Analysis of Factors Affecting Permeability of Cement-bentonite Mud Impervious Wall

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Abstract. The permeability coefficient of the cement-bentonite mud anti-seepage wall is measured by triaxial permeability test (100kPa confining pressure 80kPa osmotic pressure), variable head permeability test and one-dimensional consolidation test (100kPa consolidation pressure). Under the conditions of different indoor mixing proportions, the effects of water-cement ratio, water bentonite ratio, curing age, and a small amount of silty clay soil on the permeability of the impervious wall were studied. The test results show that: (1) The average value of the ratio of the permeability coefficient of the variable head test and the triaxial permeability test is 16.75 and 16.73 at the age of 28d and 60d, respectively, and the coefficient of variation is 0.27 and 0.35, respectively; The average value of the ratio of the permeability coefficient of the one-dimensional consolidation test and the triaxial permeability test was 1.20 and 1.21 at the age of 28d and 60d, respectively, and the coefficients of variation were 0.24 and 0.17, respectively. (2) When the water-cement ratio is between 5.88 and 3.85 and the water-bentonite ratio is between 7.14 and 3.85, the permeability coefficient decreases significantly with the increase of age. The ratio of the permeability coefficients at 60d and 28d in age is not significant depending on the test method. (3) When the water-cement ratio and water-bentonite ratio in the mud are certain, the silty clay is blended, and the water-soil ratio decreases from 50 to 10, and the permeability coefficient decreases linearly.

1. Introduction

Tion and failure characteristics of plastic concrete through the stress-strain curve test of 15 groups. As a new type of impermeable material, cement-bentonite mud has the characteristics of low compressive strength (no more than 5MPa), low elastic modulus (no more than 1000MPa), high ultimate strain and high impermeability. This kind of cutoff wall is often used in the seepage prevention of some environmental protection projects (landfill, soil and water pollution, etc.). At present, there are few researches on the permeability of cement bentonite cutoff walls with different proportions in China, so it is of great significance to study this kind of wall material. Song shuaiqi et al.\cite{1} used unconfined compressive strength test, direct shear test and penetration test, and substituted cement by cement kiln ash to prepare soil-bentonite cement kiln ash plastic concrete, and studied the basic properties of this plastic concrete. Zhang wenjie et al.\cite{2} prepared the packing according to the construction process of soil-bentonite cut-off wall, and tested the permeability coefficient of the packing under effective consolidation pressure of 30, 50 and 100 kPa with the flexible wall permeameter. They tested the permeability and diffusion coefficient of the packing under the consolidation pressure of 10 kPa through the permeation-diffusion test of rigid wall soil column. Based on the principle of accelerated
leaching test, a dialysis test method was proposed to quickly determine the effective diffusion coefficient of the packing with high collapse. Jiao kai et al. [3] studied the influence of ratio of bentonite to cement on the strength characteristics of plastic concrete under low confining pressure by using conventional triaxial compression test of cylinder. Wang siwei et al. [4] studied the influence of bentonite, cement content and other factors on the deformation characteristics of plastic concrete. Ye shenghua et al. [5] suggested that rotary jet pile with grouting at the bottom of pile should be adopted for seepage control of valley landfill with a certain thickness of overburden. It is suggested that cement mixing piles be used for seepage control in plain landfills with silty or sandy soil. Jin zhongcai [6] studied how to satisfy various indexes of plastic concrete, especially the anti-permeability index, by optimizing the design of mix ratio. Xu chao et al. [7][8] explored the influence of raw materials on the permeability of the cutoff wall through the different proportions of cement-bentonite slurry. Through experiments, Jefferis [9] found that replacing part of cement with slag could significantly reduce the permeability coefficient of cement-bentonite cutoff wall. Khera [10] used calcium-bentonite, cement, slag, fly ash and sand as the proportion of the cutoff wall, and found that replacing part of cement with slag can increase the strength of hardened mud and reduce the permeability coefficient. Ding Jihui et al. [11] studied the influencing factors of the mechanical properties and permeability of the cement bentonite slurry cut-off wall through laboratory tests. The results showed that the permeability coefficient of the cement bentonite cut-off wall had a double exponential function relationship with the water cement ratio and the water bentonite ratio. The test results of the permeability coefficient of cement bentonite cutoff wall are different with different test methods and different stress states. In this paper, the effects of water-cement ratio and water-bentonite ratio on the permeability of the cement-bentonite mud cutoff wall with different ratios were studied by triaxial permeability test, variable head permeability test and one-dimensional consolidation test. In the process of mud mixing and transportation, a small amount of soil mixed in the mud will affect its permeability. Therefore, a group of cement bentonite mud is selected to explore the influence of water-soil ratio on the permeability of the cutoff wall. The construction proportion that can meet the requirements is determined, and Suggestions are put forward for the design and construction of landfill isolation wall.

2. Test Materials and Methods

2.1. Test Materials

Based on the anti-seepage construction of a sanitary landfill in hebei, the permeability coefficient is required to be less than \(1 \times 10^{-7}\)cm/s. The cement used in this test is luyu p.o42.5 ordinary Portland cement, with a density of 3.08g/cm³, a final setting time of 259min, a flexural strength of 8.9mpa and a compressive strength of 59MPa. Bentonite is an artificial sodium bentonite with a colloidal value of 200-500ml/15g and an expansion ratio of 6-8 times.

In order to study the influence of a small amount of soil mixed into the process of mud mixing and transportation, the soil in this area was selected as silty clay with a natural moisture content of 16.7%, a density of 1.87g/cm³, a liquid limit of 22.2 and a plastic limit of 14.2, clay particles of <0.005mm accounting for 16%, powder particles of 0.005-0.075mm accounting for 69.4%, and sand particles of >0.075mm accounting for 14.6%.

2.2. Test Methods

The experiment was designed with 1000g water, bentonite: 140g~260g, cement: 170g~260g, and dispersant na2co3:2g. In this experiment, 16 mixture schemes were used. Two groups of three test blocks were made for each mixture scheme. The mass ratio of water to cement is defined as \(R_{wc}\), the mass ratio of water to expansive soil is defined as \(R_{ws}\), the mass ratio of water to soil is defined as \(R_{ws}\). On the basis of the above test, select a group of mixture ratio (Rwc is 4.35, Rwb is 4.55), add an appropriate amount of soil, and maintain it for 28d for triaxial penetration test.
3. Test Results Analysis

In the triaxial permeability test, slb-1 stress-strain controlled triaxial shear permeability tester was used to measure the permeability coefficient of the sample under the condition of 100kPa confining pressure and 80kPa permeation pressure. One-dimensional consolidation test adopts WG type triple medium pressure horizontal bar consolidation instrument, standard consolidation test at 100kPa consolidation pressure, and the corresponding permeability coefficient is obtained by Terzaghi's one-dimensional consolidation theory. Variable head permeation test was carried out by TST-55 permeameter.

3.1. The Influence of Rwc and Rwb on the Permeability Coefficient Ratio of Different Test Methods

Figures 1. and 2. are different ages of 28d and 60d, Ratio nephogram of the results of variable-head permeability test and one-dimensional consolidation test and triaxial permeability test.

Figure 1. Cloud diagram of the ratio of the permeability coefficient of the variable head to the triaxial permeability test.

Figure 2. Cloud diagram of the ratio of permeability coefficient between one-dimensional consolidation test and triaxial penetration test.

It can be seen from Figures 1. and 2. that when the water-bentonite ratio is around 5.5 and the water-cement ratio is less than 4 and greater than 5, the ratio of the permeability coefficient obtained from the variable head test to the triaxial permeability is the largest, reaching 20~30 times. The minimum value of the ratio of the two permeability coefficients also reached about 10. When the water-cement ratio is about 5.0, the water-bentonite ratio is about 4 and 7 when the water-bentonite ratio is about 4 and 60d. The ratio of the permeability coefficient obtained by the one-dimensional consolidation test and the triaxial penetration is the largest, reaching 1.6. The ratio is about 1; the minimum value of the two test ratios is about 1, and the values are very close. For the 28d and 60d average permeability coefficients of the three tests: the permeability coefficient of the variable head test was $6.3 \times 10^{-7}$cm/s and $5.1 \times 10^{-7}$cm/s, and the triaxial penetration test at 100 kPa was $0.40 \times 10^{-7}$cm/s and $0.31 \times 10^{-7}$cm/s, one-dimensional consolidation test were $0.45 \times 10^{-7}$cm/s and $0.78 \times 10^{-7}$cm/s.

When the water-cement ratio is between 5.88 and 3.85 and the water-bentonite ratio is between 7.14 and 3.85, the ratio of the permeability coefficient of the head change test to the triaxial penetration test...
is 16.75 and 16.73 at the ages of 28d and 60d. The coefficient of variation was 0.27 and 0.35 respectively. The ratio of the permeability coefficient of the one-dimensional consolidation test to the triaxial permeability test was 1.20 and 1.21 at the ages of 28d and 60d, respectively, and the coefficients of variation were 0.24 and 0.17.

Under the conditions of this paper, the permeability coefficient obtained by the variable head permeability test is the largest, and the results obtained by the triaxial permeability test and the one-dimensional consolidation test are close to each other.

3.2. Influence of Rwc and Rwb on Sample Permeability Coefficient

From the water-cement ratio and the water-bentonite ratio, the variation law of the permeability coefficient of the three permeability coefficient test tests at two different ages is plotted, as shown in Figures 3. to 5.

![Figure 3](image3.png)

**Figure 3.** Relationship between permeability coefficient ~ water-cement ratio and water-bentonite ratio (100 kPa triaxial penetration, $\times 10^{-7}$ cm/s).

![Figure 4](image4.png)

**Figure 4.** Relationship between permeability coefficient ~ water-cement ratio and water-bentonite ratio (water head penetration, $\times 10^{-7}$ cm/s).

![Figure 5](image5.png)

**Figure 5.** Relationship between permeability coefficient ~ water-cement ratio and water-bentonite ratio (100 kPa one-dimensional consolidation, $\times 10^{-7}$ cm/s).
As shown in Figures 3 to 5, with the changes in Rwc and Rwb, the permeability coefficients measured by the three penetration tests have similar changes. When the water-bentonite ratio is 3.85~5.5, the increase of the permeability coefficient is smaller as the water-cement ratio increases. However, when the water-bentonite ratio is 5.5~7.14, the increase of the permeability coefficient is more obvious with the increase of the water-cement ratio. When the cement ratio is 3.85~5, the increase of the permeability coefficient is smaller with the increase of the water-bentonite ratio. When the cement ratio is between 5 and 5.5, the increase of the permeability coefficient is more obvious with the increase of the water-bentonite ratio.

Rwc is the main factor affecting the permeability coefficient. When Rwc is large, the permeability of cement-bentonite cement still meets the impermeability requirement of $1 \times 10^{-7}$ cm/s. Cement through hydration reaction to form a cement-stone skeleton, in a small amount of cement, although the mud density is small, frame is relatively thin, but its structural integrity is strong, still can resist the water infiltration pressure. Although there is a large gap between cement hydration products and cement particles, most of the gap can be filled by bentonite and other clay particles to achieve a good anti-permeability effect. In the hydration process of cement with time, the strength of the cement-stone skeleton will continue to increase, and the free water in the mud will also be consumed, which is conducive to the development of impermeability of the consolidated body. When Rwc is relatively high, as Rwb decreases, the permeability coefficient first decreases significantly and then rises; when Rwc is low, the permeability coefficient decreases as Rwb decreases.

### 3.3 Effects of Rwc and Rwb on the Permeability Coefficient Ratio of Samples at Different Ages

Figures 6 to 8 shows the variation of the 60d/28d permeability coefficient ratio of the three permeability test methods with the water-cement ratio and the water-bentonite ratio.

**Figure 6.** 60d/28d permeability coefficient ratio. **Figure 7.** 60d/28d permeability coefficient ratio. **Figure 8.** 60d/28d permeability coefficient ratio.

It can be concluded from Figures 6 to 8 that when the water-cement ratio is between 5.88~3.85 and the water-bentonite ratio is between 7.14~3.85, the relationship between the ratio of the permeability coefficient of 60d and 30d and the test method is not obvious. The average values of the ratios of the permeability coefficients of the triaxial penetration test, the variable head test and the one-dimensional
consolidation test are 0.79, 0.77 and 0.81, respectively, and the coefficient of variation of the ratios were 0.22, 0.23 and 0.28, respectively.

In the three experiments, the ratio of the permeability coefficients of 60d and 28d is between 0.4 and 1.0. It can be seen that with the growth of age, the osmotic coefficient of each mixture ratio decreases obviously. In the case of 100kPa consolidation pressure, the permeability coefficient of triaxial permeability test and one-dimensional consolidation test decreased by about $0.08 \times 10^{-7}$cm/s, and the permeability coefficient measured by variable head test decreased by about $1.25 \times 10^{-7}$cm/s.

According to the results of the triaxial permeability test, when Rwc is small and Rwb is smaller than 4.5 and larger than 6.5, the minimum permeability coefficient ratio is 0.45--0.65. When Rwc is between 4.5 and 5.5, and Rwb is between 4.5 and 7.14, the permeability coefficient ratio is also relatively small. From the results of the variable head test, when the Rwc is between 4.2 and 4.5, and the Rwb is between 4.0 and 5.0 and 6.5 to 7.0, the ratio of the permeability coefficient is 0.83 to 1.046. According to the results of one-dimensional consolidation test, when Rwc is between 4.5 and 5.5, and Rwb is between 6.0 and 7.0, the permeability coefficient ratio is also small, ranging from 0.44 to 0.84. Rwc and Rwb have a mutually restrictive relationship on the influence of the permeability coefficient ratio. When both Rwc and Rwb are small, around 4, or Rwc is between 4.4 and 5.2, and Rwb is between 4.5 and 6.5, the permeability coefficient ratio is small, around 0.5.

In the process of cement-bentonite mud increasing with age, the hydration product of cement is hardening, during which the bentonite hydration process will also combine with the free water in the mud, which will lead to the reduction of the permeability coefficient, and the value of the final permeability coefficient will also tend to be stable with time.

### 3.4. Influence of Rws on Sample Permeability Coefficient

When the water-cement ratio and water-bentonite ratio are constant, the permeability coefficient has a linear relationship with the soil and water ratio, as shown in Fig. 9., R-Square is 0.99441. The regression equation is:

$$k = 0.07597 + 0.00132R_{ws}$$

In the formula, $R_{ws}$ is the water-soil ratio. In the interaction between cement and bentonite, the addition of soil does not participate in the ion exchange reaction, but it will be wrapped by the cement stone skeleton. Therefore, in the actual working environment, mixing a small amount of soil in the process of mud mixing and transportation will well fill the pores in the consolidated body and promote the reduction of permeability coefficient.

![Figure 9. Fit curve of water-soil ratio Rws and permeability coefficient](image)

### 4. Conclusion

Among the three kinds of permeability tests, the permeability coefficient measured by the triaxial permeability test under 100kPa confining pressure is the smallest, and the permeability coefficient measured by the variable head permeability test is the largest, permeability coefficients at 28d and 60d: variable head test at $8 \times 10^{-8}$cm/s–$1.8 \times 10^{-6}$cm/s, triaxial penetration at $1.25 \times 10^{-7}$cm/s–$5 \times 10^{-9}$cm/s, one-dimensional consolidation test at $5.8 \times 10^{-9}$cm/s–$1.2 \times 10^{-7}$cm/s. At 100kPa consolidation pressure, the permeability coefficient obtained by triaxial permeability test and one-dimensional consolidation...
test is close to each other, and the ratio is between 1 and 1.6 times. The results of conventional variable head test are 10~30 times that of triaxial permeability test under consolidation pressure of 100kPa.

With the decrease of water-cement ratio, the permeability coefficient of mud consolidated body decreases; When the water-cement ratio is higher, the permeability coefficient first decreases greatly and then increases with the decrease of water-bentonite ratio. When the water-cement ratio is low, the permeability coefficient decreases with the decrease of water-bentonite ratio. In the triaxial permeability test under the consolidation pressure of 100kPa, when the water-cement ratio and water-bentonite ratio were 3.85~5.56 at the same time, the permeability coefficient was relatively small: 28d was $0.11 \times 10^{-7}$ cm/s~$0.38 \times 10^{-7}$ cm/s. 60d was $0.05 \times 10^{-7}$ cm/s~$0.30 \times 10^{-7}$ cm/s.

With the increase of 28d to 60d phase, the permeability coefficients of the various mixing ratios obtained by the three tests have significantly decreased, and the permeability ratio of 60d/28d for all three penetration tests is between 0.4 and 1.0. When the water-cement ratio and water-bentonite ratio are both very small around 4, or the water-cement ratio is between 4.4 and 5.2, and the water-bentonite ratio is between 4.5 and 6.5, the ratio of permeability coefficient between 60d and 28d is small, between 0.4 and 0.5.

In the cement-bentonite mud, silty clay with water-soil ratio between 10 and 50 is mixed, and the content of powder particles in silty clay is relatively high, and the permeability coefficient has a good linear relationship with water to soil ratio. When the quantitative Rwc and Rwb are 4.35 and 4.55, respectively, the incorporation of silty clay with a water-soil ratio between 10 and 50 will promote the reduction of the permeability coefficient of the cut-off wall.

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