Permeability Characteristics of Model Clay-Based Cutoff Wall Backfills

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Abstract. Clay-based cutoff walls have been widely applied in the landfills or site remediations. The factors that affect the hydraulic conductivity of cutoff walls formed by mixing formation with clays are still unclear. Aiming at the issue, the Fujian standard sand was used to simulate the formation and three kinds of clays were taken as the additive and slurry material for mixing and pouring. Then the hydraulic conductivity and pore size distributions were measured. The results indicated when the Clay C formed the cutoff walls with the model formation, there was a critical clay additive amount Cc⁺ corresponding to the minimum porosity, and there would be great change in the descent velocity of the hydraulic conductivity k before and after critical clay additive amount Cc⁺. In regard to Clay A and Clay B, the critical clay additive amount Cc⁺ of sand-clay specimens didn’t appear as the additive amount of Clay A and Clay B reached 25%. For Clay A and Clay B, the pore size distributions of sand-clay specimens were relatively identical, and their hydraulic conductivity k declined with decreasing porosity n. However, the pore size distributions of the mixture corresponding to Clay C gradually widened with the increasing additive amount, and they would develop towards the smaller pore size. Meanwhile, P₅₀ also declined correspondingly, and there was poor correlation between porosity n and hydraulic conductivity k. Comparatively speaking, the microscopic pore structure of the model formation improved by Clay C was the most obvious, and Clay C raising the sealing effectiveness of model formation was also best.

1. Introduction

Nowadays, the municipal solid waste treatment receives more and more attention, but the innocuous disposal of waste is still at a low level. For instance, 13 landfills (including the simple waste landfills) are now being operated in Beijing, and there are nearly 3000 waste disposal sites with no seepage control system and the innocuous disposal rate of waste about 58%. There are ten landfills (including the simple waste landfills) in Shanghai, as well as 500 waste disposal sites with no seepage control system covering over 5000 m² in the suburbs and the innocuous disposal rate of waste about 60% (Liu 2001; Zhang and Su 2003). The situation is much worse in small and medium-sized cities or other undeveloped regions. The waste degradation product may form leachate with rainwater, which is a high-concentration contaminant. Since there is no seepage control system in the waste disposal site
and simple waste landfills, which may result in severe threat on the surrounding soil and groundwater. In this case, the construction of cutoff walls by combining the formation condition, the pumping and control of underground water, etc. are feasible measures for pollution treatment. Regarding the vertical anti-seepage, grout curtain (cement bentonite slurry) is frequently applied in China (such as simple waste landfills), namely the cement slurry is sprinkled into the soil layer with jet flow, so that it could mix with soil and condense to reach the goal of anti-seepage. It is relatively hidden, and the anti-seepage effect can’t be controlled easily. But it is in low cost and simple in construction (Long and Hu 2000). While clay-based cutoff wall is one kind of diaphragm wall in which clay slurry would be used to support the excavated trench, and then the excavated soil will be refilled, so as to mix and form walls. It has a low permeability and good chemical compatibility and its quality can be controlled easier compared with grout curtain.

In terms of the permeability of clay-based cutoff wall, Devlin and Parker (1996) investigated the anti-fouling performance of soil-bentonite cutoff wall and it was concluded that when the cutoff wall was about 1 m in thickness and the hydraulic conductivity \( k \) value was smaller than \( 5 \times 10^{-6} \) cm/s, the hydraulic migration of contaminant could be controlled effectively and the escape of contaminants mainly comes from the slow molecular diffusion process. Consequently, how to mix the clay and formation to make the \( k \) value smaller than \( 5 \times 10^{-6} \) cm/s turns to be a problem concerned in the engineering. Ebina et al. (2004) carried out flexible wall permeability tests for the compacted clay-sand specimens and discovered that the \( k \) increased with the Ca/Na ratio of clay. In addition, the relationships between \( k \) and the exchangeable cation concentration of clay, the methylene blue index, as well as the mineral composition had been illustrated. About the decline way of \( k \) after the addition of bentonite Yeo et al. (2005) conducted falling-head hydraulic conductivity tests for the sand-clay and sand-bentonite, and concluded that the \( k \) decreased with an increase in bentonite content or fine particle content. When there is only low-plasticity fine particles in the mixture, the fine particle content must exceed 40% and then the \( k \) value can reach \( 1 \times 10^{-7} \) cm/s. Bandini and Sathiskumar (2009) performed flexible wall permeability tests for sand-silt mixture with different addition, showing that the \( k \) value of the mixture with 25% of the silt is about two orders of magnitude smaller than the pure sand.

The above researches revealed the relation between the \( k \) of sand-clay mixture and various macroscopic factors, but the microscopic pore structure of soil may be the internal factor influencing the permeability, and the essential reason for the macroscopic phenomenon can be learnt through the microscopic experiment. Obviously, it is not enough to only know the void ratio \( e \) or porosity \( n \) of mixture when needed analyse the change of \( k \), and it shall study the influence of clay on the permeability of the sand-clay mixture combining with the pore size distribution. Therefore, it is necessary to employ clays of different types from China for carrying out the laboratory tests.

### 2. Materials and Methods

#### 2.1. Materials

Since the formation may vary with the site conditions, unfavourable properties of in situ formation will be simulated. Model formation: medium sand-standard sand of Fujian (commercial use) of bad gradation is selected for simulation, shortened as FSS, and the basic physical properties are shown in Table 1.

| \( G_s \) | \( C_u \) | \( \rho_{\text{max}} \) (g/cm\(^3\)) | \( \rho_{\text{min}} \) (g/cm\(^3\)) | \( e_{\text{max}} \) | \( e_{\text{min}} \) |
|---|---|---|---|---|---|
| 2.64 | 5.99 | 1.74 | 1.43 | 0.85 | 0.52 |

Natural clay (in powder form): three types, namely the kaolin from Shijiazhuang of Hebei Province, shortened as clay A; attapulgite from the Nei Mongol Autonomous Region, shortened as clay B, and the bentonite from Lingshou County of Hebei Province, shortened as clay C. The basic physicochemical properties of FSS and three types of clays are measured according to the Soil Test
Method Standard GB/T 50123-1999 (Ministry of Construction P. R. China 1999) and Bentonite GB/T 20973-2007 (China Building Material Industry Association 2007), as shown in Table 2. Both the clay and standard sand are oven-dried five days under 65°C.

| Type | $G_s$ | $\omega_L$/% | $\omega_p$/% | Swell index/(mL/2g) | CEC/(mmol/100g) | Main mineral     |
|------|------|-------------|-------------|---------------------|-----------------|-----------------|
| A    | 2.68 | 39          | 23          | 2.6                 | 30.3            | Kaolinite        |
| B    | 2.72 | 52          | 26          | 4.1                 | 31.0            | Palygorskite     |
| C    | 2.75 | 181         | 53          | 17.0                | 113.7           | Montmorillonite |

2.2. Methods

Grain size distribution: grain size distribution curves were determined separately for sand and clays. The sieve analysis test was carried out for sand. The grain size distribution curves of the three types of clays were drawn by the wet analysis used in hydrometer method. Then the grain size distributions of sand and clays used in the experiments were plotted in Figure 1. According to Unified Soils Classification System (USCS), FSS is poorly graded sand (SP), Clay A is low plasticity clay (CL) and Clay B and A are high plasticity clay (CH).

Sample preparation: The FSS will be mixed evenly with a certain amount of dry clay and with a 5% clay slurry prepared to form specimens for pouring, similar to concrete mortar. To simulate the backfill in a practical construction situation, slumps of the specimens used for permeability test are created with 125 mm ± 12.5 mm (Maluvis et al. 2009). Note that the clay additive amount refers to the percentage of dry clay weight to dry sand weight.

Improved flexible wall permeability test: For the poor self-supporting specimens, the RST-1 flexible wall permeameter made by Nanjing Soil Instrument Company was improved, and a cutting ring with many small pores was added to the periphery of the specimens following Zhu et al. (2014). This created a specimen that could support itself, thus allowing a system to be constructed that could apply confining pressure on the side walls of the specimens, as shown in Figure 2a. Compared to the rigid wall permeameter, a flexible wall can prevent the influence of side wall leakage or preferential flow. Additionally, it can simulate the stress state of the cutoff wall in practical application, and permeability tests use an effective confining pressure of 100 kPa to obtain a possible minimum hydraulic conductivity. The permeant liquid selected the deionized water, the seepage pressure gap was 70 kPa, the diameter of specimens was 7 cm, and the height of specimens was 4 cm. The flexible wall permeability test referred to ASTM D5084 (ASTM 2010), and the test was conducted at a constant temperature of approximately 25°C.

Mercury intrusion porosimetry test: it is one of the most common methods for studying the microscopic pore structure quantitatively, and it has much wider range than other approaches for
testing the entrance pore diameter. Generally, the measurable entrance pore diameter scope ranges from 3.6nm to 200μm, which can reflect the pore structure of most materials (Chen 2006). The PoreMaster-60GT automatic mercury injection apparatus of American Quantachrome Company (as shown in Figure 2b) is used, the maximum pressure could reach 414 MPa, and the corresponding entrance pore is 3.6 nm. The test equipment consists of low pressure system and high pressure system, and the main technical indexes are shown in Table 3. At first, the specimens are cut into small cubes (20mm×20mm×20mm) which are located in the centre of specimens, and place them into the cold trap for freezing after the temperature is lower than -80°C, and then it shall be vacuumed for sublimation for 24 hours, which may eliminate the surface tension caused by the meniscus between gas and water phase, so that the swelling-shrinking and microscopic structure changes of soil caused by the loss of water can be minimized. Finally, the specimens going through the sublimation is placed into the sample tube for mercury intrusion porosimetry test. The test is conducted in two steps: at first, low pressure test will be performed, and then high pressure test will be carried out. Low pressure system is mainly applied for filling mercury and measuring the gross pore size, while the high pressure system is a significant part of the apparatus. Sample tube with specimens shall be placed into the high pressure oil vessel, and pressure will be applied constantly with the high-pressure oil-pump, till the pressure reaches maximum. The setting parameters of the test are: surface tension of mercury is 0.48N/m and the contact angle is 140°. The value of surface tension and contact angle of the mercury refer to the instructions of apparatus and related literatures (Delage and Lefebvre 1984; Griffiths and Joshi 1989; Mitchell 1993).

| System name   | Pore diameter range(μm) | Pressure range(MPa) | Rate of pressure change(MPa/s) | Sensor accuracy (%) | Volume accuracy (%) |
|---------------|------------------------|--------------------|-------------------------------|--------------------|---------------------|
| Low pressure  | 1080~4.26              | 0.0016~0.3447      | 0.0021                        | ±0.11              | ±1                  |
| High pressure | 10.66~0.0036           | 0.138~413.686      | 2.4132                        | ≤±0.05             | ±1                  |

Table 3 Main technical parameters of the MIP apparatus

3. Results

3.1. Influence of clay additive amount on the hydraulic conductivity of sand-clay mixture
Different additive amounts of three types of clays are compared with the k obtained in the permeability test, and Figure 3 can be obtained. With the increasing clay additive amount, the k of the mixture declines to different degrees, but there are still distinctions in the declining speed of k. In terms of Clay
A and Clay B, when the additive amount increases from 0% to 2.5%, $k$ declines from $8.47 \times 10^{-4}$ cm/s to $2.59 \times 10^{-5}$ cm/s and $4.76 \times 10^{-6}$ cm/s respectively. But after the additive amount of 2.5%, the declining speed of the $k$ keeps a stable speed. However, with respect to Clay C, during the increasing process of clay additive amount, the $k$ declines rapidly first and then tends to be flat. For the requirement that the $k$ value is smaller than $1 \times 10^{-7}$ cm/s, it can satisfy when the additive amount of Clay B and Clay C reaches 5% and 20% respectively. About the cutoff wall with the anti-fouling property, whose $k$ value should be smaller than $5 \times 10^{-8}$ cm/s, proposed by Devlin and Parker (1996), three types of clays can also satisfy the requirement through changing the additive amount. It is evident that Clay C has better performance in decreasing $k$ value of sand-clay mixtures compared with Clay A and Clay B.

3.2. Influence of clay additive amount on the porosity of sand-clay mixture

According to the fact that previous scholars mainly analyze the changes in $k$ from the perspective of the porosity $n$ or void ratio $e$, the $n$ of three kinds of sand-clay mixtures of different additive amount is also tested and calculated after the flexible wall permeability test, and as a result, the relationship between the clay additive amount and the $n$ is obtained, as shown in Figure 4.
The $n$ of FSS without clay is 40.69%. Pertaining to Clay C, the $n$ of mixture could decrease to 32.62% when the additive amount of clay reaches $C_{cr}$, but the $n$ would increase after the additive amount exceed $C_{cr}$, which may reach 42.28% at maximum and is more than the $n$ of FSS. It might be considered that if the additive amount is smaller than $C_{cr}$, the mixture is a structure which takes the sand particles as the frame and the clay particles fill the pores. With the further additive amount of clay, the clay particles participate in the overall structure, and the mixture turns to be much looser. When the additive amount of Clay A and Clay B reaches 25%, the $C_{cr}$ fails to occur. It may require more amount, so that the $C_{cr}$ may appear and then Clay A and Clay B can participate in the overall structure of the mixture.

It can be considered according to the declining $k$ reflected in Figure 3 that the increase of Clay C impacts the permeability through changing the number of pores, and the permeability of the newly-formed pores are distinct from the original pores. Consequently, it is not enough to evaluate the changes in $k$ of sand-clay mixture according to the $e$ or $n$.

### 3.3. Influence of clay additive amount on the pore size distribution of sand-clay mixture

It is of the approximative $n$, but there are differences in the permeability. It is certainly related to the forms of moisture in the pore, and meanwhile, it may be also related to the pore diameter and pore size distribution. Romero (2013) carried out the literature review for the influence of the microstructure of different compacted clayed soil on the hydraulic performance. Out of the considerations of if the pore diameter and pore size distribution impact the permeability of sand-clay mixtures, mercury intrusion porosimetry test is conducted for sand-clay mixtures with 0%, 5% and 10% additive amount of the Clay C after flexible wall permeability test, and as a result and then the pore size distribution curves and cumulative mercury curves of mixtures are obtained, as shown in Figure 5.

![Figure 5](image-url)  
Figure 5. (a) Pore size distribution curves and (b) cumulative mercury curves
It could be seen from the pore size distribution curve (Figure 5a) that, when the clay additive amount increases from 0% to 5% and then from 5% to 10%, the pore size distribution curve gradually occurs in the bimodal distribution from the unimodal distribution, and the entrance pore diameter corresponding to the main peak also declines and the peak value increases. At the same time, the cumulative mercury curve (Figure 5b) gradually develops toward the ‘lying’ trend from the ‘standing’ trend. The entrance pore size distribution grows larger and larger and the $P_{50}$ (the entrance pore diameter whose volume intruded is 50% in cumulative mercury curves) declines with increasing Clay C additive amount.

4. Discussion

It would be obtained from Figure 3 and Figure 4 that when the additive amount of Clay A and Clay B increases, the $k$ and $n$ of mixture declines rapidly first and then slowly, with consistent changing rules, which is similar to the common phenomenon, namely the smaller $n$ of soil is, the smaller $k$ will be (Mesri 1971). But it is not suitable for Clay C. When the additive amount of Clay C is smaller than the $C_{cr}$, the $k$ declines rapidly. After the $C_{cr}$, the declining trend of $k$ tends to be flat, but its $n$ still increases, for it may be caused by the distinct microscopic pore structures and basic properties of clay minerals. In addition, the bound capacity between clay particle and pore water will also result in the continuous decreasing of the $k$.

![Figure 6. (a) Pore size distribution curves and (b) cumulative mercury curves of different sand-clay mixtures](image-url)
Based on the above analysis, the entrance pore size distribution features is tested with mercury intrusion porosimetry on the sand-clay mixtures whose clay additive amount is 10%, as shown in Figure 6. At first, it can be concluded from the pore size distribution curves of mixtures (Figure 6a), the entrance pore size distribution of the mixture corresponding to Clay B is dominated by main peak. While that of the mixture corresponding to Clay A and Clay C has the phenomenon of main peak and secondary peak and the secondary peak of the mixture corresponding to Clay A occurs in the area about 100–200μm on the right of the main peak. However, the secondary peak of the mixture corresponding to Clay C occurs in the area about 0.1–10μm on the left of the main peak. At the same time, the main peak value of the mixture corresponding to Clay C is smaller than that of the mixture corresponding to Clay A and Clay B, suggesting that the mixture corresponding to Clay C has less pores with the entrance pore diameter ranging between 10μm and 100μm than the mixture corresponding to Clay A and Clay B. It might explain the macroscopic permeability and porosity well. Namely, under the same condition, when the additive amount is 10%, the n of the mixture corresponding to Clay C is greater than that of Clay A and Clay B, but the k is about two to three orders of magnitudes smaller (Figure 3 and Figure 4), which fully suggests that the results of microscopic structure tests are in accordance with the permeability tests. And then, according to the cumulative mercury curves of the mixture corresponding to three clays (Figure 6b), the curves of the mixtures corresponding to Clay A and Clay B are ‘standing’, while the curve of Clay C tends to be ‘lying’. Finally, the P50 of the mixture corresponding to Clay C and Clay B is smaller when compared to that of the mixture corresponding to Clay A.

5. Conclusion
According to the analysis and discussion of the above experiment results, the following conclusions can be drawn:
(1) When Clay C forms cutoff wall with the model formation, there is a critical clay additive amount Ccr corresponding to the minimum n and the k will decline drastically after Ccr. For Clay A and Clay B, when the additive amount reaches 25%, there is still no Ccr in the sand-clay mixture.
(2) The pore size distribution of the mixture corresponding to Clay A and Clay B is relatively identical, and as a result, the k declines with decreasing n. But regarding Clay C, the pore size distribution starts to be wide and develop towards small pores with increasing clay additive amount. Meanwhile, the P50 also declines correspondingly. There is poor correlation between the n and k.
(3) Comparatively speaking, the microscopic pore structure of the model formation improved by clay C receives the best effect, and it can also improve the water sealing effect perfectly.

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References
[1] ASTM. 2010. Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter. D5084, West Conshohocken, PA.
[2] Bandini, P., and Sathiskumar, S. 2009. Effects of silt content and void ratio on the saturated hydraulic conductivity and compressibility of sand-silt mixtures. Journal of Geotechnical and Geoenvironmental Engineering, 135 (12):1976-1980.
[3] Chen, Y., and Li, D. X. 2006. Analysis of error for pore structure of porous materials measured by MIP. Bulletin of the Chinese Ceramic Society, 25 (4):198-201.
[4] China Building Material Industry Association. 2007. Bentonite. GB/T 20973-2007, Beijing (in
Chinese).

[5] Delage, P., and Lefebvre, G. 1984. Study of the structure of a sensitive Champlain clay and its evolution during consolidation. Canadian Geotechnical Journal, 21 (1):21-35.

[6] Devlin, J., and Parker, B. 1996. Optimum hydraulic conductivity to limit contaminant flux through cutoff walls. Ground Water, 34 (4):719-726.

[7] Ebina, T., Minja, R. J., Nagase, T., et al. 2004. Correlation of hydraulic conductivity of clay–sand compacted specimens with clay properties. Applied Clay Science, 26 (1):3-12.

[8] Griffiths, F. J., and Joshi, R. 1989. Change in pore size distribution due to consolidation of clays. Geotechnique, 39 (1):159-167.

[9] Liu, H. 2001. The influence of solid waste to Shanghai geological environment and its countermeasures. Shanghai Geology, 77 (1):27-32 (in Chinese).

[10] Long, X. Y., and Hu, Z. X. 2000. Study on the application of vertical barriers to control the migration of pollutants. Geotechnical Investigation and Surveying, (1):8-12 (in Chinese).

[11] Malusis, M. A., Barben, E. J., Evans, J. C. 2009. Hydraulic conductivity and compressibility of soil-bentonite backfill amended with activated carbon. Journal of Geotechnical and Geoenvironmental Engineering, 135 (5):664-672.

[12] Mesri, G. 1971. Mechanisms controlling the permeability of clays. Clays and Clay minerals, 19:151-158.

[13] Ministry of Construction P. R. China. 1999. Standard for soil test method. GB/T 50123-1999, Beijing (in Chinese).

[14] Mitchell, J. K. 1993. Fundamentals of Soil Behavior(second edition). John Wiley & Sons, Inc., New York, 154-155 pp.

[15] Romero, E. 2013. A microstructural insight into compacted clayey soils and their hydraulic properties. Engineering Geology, 165:3-19. Romero, E. 2013. A microstructural insight into compacted clayey soils and their hydraulic properties. Engineering Geology, 165:3-19.

[16] Yeo, S. S., Shackelford, C. D., Evans, J. C. 2005. Consolidation and hydraulic conductivity of nine model soil-bentonite backfills. Journal of Geotechnical and Geoenvironmental Engineering, 131 (10):1189-1198.

[17] Zhang, H. M., and Su, B. Y. 2003. Waste landfill leachate and research development of its pollution to groundwater. Hydrogeology and Engineering Geology, 30 (6):110-115 (in Chinese).

[18] Zhu, W., Wang, R., Zuo, J., et al. 2014. Improved isotropically consolidated undrained triaxial test method for non-self-supporting materials. Geotechnical Testing Journal, 37 (4):1-11.