Study on the Effect of Chemical Conditioning on the Consolidation Characteristics of Municipal Sludge in Landfill Depot

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Abstract. Vacuum preloading is one of the effective methods for in-situ dewatering and reduction treatment of municipal sludge landfill, but because the consolidation coefficient of municipal sludge is 1 or 2 orders of magnitude smaller than that of sludge, the drainage consolidation technology will face the problem of vacuum for too long. In order to improve the consolidation characteristics of sludge, combined with the chemical conditioning technology in the field of water treatment, firstly, the chemical conditioner suitable for landfill sludge was selected. The effects of different conditioning combinations on sludge dewatering characteristics were studied by microscopic testing techniques (zeta potential analysis and environmental scanning electron microscope analysis) and vacuum filtration test and consolidation test. The results show that the combination of ferric chloride and calcium oxide can significantly improve the dewatering characteristics of sludge. After conditioning with 10% ferric chloride and 10% calcium oxide (relative to sludge dry base), the specific resistance of sludge is reduced from $2 \times 10^{13}$ m/kg to $3 \times 10^{12}$ m/kg, and the consolidation coefficient is 3.5-10 times higher than that of original sludge, which lays a foundation for improving the efficiency of vacuum preloading treatment. In addition, from the results of vacuum filtration test and consolidation test of sludge, it can be found that there is a good negative linear relationship between specific resistance and consolidation coefficient of sludge. Compared with the consolidation test, the vacuum filtration test is simple and easy, so it can be used as an effective means to select sludge conditioner or test the conditioning effect.

Keywords: Chemical conditioning, Conditioner, Microscopic analysis, Consolidation characteristics, Specific resistance

1. Introduction

With the continuous improvement of the level of urbanization in China, the output of sludge increases sharply. According to statistics, in 2010, the output of municipal sludge in China reached 20 million tons (moisture content 400%) [1]. For a long time, due to the ideological concept of "heavy water light mud", the attention and investment of sludge treatment and disposal is not enough, 80% of the sludge has not been stabilized in our country, and there is the environmental risk of secondary pollution. At present, municipal sludge from many cities in China is directly dumped next to sewage treatment plants or landfills to form sludge depots of different sizes, such as Changan in Chengdu, Xiaping in Shenzhen, Maiyuan in Nanchang, Qizishan in Suzhou and other landfills. With the increasing shortage...
of land resources, the sludge depot has seriously affected the storage capacity of landfills and the ecological function of land. In order to increase the landfill amount per unit land area of landfills and restore the ecological function of land, there is an urgent need for safe disposal of sludge depots.

After the mechanical dewatering of the sewage treatment plant, the moisture content of the sludge is still more than 400%, and then directly dumped into the sludge tank. Due to the lack of surface coverage of the sludge bank, the moisture content of the sludge under the action of rainfall is as high as 650% [2]. Because the sludge has the characteristics of high moisture content, low strength and low consolidation coefficient [2], the in-situ disposal of the sludge reservoir is faced with great challenges.

At present, the research on sludge treatment and disposal is mainly focused on sludge dewatering and solidification after leaving the factory in the field of water treatment. Sludge dewatering is mainly studied by means of physical and chemical conditioning to improve the dewatering performance of sludge. Physical conditioning is the use of physical means to change the properties of sludge, the commonly used physical conditioning methods are thermal conditioning [3], ultrasonic conditioning [4], freeze-thaw conditioning [5], and are only used in the laboratory. Chemical conditioning is the use of one or more chemical additives to destabilize and coalesce sludge colloidal particles through electrical neutralization, bridging adsorption and sweeping condensation [6-10]. At the same time, because the appropriate pH will decompose the extracellular polymer in the sludge and release part of the water, it has also been reported that the sludge dewatering performance can be improved by adjusting the PH value [11,12]. It is generally believed that the sludge dewatering performance is the best when PH is adjusted to 3. However, the above research in the field of water treatment mainly focuses on how to reduce the moisture content of sludge from 4900% to 400%, while there are few reports on the further reduction of mechanical dewatering sludge in the sludge bank. In recent years, the deep dewatering process developed by some enterprises uses high pressure or diaphragm filter press for secondary dewatering of sludge, which is mainly used for emergency reduction treatment of dewatered sludge [13]. However, it is necessary to build a new plant and purchase machinery at the same time its disposable treatment capacity is small, and the treatment efficiency is not high. In the aspect of sludge solidification, the existing research is mainly aimed at the sludge with 400% water content of the sewage treatment plant, through the use of cement, lime, slag and other additives to produce a series of physical and chemical reactions with the sludge, in order to improve the strength and solidify the pollutants [14,15]. However, the solidification technology to treat high moisture content sludge, the cost is high, coupled with in-situ treatment of mechanical excavation, transportation and other costs, the curing cost will be greatly increased. Therefore, the above methods are difficult to be applied to the in-situ disposal of sludge depots.

O’Kelly [16], Feng Yuan et al. [2] have systematically studied the geotechnical properties of sludge and found that its compression coefficient is as high as 1.5-4.5, and its consolidation coefficient is of the order of $10^{-5} - 10^{-4} \text{cm}^2/\text{s}$, which is 1-2 orders of magnitude smaller than that of ordinary ultra-soft soil ($10^{-3} \text{cm}^2/\text{s}$). Zhan Xinjie et al. [17] carried out the vacuum preloading model test of sludge degradation in sludge depot, and found that vacuum preloading could reduce the amount of sludge, but due to the small consolidation coefficient of sludge, although 0.4 m drainage plate spacing was adopted, after 2 months of vacuum, the average consolidation degree was only 40%, and the drainage was slow in the middle and later stage of the model test.

Because the consolidation coefficient of sludge is very low, in order to solve the bottleneck of poor effect of sludge vacuum preloading treatment, combined with the technical methods in the field of water treatment, this paper first selects the chemical conditioner and its combination to improve the dewatering capacity of landfill sludge. the effects of different chemical conditioning combinations on the consolidation characteristics of degraded sludge were studied quantitatively, and the relationship between sludge consolidation coefficient and specific resistance, an index characterizing sludge dewatering characteristics, was established. The purpose of this paper is to provide a basis for sludge reduction treatment of sludge depot.
2. Material and Conditioning Combination

2.1. Material
The sludge test samples were taken from a landfill sludge bank in Chengdu. The secondary biochemical treatment process of blast aeration activated sludge is adopted in the sewage treatment plant, and its landfill age is about 2 years. The basic physical properties of sludge samples are shown in table 1 below.

| Moisture content | Density (g/cm³) | Specific gravity | Organic matter content | Particle size (μm) |
|------------------|-----------------|-----------------|------------------------|-------------------|
| 860%              | 1.07            | 1.8             | 40%                    | 0.6-677           |

2.2. Conditioning Combination
According to the action mechanism of different chemical conditioners, through many attempts and considering the engineering economy, inorganic ferric chloride and calcium oxide are selected as conditioners to improve the dewatering performance of sludge: the purpose of adding ferric chloride is to neutralize the negative charge on the surface of sludge; the purpose of adding calcium oxide is to increase the skeleton material in the sludge floc. In order to study the effect of different combinations of conditioners on sludge dewatering performance, the following are divided into four schemes (as shown in table 2): scheme 1 studies the dewatering effect of adding ferric chloride alone, and the addition amount of ferric chloride is 2.5%, 5% and 10%, respectively; in scheme 2, equal amounts of ferric chloride and calcium oxide are added, and the total amount of conditioner addition is the same as that of scheme 1, and the dewatering effect of compound conditioner is studied. The third scheme controls the addition amount of calcium oxide to 10%, adds different proportions of ferric chloride, and also studies the dewatering effect of the compound conditioner; the fourth scheme first adds HCl to regulate the PH=3, of the sludge and then adds different proportions of ferric chloride, and also studies the dewatering effect of the compound conditioner on the dewatering performance of the sludge.

| Scheme | 2.5% addition | 5% addition | 10% addition |
|--------|---------------|-------------|--------------|
| Option 1 | 2.5% Ferric chloride | 5% Ferric chloride | 10% Ferric chloride |
| Option 2 | 1.25% Ferric chloride + 1.25% Calcium oxide | 2.5% Ferric chloride + 2.5% Calcium oxide | 5% Ferric chloride + 5% Calcium oxide |
| Option 3 | 2.5% Ferric chloride + 10% Calcium oxide | 5% Ferric chloride + 10% Calcium oxide | 10% Ferric chloride + 10% Calcium oxide |
| Option 4 | PH=3+ | PH=3+ | PH=3+ |
| | 2.5% Ferric chloride | 5% Ferric chloride | 10% Ferric chloride |

Note: the addition amounts of 2.5%, 5% and 10% in the table are relative to the sludge dry base; relative to the sludge wet base, the addition amounts of 2.5%, 5% and 10% are 0.26%, 0.52% and 1.04%, respectively.

3. Test Scheme
In order to study the effect of conditioner on the dewatering performance of sludge dewatering in sludge dewatering, the conditioning sludge was qualitatively analyzed by means of micro-test (zeta potential and environmental scanning electron microscope), and the microscopic action mechanism was obtained. Then the effects of different conditioning combinations on sludge dewatering performance were quantitatively studied by vacuum filtration experiment and consolidation test, and
the indexes obtained from the above two experiments were compared and analyzed, and the overall test arrangement is shown in table 3.

| Test arrangement | Zeta potential | Environmental scanning electron microscope | Vacuum filtration test | Consolidation test |
|------------------|----------------|-------------------------------------------|------------------------|-------------------|
| Option 1         | Yes            | Yes                                       | Yes                    | Yes               |
| Option 1         | No             | No                                        | Yes                    | No                |
| Option 1         | No             | Yes                                       | Yes                    | Yes               |
| Option 1         | No             | No                                        | Yes                    | Yes               |

### 3.1. Zeta Potential Analysis
Zeta potential is a measure of the intensity of mutual repulsion or attraction between sludge particles. The potentials of sludge samples with different proportions of ferric chloride were tested by ZetasizerNanoZS90. Before the test, the sludge was centrifuged in 3000r/min for 5 minutes, the supernatant was discarded, and the sludge mixture with concentration of 60g/L was mixed with deionized water.

### 3.2. Environmental Scanning Electron Microscope Analysis
Environmental scanning electron microscope ((ESEM)) is a new type of electron microscope improved on the basis of SEM, which uses multi-stage differential pressure diaphragm technology to form a gradient vacuum. Its variable pressure chamber replaces the high vacuum cavity of traditional SEM, and there is no need to carry out traditional treatment of sludge samples, including dewatering, critical point drying, gold plating and so on, so ESEM is a simple and non-destructive analysis method [18,19].

As shown in figure 1, the sludge and conditioning sludge were tested by field emission environmental scanning electron microscope (FEG650). In the experiment, the conditioned sludge samples were slightly dried at room temperature, cut the sludge with a thin blade, and then placed on the sample table. During the test, the temperature of the sample table is 5 ℃, the pressure of the sample table is 800Pa, the acceleration voltage is 20kV / 50kV, and the relative humidity is 80%.

**Figure 1.** Environmental scanning electron microscope

### 3.3. Vacuum Filtration Test
Vacuum filtration test is one of the standard tests used to evaluate the dewatering capacity of sludge in the field of water treatment, and the specific resistance of sludge can be obtained. The physical meaning of sludge specific resistance (SRF) is the resistance of unit mass sludge on the filter medium per unit area when the sludge is filtered under a certain pressure. The smaller the specific resistance of sludge is, the better the filtration performance is.
The device of the vacuum filtration test is shown in figure 2, which slowly separates the moisture of the sludge in the Brinell funnel into the measuring cylinder by vacuum suction. The device is mainly composed of Brinell funnel, measuring cylinder, buffer bottle, filter bottle, vacuum pump, vacuum meter and so on. The specific test steps are as follows: (1) testing the initial water content of sludge; (2) placing filter paper on the Brinell funnel (diameter 80mm), wetting it with water and removing gas with a glass rod; turning on the vacuum pump to adjust the vacuum pressure less than the experimental pressure (35kPa is used in the experiment), and then turning off the vacuum pump; (3) adding 100g sludge sample to the Brinell funnel, adjusting the vacuum pressure to 35kPa, and turning on the stopwatch. (4) record the volume of the filtrate at different times, adjust the pressure control valve to keep the vacuum constant, and stop the test when the 60min or vacuum is destroyed; (5) turn off the vacuum pump and test the viscosity of the filtrate.

According to the Carman formula [20], when filtering under certain pressure, the relationship between $t/V$ and $V$ is linear and satisfies the following equation:

$$\frac{t}{V} = \frac{\mu \omega}{2A^2 \Delta P} V + \frac{\mu R_i}{A \Delta P}$$  \hfill (1)

Among them: $V$-filtration volume, ml; $t$ - filtration time, s; $\Delta P$-filtration pressure, kPa; $A$-filtration area, cm$^2$; $\mu$-dynamic viscosity of filtrate, kg · s / m$^2$; $\omega$-filtration per unit volume filtrate on the filter medium, kg/m$^3$; $r$-sludge specific resistance, that is, the resistance per unit dry weight filter cake per unit filter area, m/kg; $R_r$-the impedance of the filter medium, 1/m$^2$.

Such as:

$$b = \frac{\mu \omega}{2A^2 \Delta P} \quad a = \frac{\mu R_i}{A \Delta P}$$  \hfill (2)

Then the relationship between $t/V$ and $V$ can be expressed as:

$$t/V = bV + a$$  \hfill (3)

The specific resistance $r$ can be expressed as:

$$r = \frac{2A^2 \Delta P b}{\mu \omega}$$  \hfill (4)

In Cartesian coordinate system, with $V$ as Abscissa and $t/V$ as ordinate, the slope $b$ is obtained by linear regression analysis of the measured data, and then the specific resistance of sludge can be obtained by using formula (4).

### 3.4. Consolidation Test

Consolidation test is used to quantitatively study the effect of conditioning on sludge consolidation coefficient. The test was carried out with a standard consolidation compression apparatus, but
according to the characteristics of high initial moisture content and low strength of the sludge, the first stage load was applied step by step from 3.1kPa to prevent the sample from extruding under instantaneous high pressure.

3.5. PH Regulation
In the fourth conditioning scheme, the PH value of the sludge sample needs to be adjusted. The PH value of sludge was tested according to the standard GJ/T221-2005 [21] method, that is, concentrated hydrochloric acid (11.9mol/L) with different mass ratio was added to the sludge, then the sludge sample was oscillated, and the supernatant was obtained by centrifugation after oscillation, and the PH value of the supernatant was measured by lightning magnetic PH meter. The relationship between the PH value of sludge and the addition amount of hydrochloric acid is shown in figure 3 below.

![Figure 3. PH value of sewage sludge with acid conditioning.](image)

4. Test Results

4.1. Zeta Potential Test Results
The zeta potential test results of the conditioned sludge are shown in figure 4. It can be seen from figure 3 that the Zeta potential of raw sludge is about -22.5 MV, which is close to the test result of excess sludge by Niu Meiqing and others [22]. With the increase of the amount of ferric chloride, the negative charge was gradually neutralized and the zeta potential decreased gradually. When the amount of ferric chloride is 10%, the zeta potential has been reduced to -8mV. The decrease of zeta potential shows that there are less ionized polymers on the surface of sludge flocs, the polarity between flocs is weakened, the polymerization between particles and particles is easier, the difficulty of separation from water is gradually reduced, and its dewatering capacity is improved.

![Figure 4. Zeta potential of sewage sludge conditioned with ferric chloride.](image)

4.2. Results of Environmental Scanning Electron Microscope Analysis
In the first conditioning scheme, the environmental scanning electron microscope images of sludge samples after adding different proportions of ferric chloride are shown in figure 5. As can be seen...
from the picture, the raw mud is basically granular. After the addition of ferric chloride, it was found that the sludge particles became agglomerated, and the agglomerated flocs became more obvious with the increase of the amount of ferric chloride. This is mainly because with the addition of conditioner, the polarity between sludge flocs weakens, and iron salt plays a certain bridging role, which is more likely to occur flocculation and agglomeration.

![Image](a) Raw mud (×800).  
![Image](b) 2.5% Ferric chloride (×800).  
![Image](c) 5% Ferric chloride (×800).  
![Image](d) 10% Ferric chloride (×800).

**Figure 5.** ESEM image of sewage sludge conditioned with ferric chloride.

In conditioning scheme 4, the environmental scanning electron microscope images of sludge samples after adding different proportions of ferric chloride and 10% calcium oxide are shown in figure 6. Compared with figure 5 and figure 6, the spatial structure of sludge is denser and the fine pores between particles are filled after adding calcium oxide. You can't see these things from the image.

![Image](a) 2.5% Ferric chloride +10% Calcium oxide (×800).  
![Image](b) 5% Ferric chloride +10% Calcium oxide (×800).
4.3. Effect of Conditioning on Specific Resistance of Sludge

Taking conditioning scheme 1 and scheme 3 as examples, the relationship between sludge filtration volume and time in vacuum filtration test is shown in figure 7. The filtration amount of unconditioned raw mud in 60min is only 8.75ml. In the first scheme, only ferric chloride was added for conditioning, and the amount of filtration increased obviously with the increase of the amount of ferric chloride. When the addition of ferric chloride is 10%, the amount of 60min filtration has reached 24.8ml. In the third scheme, after adding ferric chloride and calcium oxide at the same time, the filtration capacity was further increased. When 10% ferric chloride and 10% calcium oxide were added at the same time, the vacuum was destroyed after 35min, and the filtration capacity reached 45.66 ml, which was significantly higher than that when only ferric chloride was added.

![Vacuum filtration volume of conditioned sewage sludge versus time.](image)

**Figure 7.** Vacuum filtration volume of conditioned sewage sludge versus time.

Taking the first conditioning scheme as an example, the relationship between V and t/V in the sludge filtration process is shown in figure 8. It can be seen from the diagram that the relationship between V and t/V is basically linear, which is consistent with the conclusion obtained after activated sludge filtration (moisture content 4900%) [17], indicating that the filtration theory is also applicable to the vacuum filtration behavior of degraded sludge in sludge tank.
As shown in figure 8, the specific resistance of the sludge can be calculated according to the test results (the linear relationship between V and t/V). The relationship between the specific resistance of conditioned sludge and the amount of conditioner in scheme 1, 2 and 3 is shown in figure 9. In the first scheme, with the increase of FeCl$_3$ dosage, the neutralization effect was enhanced, and the sludge specific resistance showed a downward trend. When the addition amount is 10%, the specific resistance of sludge is reduced to $1 \times 10^{13}$ m/kg. In the second scheme, the same amount of ferric chloride and calcium oxide were added, and the total amount of conditioner was kept the same as that in the first scheme. It can be seen from figure 9 that when the amount of conditioner is small, the specific resistance of sludge is close to that of the scheme 1. When the total amount of conditioner added reached 10%, the specific resistance of sludge was still higher than that when 10%FeCl$_3$ was added alone in scheme 1. In scheme 3, the amount of fixed calcium oxide added from 2.5% to 10% was increased from 2.5% to 10%. Due to the strong combined effect of ferric chloride and calcium oxide, the specific resistance of sludge decreased more significantly than that of scheme 1, and when the amount of ferric chloride was 10%, the specific resistance was reduced to $3 \times 10^{12}$ m/kg.

Figure 8. The relation of t/V and V in vacuum filtration test of sewage sludge.

Figure 9. Specific filtration resistance of sewage sludge with different conditioners.

4.4. The Influence Law of Acidizing Specific Resistance

After acidizing with hydrochloric acid, the volume of sludge increases and the floc structure becomes loose. After acidizing, the sludge density decreases from 1.07 g/cm$^3$ to 1.03 g/cm$^3$, which is mainly related to the decomposition of sludge extracellular polymer caused by acidizing. The sludge PH=3, is then conditioned with ferric chloride, and the filtration test results of scheme 1 (only ferric chloride conditioning) are shown in figure 10. It can be found that when the addition amount of ferric chloride
is 2.5%, the addition of hydrochloric acid can increase the filtration amount of sludge; however, when the addition amount of ferric chloride is 10%, acidification can reduce the filtration amount of conditioning sludge. The effect of acidification on conditioning sludge is mainly divided into the following two aspects: (1) the extracellular polymer in the sludge is decomposed, releasing part of the water between the flocs, thus improving the dewatering effect; (2) the sludge floc after acidification is decomposed and the volume becomes smaller, on the one hand, the floc becomes easier to compress to form a low permeability layer on the filter medium, at the same time, the fine sludge floc blocks the filter medium so as to reduce the dewatering effect. Acidizing before adding 10% ferric chloride plays a leading role in the second aspect above, so its filtration effect is worse than that of adding ferric chloride alone.

Figure 10. Comparison of vacuum filtration volume of sewage sludge before and after acidification.

4.5. Effect of Chemical Conditioning on Consolidation Characteristics of Sludge

In scheme 1, after the addition of different proportions of ferric chloride, the consolidation coefficient of sludge is shown in figure 11. It can be seen from figure 11 that the consolidation coefficient of unconditioned raw mud is about $10^{-5}$ cm$^2$/s and remains basically unchanged in the pressure range (3kPa~200kPa). With the increase of the amount of ferric chloride, the consolidation coefficient of sludge increased in varying degrees under all levels of pressure. When the addition of ferric chloride is 10%, the consolidation coefficient of sludge increases significantly: at 6.25kPa, the consolidation coefficient is $5.3 \times 10^{-5}$ cm$^2$/s (The consolidation coefficient of 100kPa is $3.9 \times 10^{-5}$ cm$^2$/s, which is nearly 3 times higher than that of unconditioned mud. This is mainly due to the fact that the addition of ferric chloride reduces the binding capacity of sludge floc and water through electrical neutralization (see zeta potential analysis) and increases the permeability coefficient. This is consistent with the effect of conditioning contrast resistance.

Figure 11. Consolidation coefficient of sewage sludge conditioned with ferric chloride.
In scheme 3, the addition amount of calcium oxide is kept at 10%, and the consolidation coefficient of sludge with different proportions of ferric chloride is shown in figure 12. It is similar to the first scheme: with the increase of ferric chloride addition, the consolidation coefficient of sludge increases correspondingly under all levels of normal stress. Especially after conditioning with 10% ferric chloride and 10% calcium oxide, the consolidation coefficient of sludge during 6.25kPa is $10^{-4}\text{cm}^2/\text{s}$, which is close to that of general soft clay, and the consolidation coefficient of sludge at 100kPa is $4.55 \times 10^{-5}\text{cm}^2/\text{s}$, which is 3.5 times higher than that of raw sludge. In the whole stress range, the consolidation coefficient of sludge is increased by 3.5-10 times. Corresponding to the results of the pumping and filtration test of the conditioning sludge mentioned above, compared with the first scheme, the consolidation coefficient of the sludge after conditioning in the third scheme is more significant. The main reason is that the addition of calcium oxide provides skeleton material to the sludge floc, which reduces the compressibility of the sludge, and combined with the electric neutralization function of ferric chloride, it can further improve the consolidation characteristics of the sludge.

![Figure 12. Consolidation coefficient of sewage sludge conditioned with ferric chloride and 10% calcium oxide.](image)

The consolidation coefficient of sludge PH=3, with different proportion of ferric chloride added is shown in figure 13. When the addition amount of ferric chloride is 2.5% and 5%, the consolidation coefficient of sludge is slightly higher than that of scheme 1, when only ferric salt is added. In different stress ranges, the increase of consolidation coefficient is about 5% and 30%. When the addition of ferric chloride is increased to 10%, the consolidation coefficient is slightly lower than that of ferric chloride only when the stress is small. On the whole, acidification (PH=3) before ferric chloride conditioning can not effectively improve the drainage and consolidation characteristics of sludge, which is basically consistent with the vacuum filtration test results after acid conditioning.
Figure 13. Consolidation coefficient of sewage sludge conditioned with ferric chloride and acid.

Compared with the consolidation test, the vacuum filtration test time is shorter, and the test device is simple, so it can be used for rapid detection in the field to determine the effect of in-situ chemical conditioning of the sludge reservoir. The establishment of the relationship between specific resistance and consolidation coefficient will provide a quantitative basis for rapid determination. Since the specific resistance of sludge is obtained under 35kPa vacuum pressure, according to the consolidation coefficient of the corresponding load, the specific resistance is taken as Abscissa and the consolidation coefficient is ordinate. The correlation between the two is shown in figure 14. It can be found from the diagram that there is a good negative correlation between sludge specific resistance and consolidation coefficient: the smaller the specific resistance is, the better the dewatering effect is, and the greater the consolidation coefficient is. The quantitative relationship can also be used as a basis for selecting the optimal combination of conditioners.

Figure 14. The relation of specific filtration resistance and consolidation coefficient of sewage sludge.

4.6. Connection and Difference between Vacuum Filtration Test and Consolidation Test

Through the test device in figure 2, it can be found that compared with the vacuum preloading consolidation test of geotechnical engineering, the principle of vacuum filtration test is similar, except that the boundary conditions are not sealed. Because the permeability of sludge is very small, it can play a sealing role in the early stage of filtration, so it can be seen that the process of vacuum filtration in vacuum filtration test is similar to that of vacuum preloading consolidation drainage. The test results also confirm that there is a strong correlation between the specific resistance and the consolidation coefficient of sludge: the smaller the specific resistance of sludge is, the greater the consolidation
coefficient is. It can be seen that the simple vacuum filtration test can be used as an important means for rough selection of conditioning agents and preliminary determination of consolidation coefficient of conditioned sludge.

5. Conclusions
In order to improve the consolidation coefficient of sludge and combined with the engineering economy, the conditioners to improve the dewatering capacity of sludge were selected, and the effects of different conditioning combinations on the consolidation characteristics of sludge were studied quantitatively, which laid the foundation for the treatment of sludge bank sludge by vacuum preloading technology. the conclusions are as follows:

(1) The zeta potential of sludge decreased with the addition of conditioner. It reduces the binding ability of sludge particles and water, which is also the main reason for the improvement of its permeability. The results of environmental scanning electron microscope test showed that the sludge flocs agglomerated after the addition of ferric chloride, and the addition of calcium oxide would make the structure of sludge flocs more compact, resulting in the increase of compression modulus.

(2) The effect of sludge filtration and dewatering can be greatly improved by adding conditioning agent. The combination of conditioner ferric chloride and calcium oxide can significantly increase the dewatering rate of sludge. With the addition of 10% ferric chloride and 10% calcium oxide (equivalent to sludge dry base), the specific resistance of sludge is reduced from $2 \times 10^{13} \text{m/kg}$ to $3 \times 10^{12} \text{m/kg}$. However, acidification of sludge before adding chemical conditioner can not improve the dewatering performance of sludge.

(3) The consolidation test results show that the addition of 10% ferric chloride and 10% calcium oxide (equivalent to sludge dry base) can significantly improve the consolidation characteristics of sludge, and its consolidation coefficient is increased by about 3.5-10 times, and its value is about $4.5 \times 10^{-5} \text{cm}^2/\text{s}$-$10^{-4} \text{cm}^2/\text{s}$. At low pressure, the consolidation coefficient of conditioned sludge is close to that of soft soil, which lays a foundation for the implementation of vacuum preloading. Acidification before conditioning can not effectively improve the consolidation characteristics of sludge.

(4) There is a good negative linear relationship between the specific resistance and the consolidation coefficient of the sludge. compared with the consolidation test, the vacuum filtration test is simple and easy. Therefore, the vacuum filtration test can replace the consolidation test as an effective means to select sludge conditioning agent or test the conditioning effect.

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References
[1] China Environmental Annual Review Society 2011 China Environmental Yearbook Beijing: China Environmental Science Press.
[2] Feng Y, Luo X Y, Lin W A, Zhan L T, Han K, Chen Y M 2013 Geotechnical properties measurement of sewage sludge at a disposal site Rock and Soil Mechanics 34(1): 115-122.
[3] Chu C P, Liu Z W, Lee D J, Chang B V, Peng X F 2002 Using boiling for treating waste activated sludge Tsinghua Science and Technology 7(2): 155-159.
[4] Yin X, Que Z L, Lu X P, Han P F, Wang Y R 2005 Influence of ultrasound intensity and treatment time on bound water in sludge Chemical Industry and Engineering Process 24(3): 307-312.
[5] Huang Y C, Zhang W J, Jin Q D, Hao L N 2005 Study on efficiency of sludge sedimentation and dewatering of natural freezing/thawing treatment Safety and Environmental Engineering 5(4): 43-46.
[6] Liu H, Li Y L, Shi Y F, Shu H, Yang J K 2011 Influence of inorganic composite conditioner on dewatering performance of sewage sludge *Environmental Chemistry* 30(11): 1877-1882.

[7] Pan J R, Huang C, Chen G F 2000 Effect of surfactant on alum sludge conditioning and dewaterability *Water Science and Technology* 41(8): 17-22.

[8] Zhao Y Q, Bache D H 2001 Conditioning of alum-sludge with polymer and gypsum *Colloid and Surfaces A: Physicochemical and Engineering Aspects* 194(1-3): 213-220.

[9] Hu F P, Wang L Y, Guan X T 2008 Experimental study on conditioning residual activated sludge by dual conditioners *Environmental Science & Technology* 31(12): 28-30.

[10] Lee C H, Liu J C 2000 Enhanced sludge dewatering by dual poly-electrolytes conditioning *Water Research* 34(18): 4430-4436.

[11] He W Y, Yang H Z, Gu G W 2006 Acid treatment of waste activated sludge for better dewaterability *Environmental Pollution & Control* 28(9): 680-682.

[12] Chen Y G, Yang H Z, Gu G W 2001 Effect of acid and surfactant treatment on activated sludge dewatering and settling *Water Research* 35(11): 2615-2620.

[13] Chen B X, Zhang C, Wang G H, Lai Q H, Xu Y H, Sun X 2011 Application of advanced sludge dewatering process at Qige WWTP, Hangzhou *China Water & Wastewater* 27(8): 83-85.

[14] Cao Y H, Yao S W, Zhao L J 2006 Engineering properties and microstructure feature of solidified sludge *Rock and Soil Mechanics* 27(5): 740-744.

[15] Jin Y, Song F Y, Zhu N W, Guo T T 2011 Experiments on solidification of sewage sludge with different solidifying agents *Environmental Pollution and Control* 33(2): 74-78.

[16] O’Kelly B C 2008 Geotechnical properties of a municipal water treatment sludge incorporating a coagulant *Canadian Geotechnical Journal* 45(5): 715-725.

[17] Zhan X J, Lin W A, Zhan L T, Luo X Y, Chen Y M 2013 Model experimental study on vacuum preloading of municipal sludge *Rock and Soil Mechanics* 34(S1): 88-96.

[18] Fu B, Liao X Y, Ding L L, Ren H Q 2009 Application of ESEM in the visualization of microbial community of granule sludge and suspended carrier biofilm *China Environmental Science* 30(1): 93-98.

[19] Tang X M, Dai S W 2001 ESEM observation for biological samples *Journal of Chinese Electron Microscopy Society* 20(3): 217-223.

[20] Coackley P, Jones B R S 1956 Vacuum sludge filtration I: Interpretation of results by the concept of specific resistance *Sewage and Industrial Wastewater* 28(8): 963-976.

[21] Ministry of Construction of the People’s Republic of China 2005 Method for Inspection of Sludge from Municipal Sewage Treatment Plants CJ/T221-2005 Beijing.

[22] Niu M Q, Zhang W J, Wang D S, Xu X, Duan J 2012 Study on effect of chemical conditioning using different coagulants on sludge dewatering performance *Acta Scientiae Circumstantiae* 32(9): 2126-2133.

[23] Thapa K B, Qi Y, Clayton S A, Hoadley A F A 2009 Lignite aided dewatering of digested sewage sludge *Water Research* 43(3): 623-634.

[24] Mickael R, Jean V, Jérémy O, Emilie D F, Baudez J C 2012 Compression dewatering of municipal activated sludge: effects of salt and pH *Water Research* 46(14): 4448-4456.