and stirred it to fully dissolve, and then we added 100 mL solution into 810 mL sediment and mixed it evenly. At the same time, 5 g, 10 g, 15 g and 20 g PAFC were placed into a 1000 mL measuring cylinder and then stirred to dissolve completely. We added 100 mL of solution into the measuring cylinder containing 810 mL

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of sediment, and the flocculation precipitation effect was observed. In this paper, the flocculant dosage was expressed by X g /L that means placing Xg of flocculant in 1 L of water and taking 100 mL of solution which added to 810 ml of the dredged sediment, the flow chart is shown in *Fig. 3*.

(a) (b) (c)

Figure 2. *Flocculants used in the tests: (a) APAM (b) PAFC (c) CPAM*

Table 1. *Composition of dredged sediment (%)*

Main oxides	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	TiO_2	SO_3
Content	68.8	17.0	6.7	3.0	1.7	1.4	1.0	0.2

Figure 3. *Flow chart of the tests*

(2) Water content test: The sediment with the optimal flocculant dosage in the above test carried out for the water content test, the sediment was divided into three parts after flocculation, and we took the upper, middle, and lower samples to test the water content.

(3) Particle size distribution test and zeta potential test: The sediment particle size analysis was conducted in the tests, Malvern Mastersize 2000 and Malvern ZS90 were used as the test instruments.

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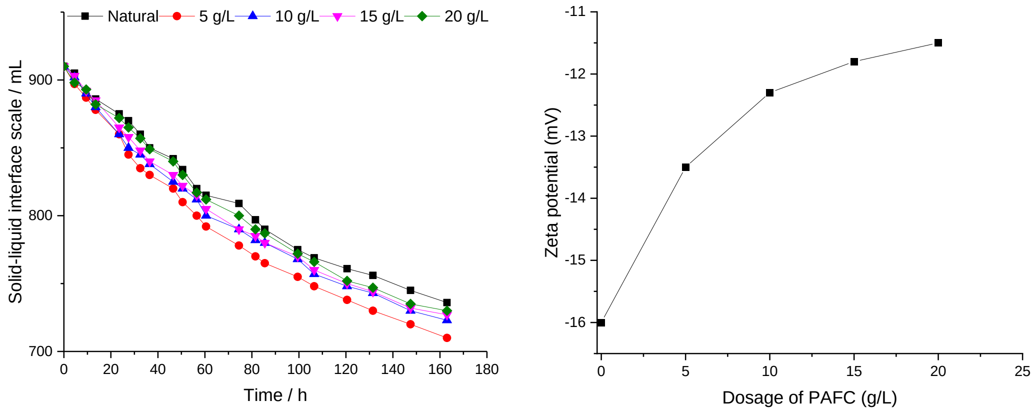
(4) Scanning electron microscope (SEM) test: The natural dredged sediment and flocculated sediment samples were selected for the SEM testing, the samples were dried at natural temperature, and the fresh section of the samples were treated with gold spraying to observe their internal microstructures.

Results and discussion

Inorganic flocculants

Fig. 4(a) shows that PAFC can improve the precipitation of dredged sediment. When added PAFC dose was 5 g/L, the precipitation effect was the optimal, and then gradually weakened with increasing the PAFC dose. The zeta potential of the sediment is negative, when PAFC is added, the negatively charged colloidal particles adsorb the dissolved positively charged monomer and polynuclear hydroxyl complex, compressing the double electric layer, neutralizing the surface charge, and binding the particles, and these properties are beneficial to the settlement (Zhang et al., 2015; Zhao et al., 2021). We found that when the dosage of PAFC was higher, its flocculation effect decreased, and the zeta potential showed a decreasing trend in *Fig. 4(b)*, the optimal dosage of PAFC is 5 g/L and the zeta potential is not near the zero point, which is different from those in the literature (Sun et al., 2012; Dai et al., 2018; Gao et al., 2019; Zhao et al., 2021). We believe that the electric neutralization ability is not the only factor affecting the flocculation effect, the flocculation precipitation is a complicated process, which is not only affected by the sediment particle properties, but also has a strong relationship with the stress of particles.



(a) (b)

Figure 4. *Dredged sediment with PAFC: (a) Flocculation precipitation with PAFC, (b) Zeta potential after adding PAFC*

Organic flocculants

Fig. 5(a) and *Fig. 6(b)* show that adding appropriate dosages of APAM and CPAM also can promote the sediment flocculation. The optimal dosage of APAM is 2 g/L, and the optimal dosage of CPAM is 1 g/L, if more than this dosage, it would have a bad effect on the flocculation. Some think it is the reason that the effective net trapping of fine particles and colloids through the bridging effect of long chains to form flocs, when the

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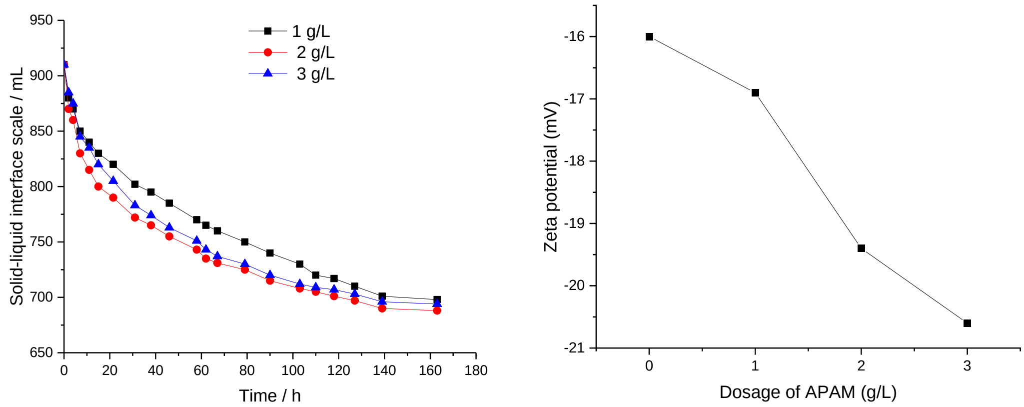
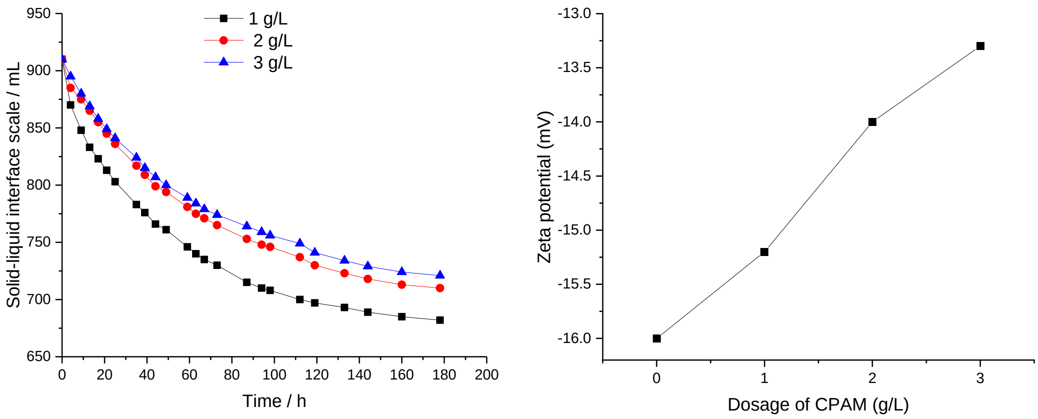
addition amount is too high, this bridging effect will be weakened (Wang et al., 2013, 2020b). The other scholars also believe that when excessive APAM and CPAM are added to the sediment, flocculants will wrap sediment particles, flocs and encapsulated water will increase, water will be difficult to remove in the flocs with a loose structure, and flocculation will decline (Wang et al., 2013, 2020c). Others also think that the stability of sediment is related to the zeta potential (Wang et al., 2019). And from *Fig. 5(b)* and *Fig.6(b)* also show that adding APAM and CPAM can change the zeta potential of the sediment, adding APAM can improve the zeta potential, the zeta potential decreased with the CPAM dosage, the zeta potential at the optimal dosage is also not at the zero point. They are similar with PAFC, perhaps the forces between particles can explain the phenomenon, that is, the higher the solid content, the greater of mutual interference during the descending process, the zeta potential and the particle interaction force in the particle settling process affect the settling together.



(a) (b)

Figure 5. *Dredged sediment with APAM. (a) Flocculation precipitation with APAM, (b) Zeta potential with APAM*



(a) (b)

Figure 6. *Dredged sediment with CPAM. (a) Flocculation precipitation with CPAM, (b) Zeta potential after adding CPAM*

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Sediment particle size

As shown in *Fig. 7*, the particle size of sediment has a large difference in comparing natural sedimentation with flocculation precipitation, and the overall particle size curves shift to the left, it indicates that the particle size of sediment after adding flocculant increased. And the curve with added CPAM has the largest deviation to the left, followed by the curve with APAM, and finally with PAFC, the reference particle size curve was the original sediment. The reason is that the addition of flocculants binds fine particles of sediment and colloids into a whole, forming floc, which produces settlement under the action of gravity (Wang et al., 2020b).

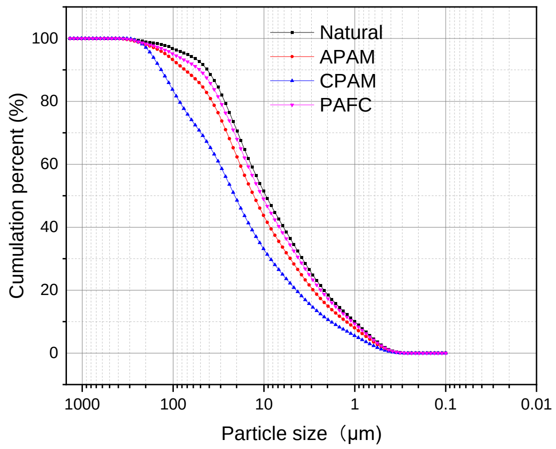

Figure 7. *Dredged sediment particle size curves*

Water content

Fig. 8 shows the water content in different locations of the sediment after removing the supernatant with the same time. Generally, the upper part of the sediment has a higher water content, followed by the middle part, and the bottom part of the sediment has the lowest water content. With the adding flocculant, there is little difference in the water content in the upper part, and there is a larger difference between the middle and the bottom part. The water content in the same part with APAM and CPAM is slightly different, they are lower than that of the sediment without flocculant. The water content after adding PAFC is higher than that of the sediment with CPAM and APAM, and it also lower than that without flocculant. After sediment precipitation, the supernatant is filtered out, the sediment particles in the upper are smaller for each test, the distance between the sediment particles is larger, and it is close to original water content. Starting from the middle to the bottom, the water content is quite different from that of natural sediment, because the sediment added with flocculant forms flocs in the precipitation process, the sediment and flocs at the bottom are consolidated by self-weight, and the pore water inside the flocs is discharged, increasing the compactness, so the water content is relatively low. Meanwhile, it is found that the water content of organic flocculants is higher than that of inorganic flocculants, this also indicates that the flocculating effect of inorganic flocculants is weaker. Due to natural sedimentation, the size of sediment particles is smaller than that of sediment after flocculation precipitation, and the water-holding performance is better. Meanwhile, particles in the compression consolidation of natural sediment is very loose, so it has a higher water content.

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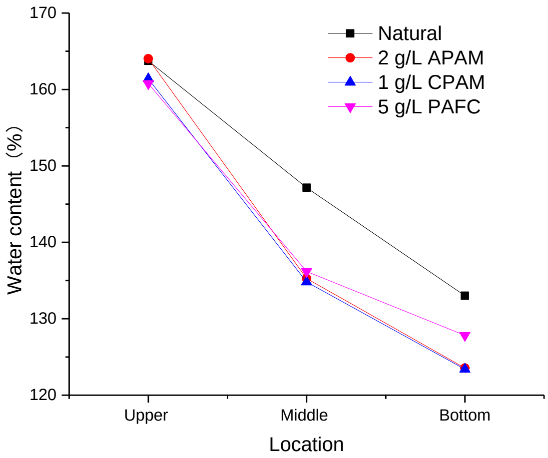

***Figure 8.** Water content of different parts with flocculants*

Microstructural analysis

In the SEM image of the natural dredged sediment in *Fig. 9(a)*, the size distribution is fine and uniform, the particles contact with each other, and they are already stable particles, and the sinking particles are stable when they are in the sinking process or they are in the equilibrium position, the contact between the particles is mainly face to face contact. We also can see that the addition of PAFC increases the pores between particles even if the coarse particles increase, and the contact between particles also changes in *Fig. 9(b)*. From *Fig. 9(c)* and *Fig. 9(d)*, particles are contacted by angle, edge-to-surface or edge-to-edge contact, the orientation of sediment particles is not fixed, the particle size increases, the structure becomes loose, and the pores become larger. SEM shows that flocculants can change the structure of the sediment in the settling process, and it is also proved that flocculants can increase the size of sediment particles and accelerate the separation of sediment and water.

Analysis of sediment precipitation

Settling stage on precipitation

The sedimentation process can be divided into free sedimentation and interference sedimentation. Free sedimentation refers to the non-interference sedimentation of solid particles in the dispersed phase under the action of gravity, while interference sedimentation refers to the sedimentation of mutual interference between particles under the sedimentation due to the high local solid content, as shown in *Fig. 10*.

From *Fig. 10*, we can infer that the particle settling velocity is equal to the upward flow of water by the simplified sedimentation process, according to the Darcy's law (Wang et al., 2022a):

$$U=KI=KH/L \qquad \text{(Eq.1)}$$

where, K is the hydraulic permeability coefficient, and I is the hydraulic gradient (I=H/L). During the interference settlement stage, the permeability coefficient and settlement velocity of flocs decrease gradually.

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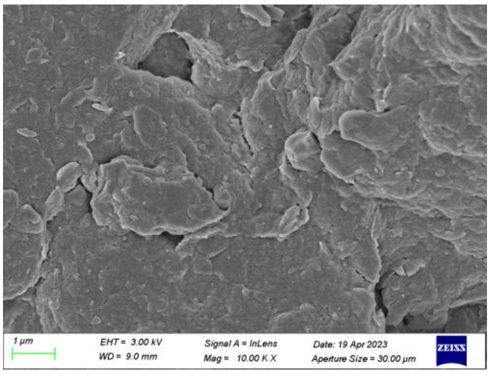
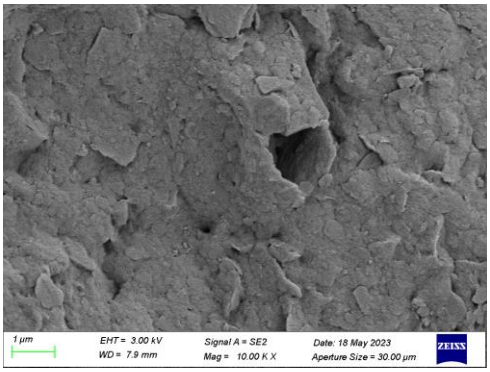
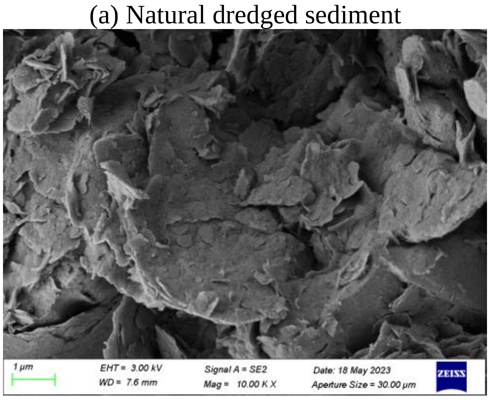


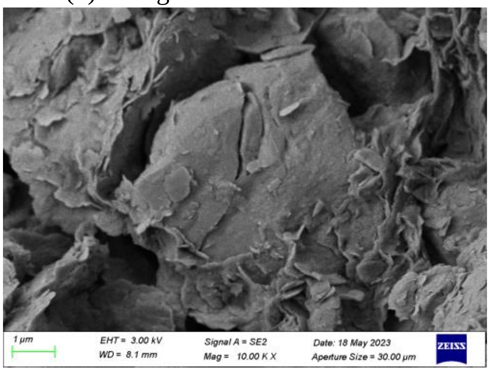
(a) Natural dredged sediment



(b) Dredged sediment with PAFC



(c) Dredged sediment with APAM



(d) Dredged sediment with CPAM

Figure 9. *SEMs of dredged sediment with flocculants*

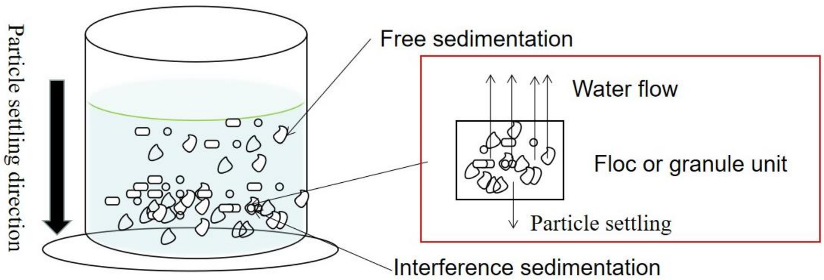


Figure 10. *The sedimentation process*

Effect of flocculant and water content on sedimentation

It is assumed that when the particles are stationary, the particles are subject to their gravity (G) and buoyancy (F), and when the particles begin to move, it is assumed that the sediment particles are subject to inter particle resistance N. Then, according to Newton's second law, the force analysis of particles can be obtained:

$$G - F - N = m\frac{du}{dt} \quad \text{(Eq.2)}$$

According to the formula, the sinking velocity (u) of the sediment is large at the initial stage of the test, and the sinking velocity decreases gradually with time. The effects of flocculants action and water content on sediment subsidence can be analyzed as follows:

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(1) For the higher water content sediment, the distance between the particles is large, and the interaction between the particles in the sinking process is small, so the subsidence resistance N is small. When flocculants are added, particles flocculate into flocs, the total surface area of particles decreases, and the water sinking resistance is reduced. According to the formula, the subsidence speed increases. When excessive flocculant is added, the steady-state sediment destabilized again, the overall surface of the particles increases, and N increases in the subsidence process, so the subsidence speed decreases.

(2) For higher solid content sediment, the particles collide with each other during the sinking process, the resistance N increases, and the sinking speed decreases. When flocculants are added, the added flocculants destabilize the sediment, flocculate the fine particles into flocs, and the small particles in Brownian motion flocculate into large particles, the surface area of the floc also decreases, the resistance (N) of the particles in the sinking process decreases, and the settling velocity increases.

Discussion

In this paper, we can learn that zeta potential is not the only key factor affecting the sediment dehydration, the flocculation dehydration effect of dredged sediment is also closely related to the added dosage of flocculants and the water content (Hou et al., 2019). In other words, the dehydration effect is influenced by the properties of sediment and the mechanical properties of particles in the sinking process. We know PAFC can reduce the zeta potential of the dredged sediment particles, but in the practical application of dredged sediment dehydration, there are many factors affecting the stability of dredged sediment. If we simply rely on the zeta potential to determine the optimal content of flocculants, it is likely to cause that added flocculants dosage will not be applicable (Feng et al., 2017), and the same as APAM and CPAM. In sewage or sediment with low solid content, adding flocculants can shorten the settling time, and the flocculation effect is very obvious. However, if sediment with a high solid content, the flocculation settling efficiency is not as good as that in sediment with a low solid content (Sui et al., 2017). In short, the flocculation dehydration is suitable for dredged sediment with a low water content, while the flocculation effect of dredged sediment with a high water content is not ideal. In practical application, flocculation dehydration should be based on the solid content of the sediment, if sediment with low water content, it can be diluted to high water content or dehydrated by other methods, such as vacuum dehydration and electroosmotic dehydration (Deng et al., 2009). The sediment volume scale also can affect the optimal dosage of flocculant comparing with the literature (Wen and Yao, 2023), we ignored the difference of the sediment water content in the two tests, we found that the sediment volume not only affect the flocculant dosage but also affect the sedimentation velocity and sediment water content after flocculation.

Conclusion

In this paper, the conclusions are summarized as follows:

(1) There is an optimal flocculant dosage for the dredged sediment, and exceeding the optimal dosage will hinder the flocculation dehydration of dredged sediment, the optimal dosages of PAFC, APAM and CPAM were 5 g/L, 2 g/L and 1 g/L, respectively.

(2) The larger the dosage of PAFC is, the smaller the zeta potential, the larger the dosage of CPAM, the smaller the zeta potential, and the larger the dosage of APAM is,

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the larger the zeta potential. The zeta potential is not the decisive role in the dehydration of dredged sediment, and the water content also can affect the flocculation.

(3) The addition of flocculants will increase the dredged sediment particle size, and CPAM has the most obvious effect, followed by APAM and PAFC. After sedimentation, the water content of the sediment in the bottom is the lowest, followed by the middle, and the water content in the upper is the highest, as the opposite for the particle size.

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Conflicts of Interests. The authors declare that they have no conflicts of interests to report regarding the present study.

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