Variation laws of water content of lake silt in the process of flocculation concentration dehydration

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Abstract. In order to address the issues regarding the high water content, poor dewatering performance, and occupied space of landfill, the physical property tests and experiments on the lake silt samples were conducted. The effects of cationic polyacrylamide (CPAM), lime dosage, and dehydration time on the dehydration performance indexes such as the concentration ratio, the water content, and the decreasing ratio of water content of the lake silt with the initial water content of 91% were investigated. The results revealed that the concentration ratio reached 3.6 times when the dosage of CPAM was 40mg/L, and the water content decreased to 70% and the decreasing ratio of water content decreased to 29% after dehydration for 10min. The concentration ratio was about 2.6 times when the dosage of lime was 3.8g/L, and the water content decreased to 73% and the decreasing ratio of water content decreased to 24% after dehydration for 10min. The variation laws of water content of the lake silt with initial water content of 91%, 85%, and 80% after flocculation concentration dehydration was studied based on the concept of the decreasing ratio of water content. It was concluded that the decreasing ratio of water content was independent of the initial water content. It was only significantly proportional when the dosage of CPAM was 15~45mg/L and lime was 1~7g/L. The linear constant depended on the intrinsic properties of the lake silt. According to the variation laws of the water content and the water-hinge hypothesis, the calculation formula of the water content was proposed and the mechanism of critical addition value breaking the silt hinge in flocculation concentration dehydration was formulated.

1. Introduction
In recent years, more than 500 million cubic meters of river and lake silt are produced every year with the large-scale development of water environment treatment projects in China. Silt, as a reservoir of pollutants and endogenous pollutants in lakes, has long been recognized by people [1]. This kind of silt is mainly composed of fine-grained soil, rich in organic matter and various pollutants, and characterized by high water content, low strength, large humus content, etc., which has an impact on the environment without treatment or disposal [2,3]. Therefore, the rapid and effective treatment of these silt with high water content and high pollution plays an important role in reducing environmental pollution, saving occupied space and realizing resource utilization [4-6]. Foreign silt dehydration methods mainly include solidification treatment, stage pressing dehydration, mobile continuous dehydration and high-pressure dehydration [7]. In China, it is still carried out in the way of storage yard, which takes a long time to dehydrate and occupies a large area, and is prone to secondary pollution [8-10]. It is found that there are few kinds of literature about silt dehydration technology with high water content at home and abroad, and the research on flocculation...
concentration dehydration technology is mainly focused on the field of municipal biochemical silt treatment. In view of its advantages such as maturity, simplicity, etc., this method can be extended to the field of desilting silt dehydration with high water content. However, this technology is rarely used in this field at present. Compared with biochemical silt, the desilting silt has the characteristics of high water content, high impurity content such as organic matter and heavy metal ions, poor settling performance and an unstable charged system [11,12]. Obviously, desilting silt is more difficult to dehydrate.

In terms of technology research and development, the dehydration performance and mechanism of flocculant used in desilting silt with high water content are still in the initial stage. The dehydration treatment of silt is focused on the solidification pretreatment in the field of geotechnical technology [13-16]. However, silt treatment, as tail end treatment, has not been paid much attention in water treatment technology. Therefore, the basic physical properties of lake silt with high water content in Binjiang District, Hangzhou were tested, and the lake silt dehydration experiment was carried out by flocculation concentration technology. Also, the silt dehydration performance was improved by adding cationic polyacrylamide (CPAM) and quickline (CaO). This work studied the variation laws of silt water content before and after flocculation concentration dehydration, and discussed the mechanism of flocculation concentration dehydration. Combined with the calculation and derivation, the theoretical guidance was offered for the design and engineering application of lake silt dehydration treatment.

2. Materials and methods

2.1. Reagents and instruments

2.1.1. Reagents. The lake silt used in the experiment is taken from a lake in Binjiang District, Hangzhou. The sampling point is 120.2142 degrees east, 20.1657 degrees north, and silt-water boundary layer is 0-60cm. In order to ensure the representativeness of the sample, one-time centralized multi-point sampling is carried out. After the collected silt sample is fully mixed, the large-size debris is removed with a sieve (110 mesh), and then the dark plastic barrel is used for sealing and storage. Cationic polyacrylamide (CPAM) with 10% cationic degree is used in flocculant. The characteristic viscosity value is 16.8 dL/g, and the mass concentration is 0.5%. The dehydrating agent is quickline (CaO) dried at 105 ℃ for 24h, with mesh size > 200mesh and particle size < 74μm, which is sealed for storage.

2.1.2. Instruments. Silt sampler (ETC-200, China); electric blast constant temperature drying oven (101A-1, China); electronic balance (Ohaus AR224CN, USA); ultraviolet and visible spectrophotometer (752N, China); pH meter (PHS-3E, China); particle size analyzer (FBS-1076, China); viscometer (NDJ-79, China); zeta potential meter (JS94H-2, China); coagulation test six unit mixer (ZR4-6, China); constant temperature water bath (XMTD203, China), etc.

2.2. Test methods

Firstly, the basic physical properties of lake silt were tested and analyzed. Then, CPAM or quickline were added separately to investigate the influence of the agent on the dehydration performance indexes such as concentration ratio, water content, water content reduction ratio, etc. At last, the variation laws of water content and the mechanism of flocculation concentration dehydration were studied and analyzed. The experiment was carried out at room temperature. Six 1L beakers were added with 1L of collected silt samples which were fully stirred. After adding CPAM or quickline at a certain dosage gradient, the silt samples were stirred for 30s at a rapid speed (450rpm), and then stirred for 10s at a slow speed (60rpm). The silt flocculation phenomenon was observed, and the silt concentration ratio and the water content of the mud cake after pressure filtration were measured. The performance indexes of silt flocculation concentration dehydration are composed of concentration ratio, water content and decreasing ratio of water content.
Silt concentration ratio (C) refers to the ratio between the mass of silt mixture and the mass of deposited silt after settling for a certain time.

\[ C = \frac{M}{M_m} \]  

In formula (1), M is the total mass of silt mixture, and \( m_t \) is the mass of supernatant after settling \( t \) time of silt mixture.

Silt water content (P) refers to the ratio between the water content mass of silt mixture and the total mass of silt mixture.

\[ P = \frac{M - m_1}{M} \times 100\% \]  

In formula (2), \( m_1 \) is the mass of dry silt in the silt mixture.

The decreasing ratio of water content (\( \eta \)) refers to the ratio between water content reduction value before and after silt dehydration and water content before dehydration.

\[ \eta = \frac{P_0 - P_t}{P_0} \times 100\% \]  

In formula (3), \( P_0 \) is the water content before silt dehydration, and \( P_t \) is the water content after silt dehydration \( t \) time.

3. Results and discussion

3.1. Analysis on silt properties

Table 1 shows the basic physical properties of the lake silt sample used in the experiment, and the silt is collected from a lake in Binjiang District, Hangzhou. The properties are analyzed and measured based on the standard method of geotechnical test (GB/T 50123-1999).

| Natural water content | pH | Solid content | Organic matter content | Potential mV | Viscosity Pa’s | Proportion Gs | Weight γ(kN/m²) | Plastic limit \( \omega_p \)(%) | Liquid limit \( \omega_L \)(%) | Plastic index Ip |
|----------------------|----|---------------|-----------------------|--------------|---------------|---------------|-----------------|----------------|----------------|-------------|
| 125%                 | 6.7| 26%           | 2.8%                  | -18.5        | 0.865         | 2.62          | 11.82           | 29.43          | 45.32          | 16.89       |

The curve of silt particle size distribution and cumulative percentage content is shown in Figure 1. It can be seen from Figure 1 that the clay content (< 5μm) is 2.65% and the silt content (5-74μm) is 89.60%, and the sand content ( > 74μm) is 7.75%. Most of the particle size of the silt used in the experiment is 5-74μm. Consequently, the particle size used is small with high water content, and its particle size distribution is closer to that of silty clay.

![Figure 1. The curve of silt particle size distribution and cumulative percentage content](image-url)
3.2. Effect of CPAM dosage on flocculation concentration

Figure 2 shows the effect of CPAM dosage on silt flocculation concentration ratio. The CPAM dosage increased from 5mg/L to 60mg/L with a gradient of 5mg/L. With the increase of CPAM dosage, the silt concentration ratio increased first and then decreased. When CPAM dosage increases from 5mg/L to 30mg/L, the increase of silt concentration ratio is significantly lower than the increase of dosage from 30mg/L to 50mg/L, which indicates that there is a stable critical point in the silt particle system. When CPAM dosage is less than 30mg/L, the flocculation effect of CPAM can not break through this stable critical point, and the floc particles formed in the system are small. With the increase of flocculation concentration time and dosage, the particle size increases gradually. When the dosage is more than 30mg/L, the flocculation effect exceeds the stable critical point. It can be found that the floc particles in the system are large and the alum flowers are obvious. However, the structure is loose and the sedimentation is poor. By increasing CPAM dosage, it is found that the concentration ratio tends to be stable, with compact floc structure and good settling performance. The concentration ratio is at the highest value, reaching 3.6 times. However, the concentration ratio does not increase but decreases as the dosage continues to increase (> 50mg/L). This may be due to the fact that the excessive positive charge brought by CPAM will cover the surface of silt particles again to form a new positive charge stabilization system after CPAM reaches an optimal dosage. The repulsion force between the same charge prevents the flocculation, which affects the increase of silt flocculation concentration ratio [17]. It can be considered that the proper amount of flocculant can promote silt flocculation concentration.

Figure 2. Effect of CPAM dosage on flocculation concentration

Figure 3 shows the variation of water content and decreasing ratio of water content with dehydration time after silt dehydration with initial water content of 91% when CPAM dosage is 45mg/L. It can be seen from Figure 3 that the water content of silt after dehydration decreases with the increase of dehydration time, and the dehydration mainly occurs within 10 minutes before the pressure filtration dehydration. The water content of treated silt decreased to 70% and the decreasing ratio of water content decreased to 29.17% after dehydration for 10min.
Figure 3. The relationship between water content, decreasing ratio of water content and dehydration time after flocculation concentration dehydration with CPAM respectively

3.3. Effect of lime dosage on flocculation concentration

Figure 4 shows the influence of lime dosage on silt concentration ratio. The lime dosage increased from 2.28mg/L to 9.12mg/L with a gradient of 0.76mg/L. With the increase of lime dosage, the silt concentration ratio increased first, then decreased and then increased. When the lime dosage increased to 3.8mg/L, the concentration ratio gradually decreased, and it recovered to the highest point when the dosage was 7.6mg/L. At this time, the effect of concentration ratio was similar to that of 3.8mg/L, reaching about 2.6 times. Furthermore, the concentration ratio is at the valley value when the lime dosage is 4.5~6.8mg/L, which also proves that there is a critical point of stability in the silt particle system. Only after the lime reaction gradually breaks through the critical force of the stable system, the system can be destabilized. When the lime dosage continues to increase (> 7.6mg/L), the concentration ratio will decrease instead. It is observed that the powder will be dissolved at the bottom of the silt. This may be due to the fact that adding too much lime can neutralize the charge on the surface of silt particles, and make the destabilization system reabsorb charged ions to form a new charge balance. This causes the particles to stabilize again and affects the enhancement of silt concentration ratio [18]. It can be concluded that a proper amount of lime can promote silt concentration.
Figure 4. Effect of lime dosage on concentration ratio

Figure 5 shows the variation of water content and decreasing ratio of water content with dehydration time after silt concentration dehydration with initial water content of 91% when lime dosage is 3.8g/L. It can be seen from Figure 5 that the water content of silt after dehydration decreases with the increase of dehydration time, and the dehydration mainly occurs within 5 minutes before the pressure filtration dehydration. The water content of silt after dehydration decreased to 75% and the decreasing ratio of water content decreased to 20.51% after dehydration for 5 min. The water content of silt after dehydration decreased to 73% and the decreasing ratio of water content decreased to 24% after dehydration for 10 min.

Figure 5. The relationship between water content, decreasing ratio of water content and dehydration time after dehydration treatment with lime respectively

3.4. Research on the variation laws of water content

Figure 6 shows the effect of CPAM dosage on water content after silt flocculation concentration dehydration with different initial water content. Figure 7 shows the effect of CPAM dosage on decreasing ratio of water content after silt flocculation concentration dehydration with different initial water content. It can be seen from Figure 6 that the water content of silt cake after dehydration decreases with the increase of CPAM dosage. The curve of relation between water content after silt dehydration with high initial water content and CPAM dosage is above the low initial water content.
can be considered that CPAM dosage and initial water content have a great impact on the water content after silt dehydration. It can be seen from Figure 7 that the decreasing ratio of water content before and after silt dehydration is almost independent of the initial water content along with CPAM dosage. The decreasing ratio of water content increases linearly with the increase of CPAM dosage, especially in the range of CPAM dosage from 15 to 40mg/L. From the trend line analysis, the linear regression equation is obtained as formula (4). The linear constant is 0.4259, and the linear correlation coefficient is 0.972.

\[ \eta = k \cdot \Delta m \quad (4) \]

In formula (4), \( \eta \) is the decreasing ratio of water content (%) before and after silt dehydration. \( \Delta m \) is CPAM dosage (mg/L), and \( K \) is a linear constant value. According to formula (4), \( K \) value is not related to the initial water content and CPAM dosage of silt, but is determined by the inherent characteristics of silt.

Similarly, Figure 8 and Figure 9 show the effect of lime dosage on water content and decreasing ratio of water content after silt flocculation concentration dehydration with different initial water content. It can be seen from Figure 8 that the water content of silt cake after dehydration decreases with the increase of lime dosage. The curve of relation between water content after silt dehydration with high initial water content and lime dosage is above the low initial water content. Similar to the flocculation concentration rule of CPAM silt, lime dosage and initial water content have a great impact on the water content after silt dehydration. It can be seen from Figure 9 that the decreasing ratio of water content before and after silt dehydration is almost independent of the initial water content along with lime dosage. The decreasing ratio of water content increases linearly with the increase of lime dosage, especially in the range of lime dosage from 1.0 to 7.0g/L. It can be concluded that silt dehydration law between lime and CPAM is similar. From the trend line analysis, the linear regression equation is obtained as formula (5). The linear constant is 4.1064, and the linear correlation coefficient is 0.9489.

Figure 6. Effect of CPAM dosage on water content after silt dehydration with different initial water content
Figure 7. Effect of CPAM dosage on decreasing ratio of water content after silt dehydration with different initial water content

Figure 8. Effect of lime dosage on water content after silt dehydration with different initial water content

Figure 9. Effect of lime dosage on decreasing ratio of water content after silt dehydration with different initial water content
Combined with CPAM and lime flocculation concentration dehydration experiment and dehydration performance analysis, the water content variation laws can offer guidance for lake silt treatment and lake comprehensive management application. Through the flocculation concentration dehydration experiment of adding CPAM or lime to the silt with the initial water content $P_0$, the relationship between the dosage $\Delta m$ and the water content $\eta_t$ after silt dehydration is established. The formula can be used to deduce the water content $P_t'$ after silt dehydration with different initial water content $P_0'$ and different dosage $\Delta m'$. The derivation process is as follows: the relationship between the dosage $\Delta m$ and the water content $P_t$ after silt dehydration is determined through the experiment of silt with the initial water content $P_0$. Based on the known conditions of different initial water content $P_0'$, and different dosage $\Delta m'$, the water content $P_t'$, after silt dehydration is calculated.

\[
\eta_t = \frac{P_0 - P_t}{P_0} \times 100\% \quad (5)
\]

\[
k = \frac{\eta_t}{\Delta m} = \frac{P_0 - P_t}{P_0 \Delta m} \times 100 \quad (6)
\]

\[
P_t' = 1 - \frac{k \Delta m / 100}{P_0'} \quad (7)
\]

3.5. Analysis on the mechanism of flocculation concentration dehydration

In the natural state, the silt particles belong to the charged stable system, which is difficult to break off and form large flocs without external force. Adding CPAM or lime can adjust the internal characteristics of fine particles in the silt stabilization system and create a dehydration environment [19]. Comprehensive analysis shows that the mechanism of silt flocculation concentration dehydration includes the destabilization mechanism of the inherent system and the flocculation mechanism of flocculant. The destabilization of silt stable system is the result of the interaction between the two systems.

As can be seen from Figure 2 and Figure 4, there is a critical value of CPAM or lime dosage for silt with a certain water content. Beyond this critical value, the silt concentration ratio and flocculation effect are obviously improved. This also indirectly confirms the existence of the water hinge hypothesis between particles in the silt system proposed by Dangwei Wang et al [20]. The water hinge hypothesis holds that polar water molecules form chain arms around the particle hydration film in the stable system of silt particles, and the chain arms of adjacent particles are connected to bind the particles together. Under the action of water hinge, different silt particles are close to and linked with each other. On the other hand, the same charge repulsion also has an effect on the maintenance of stable silt system. The flocculation mechanism of flocculant can be simply considered as the composition of flocculant in water to produce compression double electric layer, adsorption neutralization, adsorption bridging, etc. It can be visualized that the process of flocculation concentration dehydration is a process of water hinge stability, flocculant destabilization, and mutual attack and prevention among the water molecules in the silt system.

Experimental analysis shows that adding CPAM or lime will first consume a small amount of chemicals to destroy the water hinge to maintain the stability of the silt system, and release the water hinge from the limit of partial water in the silt. In this process, the flocculant is consumed, but there is no flocculation phenomenon. Until the destruction process of water hinge is completed, the floc will appear after adding the flocculant, which shows the existence of the critical value in the experimental process. At the same time, the mechanism of flocculation destabilization shows superiority with the continuous increase of flocculant. The cation carried by flocculant neutralizes the negative charge in the silt system, and $\zeta$ potential is reduced. Consequently, the system tends to destabilize, and it is easy to form silt flocs. However, excessive flocculant will make the silt recharged, resulting in the stability of the system.

The difference is that although CPAM flocculation concentration dehydration is almost the same as lime, their dehydration mechanism is slightly different. The former is mainly composed of
compression double voltage, neutralization and adsorption bridging in flocculation mechanism. Apart from the above three flocculation mechanisms, there are also chemical reactions and chemical exothermic. This will increase the temperature of silt system and create conditions for creating and improving dehydration environment.

4. Conclusion
Through experimental research and law analysis, the following conclusions are drawn.
First, CPAM and lime have certain effect on silt flocculation concentration dehydration. For silt with an initial water content of 91%, the concentration ratio can reach 3.6 times when CPAM dosage is 40mg/L. The water content decreased to 70% and the decreasing ratio of water content decreased to 29% after dehydration for 10min. The concentration ratio can reach 2.6 times when lime dosage is 3.8g/L. The water content decreased to 73% and the decreasing ratio of water content decreased to 24% after dehydration for 10min.
Second, CPAM and lime dosage, the initial water content of silt influence water content after silt dehydration. The decreasing ratio of water content has nothing to do with the initial water content of silt, and only has a significant linear proportional relationship with CPAM and lime dosage in a specific interval. This linear relationship is obvious in the range of CPAM dosage (15~45mg/L) and lime dosage (1~7g/L). The linear relationship constant is determined by the inherent characteristics of silt.
Third, the mechanism of silt flocculation concentration dehydration includes the destabilization mechanism of inherent system and the flocculation mechanism of flocculant. The destabilization of silt stable system is the result of the interaction between the two systems. Based on the water hinge hypothesis between silt particles, the critical values of CPAM and lime dosage are explained. The critical value is mainly used to destroy the water hinge to maintain the stability of the silt system, and remove the water hinge from the silt.
Fourth, based on the decreasing ratio of water content concept, the calculation method of water content after silt flocculation concentration dehydration is put forward. Through the flocculation concentration dehydration experiment of adding CPAM or lime to the silt with the initial water content $P_0$, the relationship between the dosage $\Delta m$ and the water content $\eta$ after silt dehydration is established. The water content $P_t$ after silt dehydration with different initial water content $P_0$ and different dosage $\Delta m$ is calculated, which is convenient to guide the practical application of silt flocculation concentration dehydration treatment and lake comprehensive management.

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