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Municipal sludge as landfill barrier material

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Abstract: The aim of this research is to find substitute barrier materials for natural clay from two kinds of municipal sludge: waterworks sludge(S_w) and dredging sludge(S_d). Laboratory tests were performed firstly to determine their Atterberg limits and hydraulic conductivity. Based on the results, the use of waterworks sludge was recommended. Then, shear strength tests were performed and it was found the shear resistance property of waterworks sludge is strong enough to maintain slope stability. In order to evaluate the possibility of secondary pollution, the heavy metal contents of waterworks sludge was determined and the results indicated that secondary pollution is unlikely happened. Finally, economic analysis proves that reusing waterworks sludge as barrier will reduce the lost a great for both landfill and waterworks. Based on the results, waterworks sludge was proposed to use and a further long-term simulated landfill test was suggested.

Keywords: waterworks sludge; dredging sludge; barrier material; Atterberg limits; hydraulic conductivity; shear strength

Introduction

Landfill is the most important waste disposal means in China because more than 90 percent of municipal domestic waste is sent to sanitary landfills. In landfill operation, one of the most important steps is to cover the waste with low hydraulic conductive materials, to eliminate or minimize the percolation of rainwater into the waste, and to suppress the off-site migration of landfill gases. In China, the most widely used landfill capping material is natural clay.

Located in Shanghai, with a capacity of 3750 t/d, Laogang Landfill is one of the biggest landfills in China. In Shanghai, the high cost of natural clay for use as landfill capping material drove us to identify a cheaper substitute material. After a preliminary survey of potential substitute materials in Shanghai, we chose two kinds of municipal waste, i.e. waterworks sludge and dredging sludge, as candidate materials.

It have been found that some new materials suitable for replacing natural clay as landfill capping, including harbour sludge(Tresselt, 1998), compound clay mixture(Al-Tabbaa, 1998; He, 1998; Shi, 2003), mudstone material(Chyi, 1998), coal fly ash-lime dust-bentonite mixture (Nhan, 1996), pulp and paper mill residuals(Malmsteal, 1999) and so on. In order to assess the feasibility of new materials as landfill barrier material, a variety of these materials' properties, including Atterberg limits, organic content, grain-size distribution, permeability, leach ability, compressibility, stress-strain behaviour, and swell behaviour were examined.

In China, the compulsory standard CJJ 17-2001, Technical Code for Sanitary Landfill of Municipal Domestic Refuse, specifies only one requirement for the barrier material, i.e. the hydraulic conductivity of the material should not exceed 10^{-9} m/s. Such impermeable material can effectively prevent rainwater's infiltration. However, in order to make a more comprehensive evaluation of the sludges' performance as capping material, we investigated the Atterberg limits, organic content, permeability, compressibility, shear strength and heavy metal content of both sludge. Atterberg limits are used to pre-evaluate hydraulic conductivity. Permeability and compressibility properties are used to evaluate whether these sludge satisfy the only requirement specified in industry standard CJJ 17-2001. Shear strength is used to deduce the stability of slopes constructed using the sludge, which was less studied in past. Heavy metal content is used to estimate the possibility of secondary pollution. Additionally, economic analysis is performed to calculate the cost saved if the sludge is reused as landfill barrier material.

1 Experimental

1.1 Materials and sample preparation

Waterworks sludge sample was taken from Minghang Waterworks, located in the south of Shanghai, and dredging sludge sample was taken from a branch of Suzhou Creek. Water content of the centrifugally dewatered waterworks sludge was determined to be 61%. The dredging sludge was centrifugally dewatered *in situ*, with water content decreased to 65%. However continuous seepage from the sample during the transportation and storage further reduced the water content of the sample to 39% before tests were undertaken.

1.2 Atterberg limits test and organic content test

The Atterberg limits test included two parts, i.e. liquid limit test and plastic limit test. For determination of the liquid limit, there are two methods that may be used, Cone penetrometer method and Casagrande apparatus method, and in this research we took the former method. Both Atterberg limits test and organic content test were measured following industry standard SL 237-1999.

In the liquid limit test, a cone penetrometer was placed on the surface of sludge and the liquid limit was calculated according to the velocity and depth the cone penetrates into the sludge.

In the plastic limit test, the sludge was rolled against a glass plate. When the sludge was rolled into a 3 mm diameter bar and cracked, its water content as its plastic limit was determined.

In the organic content test, the potassium dichromate method was used to determine the organic carbon content of sludge, and organic content was calculated by multifying the organic carbon content by 1.724, an experiential coefficient.

1.3 Hydraulic conductivity and compressibility test

An air-pressed compaction permeameter was used to determine both the permeability and compressibility properties of the sample(Fig.1).

A consolidation ring filled with the sludge specimen was placed into the rigid cell on top of the lower porous plate. The upper porous plate and the metal cap were then placed on the surface of the ring in sequence. The diameters of both

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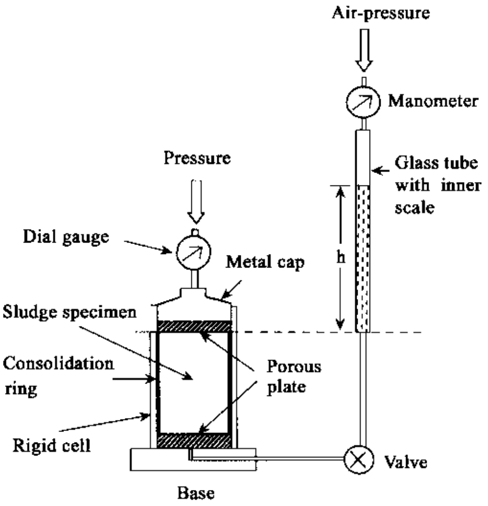

Fig.1 Air-pressure compaction permeameter

the top porous plate and the cap were about 0.5 mm smaller than the insider diameter of the consolidation ring, in order to permit free compression of the sludge specimen. A dial gauge was clamped securely above the metal top to measure the compression of the specimen.

Compressibility tests were carried out according to SL 237-1999. Through a loading device, the following pressures were sequentially exerted on the metal cap, 50 kPa, 100 kPa, 200 kPa, and 300 kPa. Each pressure increment was held constantly until the primary consolidation of the specimen had ceased. Once the consolidation under each pressure was completed, the dial gauge reading of the displacement of the metal cap was recorded. According to these recordings, the densities of the sludge under different pressures were calculated.

Permeability tests were performed following the procedures specified in SL 237-1999. With the valve opened, under the air pressure, water was passed from the glass tube to the base, then upwards through the lower porous plate, the sludge specimen and then through the upper porous plate, to finally exit the permeameter cell through the gap between the edge of the metal cap and the inside wall of cell. The air pressure value on the manometer was recorded, and the height change of the water in glass tube, which was later used to calculate the volume of water passing through the specimen during a given interval of time, was continuously recorded from the inner scale.

The dry density of the specimen on each consolidation stage was calculated using the Equation (1).

$$\rho_i = \rho_0 \frac{h_r}{h_r - \delta_i}, \qquad (1)$$

where, ρ_i is the dry density of specimen at each stage of consolidation (kg/m^3); ρ_0 is the initial dry density of specimen, which was measured before the test was performed (kg/m^3); h_r is the height of the consolidation ring(m); δ_i is the displacement of the metal cap, recorded by the dial gauge (m).

The coefficient of permeability on each consolidation stage was calculated from Equation (2).

$$k_i = 2.3 \frac{a(h_r - \delta_i)}{At} \lg \frac{\rho_w g h_1 + P}{\rho_w g h_2 + P}, \qquad (2)$$

where, k_i is the permeability coefficient of specimen at each stage of consolidation(m/s); a is the area of cross section of the glass tube(m^2); h_r is the height of the consolidation ring (m); δ_i is the displacement of the metal cap, recorded by the dial gauge (m); A is the area of cross section of the consolidation ring(m^2); t is the given interval of time(s); ρ_w is water density(10^3 kg/m^3); g is acceleration of gravity (10 N/kg); h_1 is the initial height of water in the glass tube (m); h_2 is the height of remaining water in the glass tube after the given interval of time (m); P is the air pressure (kPa).

1.4 Shear strength test

The direct shear method was used in this test. A schematic diagram of the apparatus used is shown in Fig.2.

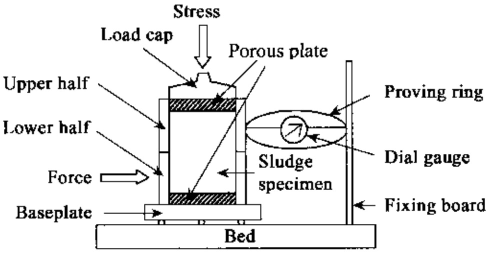

Fig.2 Schematic diagram of shear strength test apparatus

The shear strength test was carried out according to SL 237-1999. Sludge specimen was gently pushed from a consolidation ring into the cylindrical cell of shear box that was divided into two halves. The lower half was fitted on the movable base plate. Through the load cap centrally aligned with the upper half, a series of loads were applied vertically to the specimen. During the consolidation, water in the specimen was drained out through porous plates. With the application of horizontal force, the lower half moved along the bed. Shear stress in the specimen resulted from the relative movement between the upper half and the lower half, causing deformation of the proving ring that was fixed between the upper half and the fixing board. The deformation was recorded by the dial gauge fitted inside the ring, and the relationship between the deformation of the ring and the force applied on the ring was experimentally determined prior to the test. According to the movement of the shear box and the increment of the deformation of proving ring, the shear stress in the sludge specimen would increase to a limit, with the pointer of the dial gauge suddenly reversing. The maximum reading of the dial gauge was recorded and the corresponding maximum shear stress in the specimen was calculated.

The Mohr-coulomb law describes the relationship between the maximum shear stress and the loading pressure (Murthy, 2003), as shown in Equation (3).

$$\tau = c + \sigma \cdot \tan\varphi, \qquad (3)$$

where, τ is the maximum shear stress of specimen(kPa); c is the cohesion strength of specimen(kPa); σ is the loading pressure applied on specimen(kPa); φ is the friction angle of specimen(degree).

According to the above equation and the data obtained from the test, the cohesion strength and the friction angle of both kinds of sludge were calculated.

1.5 Heavy metal content test

Cr, Ni, Cu, Pb and Cd contents were measured by atomic absorption spectrophotometry in accordance with national standards of China, i.e. GB/T 17137-1997, GB/T 17138-1997, GB/T 17139-1997 and GB/T 17141-1997.

2 Results and discussion

2.1 Atterberg limits and organic content

Atterberg limits and organic content are shown in Table 1. Plasticity index is the difference between the liquid limit and plastic limit.

Atterberg limits are useful in estimating the feasibility of material as liner. According to Benson (Benson, 1994), a geometric mean of hydraulic conductivity, which is lower than 1.0×10^{-9} m/s, could be achieved if the liquid limit is greater than 20% and the plasticity index is greater than 7. According to the results shown in Table 1, both kinds of sludge have the potential to be barrier material.

Table 1 Atterberg limits and organic content of two kinds of sludge

Sample	Water content, %	Liquid limit, %	Plastic limit, %	Plasticity index	Organic content, %
S_w	61	58	40	18	4.3
S_d	39	34	20	14	0.7

2.2 Hydraulic conductivity and compressibility

Table 2 shows the output data of hydraulic conductivity and compressibility of the samples under a series of loads.

Table 2 Hydraulic conductivity and compressibility of two kinds of sludge

Sample	S_w				S_d			
Load, kPa	50	100	200	300	50	100	200	300
Dry density, 10^3 kg/m^3	1.20	1.24	1.26	1.29	1.41	1.44	1.48	1.51
Hydraulic conductivity, 10^{-9} m/s	4.30	1.30	0.85	0.76	3.50	2.40	2.10	1.70

In Fig.3, hydraulic conductivity of two kinds of sludge is plotted, as ordinate, against loading pressure, as abscissa. From Fig. 3, we can see that under a loading pressure around 150 kPa the hydraulic conductivity of S_w will fall to below 1.0×10^{-9} m/s, which is in accordance with the requirement of industry standard CJJ 17-2001. However, the hydraulic conductivity of S_d hardly satisfies the standard requirement, even under a high loading pressure of 300 kPa. Based on the above comparison of hydraulic conductivity, we recommend waterworks sludge for use as barrier material rather than dredging sludge.

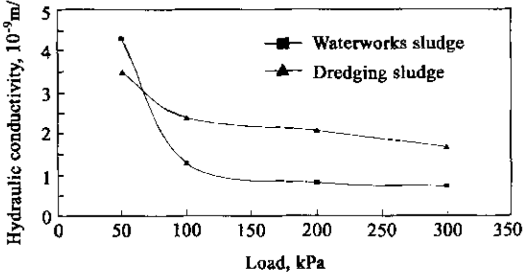

Fig. 3 Relationship between the hydraulic conductivity of both kinds of sludge and loads applied on them

2.3 Shear strength

Fig.4 shows the shear strength test result of waterworks sludge.

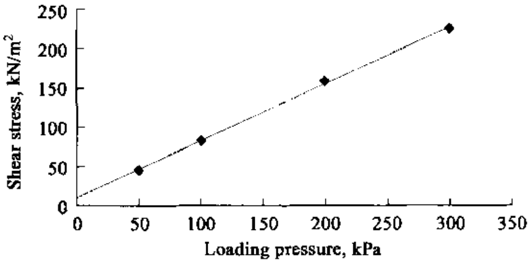

Fig.4 Shear stress on series of loading pressure

According to Equation (3), the cohesion strength of the sludge is calculated to be 11 kPa, and the friction angle to be 36 degree.

The cohesion strength and the friction angle of waterworks sludge are used to assess the resistance to sliding of the sludge slope. According to Majdi (Majdi, 1995), the slope stability factor of safety, considering seepage forces parallel to the slope above the potential sliding surface, is

$$\eta = \left(1 - \frac{T_W \gamma_W}{T_C \gamma_C}\right) \frac{\tan\varphi}{\tan\beta}, \qquad (4)$$

where, η is the factor of safety; T_W is the thickness of water above the sliding surface (m); T_C is the thickness of soil cover above the sliding surface (m); γ_W is the density of water (10^3 kg/m^3); γ_C is the sludge wet density (which was determined to be 1.8×10^3 kg/m^3); φ is the friction angle of the sludge (degree); β is the slope angle (degree).

Transform the above equation and we get the expression of slope angle.

$$\beta = \arctan\left[\left(1 - \frac{T_W \gamma_W}{T_C \gamma_C}\right) \frac{\tan\varphi}{\eta}\right], \qquad (5)$$

Since there is no requirement on the stability of landfill slope in laws, regulations and standards in China, we refer to the specifications on other correlated slopes. In national standard GB 50330-2002, the slope stability factor is required to be larger than 1.35, hereby, we assign this value to the η in Equation (5).

Under the worst situation, where the cover system does not include an effective drainage layer above the barrier layer and the soil above the potential sliding surface is saturated with rainwater, T_W equals to T_C. The value of β under such extreme condition is calculated to be 16 degrees according to Equation (5). The result means that, under any condition except earthquake, the landfill slope of waterworks sludge will remain stable with a slope angle less than 16 degrees. The slope angle of Laogang Landfill is generally designed to be less than 10 degrees, so the waterworks sludge could be safely used as barrier material in Laogang Landfill.

2.4 Heavy metal content

Heavy metal contents are shown in the second row of Table 3, with the limit content of corresponding heavy metal specified in the national standard of China GB 4284-84 shown in the third row of the table for the purpose of comparison.

From Table 3, it can be seen that the content of five kinds of heavy metal is far below the limit stipulated by the relevant national standard for agricultural use sludge. Since the waterworks sludge is suitable to be reused for agricultural purpose, it can be concluded that, being applied as landfill barrier, the waterworks sludge will not comprise a significant source of heavy metal pollution.

Table 3 Comparison between heavy metal contents of waterworks sludge and the limit content of national standard of China

	Cr, mg/kg	Ni, mg/kg	Cu, mg/kg	Pb, mg/kg	Cd, mg/kg
Waterworks sludge	114	41.1	61.2	26.8	0.0324
Limit content	600	100	250	300	5

2.5 Economic analysis

Economic analysis is performed to show how much can be saved by substituting waterworks sludge for natural clay.

To be reused on landfill, waterworks sludge should be dewatered to 60% water content, transported to landfill, laid on waste, and then compressed by compacting. Currently, waterworks sludge is dewatered and transported to landfill for disposal at a fee of over 20 RMB Yuan per ton, and the landfill purchases natural clay to apply as barrier material. Obviously, by reusing waterworks sludge as barrier material, waterworks can save on disposal fees and the landfill operators can save the amount used to purchase natural clay.

The area to be covered with barrier in Laogang Landfill is 3.2 million square meters. According to the industry standard CJJ 17-2001, the depth of barrier ought to be no less than 0.2 m. So the landfill needs 640 thousand cubic meters natural clay or waterworks sludge. The price of natural clay suitable for final cover is 30 RMB Yuan/m^3. So, purchasing natural clay as barrier material would cost Laogang Landfill about 19 million RMB Yuan. For waterworks, landfill disposal fee for 640 thousand cubic meters sludge cost about 23 million RMB Yuan.

From the analysis above, it can be concluded that the reuse of waterworks sludge as landfill barrier material can save about 42 million RMB Yuan.

2.6 Other factors

Besides the properties we have investigated, there remain other factors that should be taken into consideration before that waterworks sludge is adopted for cover material at Laogang Landfill, in particularly the long-term behaviour of the compacted waterworks sludge. For example, waterworks sludge tends to crystallize under a 0.4 m depth of cover of soil as time progresses, which may change the structure and affect the permeability property of the sludge. Another concern could be that nonuniform settlement of the municipal domestic waste beneath the compacted waterworks sludge may result in cracks in the sludge layer and then permeation of rainwater. It is therefore recommended that a simulated landfill test is needed to observe long-term behaviour of compacted waterworks sludge.

3 Conclusions

Based on the above results, the following conclusions can be drawn: (1) According to the Atterberg limits, two kinds of sludge have the potential low-hydraulic-conductivity ability to satisfy the industry standard's requirement. (2) The comparison of hydraulic conductivity behaviour between two sludge shows that the waterworks sludge is much better than the dredging sludge as barrier material. Equipped with a compactor that could apply a pressure of 150 kPa, Laogang Landfill can reuse waterworks sludge as capping material while not violating industry standard CJJ 17-2001. (3) Even when used on slopes up to 16 degree, the slope of waterworks sludge will remain stable. It is statically safe enough for Laogang Landfill to reuse waterworks sludge as barrier. (4) The heavy metal content of waterworks sludge is too low to comprise a secondary pollution resource after the sludge is applied as final cover. (5) It will save at least 42 million RMB Yuan if Laogang Landfill adopts our recommendation to apply waterworks sludge as barrier material.

Based on the properties of sludge we investigated and the economic analysis above, we suggest reusing waterworks sludge as barrier material in Laogang Landfill. It is also recommended that a long-term simulated landfill test be undertaken to further verify the feasibility of reusing waterworks sludge as barrier material at Laogang Landfill.

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