Analysis of Factors Affecting Performance of Cement-Bentonite Mud Impervious Wall

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Abstract. The triaxial unconsolidated undrained test, unconfined compressive strength test and variable head penetration test were used to study the water-cement ratio ($R_{wc}$ between 3.85 and 5.88) and water-bentonite ratio ($R_{wb}$ between 3.85 and 7.14) in different indoor mix ratios. Effect on mechanical properties and permeability of cement-bentonite mud impervious wall. The test results showed that:(1)The unconfined compressive strength of cement-bentonite anti-seepage wall has a double exponential function relationship with water-cement ratio and water-bentonite ratio.(2)When the water-bentonite ratio is constant, the deformation modulus increases with the decrease of water-cement ratio. When the water-cement ratio is constant, the influence of water-bentonite ratio on deformation modulus is not obvious, but too much bentonite will reduce deformation modulus.(3)As the strength of the cut-off wall increases, the modulus of deformation also increases, and there is a good linear relationship between the two.(4)The permeability coefficient of cement-bentonite anti-seepage wall has a double exponential function relationship with water-cement ratio and water-bentonite ratio.

1. Introduction
Cement-bentonite mud is a kind of self-hardening mixed material synthesized from cement, bentonite, water and external admixture, with low compressive strength (not more than 5MPa) and low elastic modulus (not more than 1000MPa)[1]. It has the characteristics of large ultimate strain and high impermeability, and is often used in environmental protection projects. Considering that the cement has a stronger cementation effect through the hydration reaction, the formed solid body has higher strength and can achieve better deformation control. Therefore, the cement-bentonite mud anti-seepage wall has higher practicability. At present, the development of cement-bentonite slurry cutoff wall material in China is slow, and the stress state and anti-seepage effect of vertical cutoff wall used in environmental protection engineering are different from other walls. Therefore, studying the mechanical properties and anti-seepage performance of cement-bentonite mud anti-seepage wall is of great significance in the rational use and promotion.

Evans et al. found that the cement has a stronger cementation effect through the hydration reaction, and the formed solid body has higher strength and can achieve better deformation control[2]. Royal found that the cement-bentonite material did not stabilize its physical parameters after 28 days, but it took 60 days or more[3]. Grant found that the solidified body obtained by the agitated mud on site was low in strength and high in permeability[4]. Jiao et al. studied the influence of the ratio of bentonite to cement on the strength characteristics of plastic concrete under low confining pressure[5]. Deschenes conducted a mechanical test on cement-bentonite mud for 3 to 103 days and found that the strength of the mud increased significantly in the early stage of curing[6]. Huang et al. found that the ultimate strain of cement bentonite materials cured for 28d decreased with the increase of cement content by testing the influence
of cement content on ultimate strain\(^7\). Dai et al passed the test to show that the cement-bentonite under certain ratio can meet the requirements of the impervious property of the anti-seepage slurry\(^8\). Jefferis obtained from the cement-bentonite consolidation test, which can significantly improve the impermeability of the cut-off wall by replacing the cement with a small amount of slag\(^9\). According to Khera, considered that the optimum content of bentonite should be controlled to about 18\%\(^10\). Zhang measured the permeability of the soil-bentonite anti-seepage wall through the flexible wall penetration test, and found that the consolidation pressure increased from 30 kPa to 100 kPa, and the permeability coefficient would be 5.21\times10^{-8} \text{ cm/s} to 3.78\times10^{-8} \text{ cm/s}. The permeability coefficient of the rigid wall penetration test was measured to be 7.14\times10^{-8} \text{ cm/s} under the 10 kPa consolidation pressure\(^11\). The triaxial unconsolidated undrained test, the unconfined compressive strength test and the variable head penetration test are used to study the mechanical properties and permeability factors of the cement-bentonite mud cutoff wall under different ratios.

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\times10^{-7} \text{ cm/s}. The cement used in this test is ordinary Portland cement, with a density of 3.08g/cm\(^3\), 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/cm\(^3\), 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 mass ratio of water to cement is defined as \( R_{wc} = w_c / m_c \); the mass ratio of water to expansive soil is defined as \( R_{wb} = w_b / m_b \); the mass ratio of water to soil is defined as \( R_{ws} = w_s / m_s \). Where \( w_c \) is the mass of water, g; \( m_c \) is the mass of cement, g; \( m_b \) is the mass of bentonite, g; \( m_s \) is the mass of the soil, g.

The experiment was designed with 1000g water, bentonite: 140g-260g, cement: 170g-260g, and dispersant Na\(_2\)CO\(_3\):2g. 16 mixture schemes were used. Two groups of three test blocks were made for each mixture scheme. \( R_{wc} = 3.85-5.88, R_{wb} = 3.85-7.14 \).

3. Test Result Analysis

Taking into account the strength of the cement-bentonite mud after the solidification of the sample is less than 1MPa, and the shear rate and other factors, the unconfined compressive strength test and the triaxial unconsolidated undrained test are all based on the TSZ automatic triaxial instrument. The head change test was carried out using a TST-55 permeameter.

3.1. Influence of \( R_{wc} \) and \( R_{wb} \) on Unconfined Compressive Strength of Samples

The relationship between unconfined compressive strength and \( R_{wc} \) and \( R_{wb} \) is fitted in a double exponential relationship:

\[
 f(q_s) = C_1 \exp\left(-R_{wc}/t_1\right) + C_2 \exp\left(-R_{wb}/t_2\right) + C_3 \exp\left(-R_{wc}/t_2\right) + C_4 \quad (\text{kPa})
\]

(1)

The values of the fitting parameters are shown in Table 1. The square of the correlation coefficient is greater than 0.9, and the curve has a high degree of fit. The fitted cloud image is shown in Figure 1.
Table 1. Fitting parameter values

| age  | R-Square | C1      | C2      | C3      | C4      | t1      | t2    |
|------|----------|---------|---------|---------|---------|---------|-------|
| 28d  | 0.96998  | 15917.3 | -714.35 | -2706.74| 177.505 | 4.49762 | 2.00746|
| 60d  | 0.97745  | -215.452| 4.44844 | 6524.814| -53.3155| -2.47948| 1.64702|

Figure 1. Fitting the relationship between $q_u$ and $R_{wc}$ and $R_{wb}$

Figure 1. is a cloud plot of unconfined compressive strength and $R_{wc}$ and $R_{wb}$ at different ages. As shown in Figure 1., the unconfined compressive strength decreases with increasing $R_{wc}$ and $R_{wb}$, but with a different degree of reduction. The increase in $R_{wc}$ has a significant effect on the reduction of strength and has a strong regularity. The increase of $R_{wb}$ will reduce the strength, but the regularity is not strong. At 28 days, $R_{wb}$ increases from 4.7 to 5.5, and the strength decreases from 400 kPa to 200 kPa. The regularity is strong.

Figures 2. and 3. are the fitted curves of $R_{wc}$ and $R_{wb}$ and unconfined compressive strength at different ages. It can be seen from Fig. 2. that when the proportion of other raw materials is constant, the intensity values of all the curves are increased by the decrease of the $R_{wc}$. After fitting, it is found that when $R_{wb}$ is constant, the $R_{wc}$ is 3.85 to 7.14, and its corresponding unconfined compressive strength is a single exponential function, and the correlation coefficient is above 0.97.

As shown in Figure 3., the $R_{wc}$ is 5.88, and the $R_{wb}$ is reduced from 7.14 to 5.56. The unconfined compressive strength of the consolidated bodies 28d and 60d is increasing. The $R_{wb}$ is 5.56. After that, the strength decreased significantly; when the $R_{wc}$ was equal to 5.00, 4.35 and 3.85, the unconfined compressive strength of the $R_{wb}$ decreased from 7.14 to 3.85, and it was found to be a single exponential function after fitting. And the correlation coefficient is greater than 0.93.

Figure 2. Fitting the relationship between $q_u$ and $R_{wc}$
3.2. Influence of $R_{wc}$ and $R_{wb}$ on Deformation Characteristics of Specimens

Figure 4. shows the relationship between the deformation modulus and $R_{wc}$ and $R_{wb}$. It can be seen from Figure 4. that as the $R_{wc}$ decreases, the deformation modulus gradually increases. It can be seen that the cement plays a major role in the strength of the consolidated body. With the increase of the cement content, the plasticity of the solid body is unrecovarable, and the deformation modulus is continuously increased. When the age is 28 days and the $R_{wb}$ is 7.14 and 5.56, the total increments of deformation modulus are 10.31 MPa and 2.94 MPa, respectively, which are relatively small. When the age is 60 days and the $R_{wb}$ is 4.55 and 3.85, the increments of deformation modulus are relatively large, reaching 19.96 MPa and 23.62 MPa. When the amount of cement, dispersant and water is constant, the effect of $R_{wb}$ on the modulus of deformation is considered. The deformation modulus of the two ages is not obvious with the $R_{wb}$.

3.3. Relationship between Strength and Deformation Characteristics

As the strength of the cut-off wall increases, the modulus of deformation increases, and there is a good linear relationship between the two. The 28d and 60d ages are shown in the figure below. The correlation coefficient of 28d is equal to 0.9406, and the fitting straight line equation of $E_{50-28d}$ and $q_{u-28d}$ is as follows:

$$E_{50-28d} = (59.75 \pm 1.60)q_{u-28d} \text{ (kPa)}$$  \hspace{1cm} (2)

The correlation coefficient of 60d is equal to 0.9464, and the fitting linear equation of $E_{50-60d}$ and $q_{u-60d}$ is as follows:

$$E_{50-60d} = (47.55 \pm 2.92)q_{u-60d} \text{ (kPa)}$$  \hspace{1cm} (3)
3.4. Effect of $R_{wc}$ and $R_{wb}$ on the Permeability Coefficient of the Sample

The permeability coefficient of the cut-off wall is fitted with $R_{wc}$ and $R_{wb}$ according to a double exponent:

$$f(k) = C_1 \exp\left[\left(-\frac{R_{wb}}{t_1}\right)\right] + C_2 \exp\left(-\frac{R_{wc}}{t_2}\right) + C_3 \exp\left(-\frac{R_{wb}}{t_1}\right) + C_4 \left(\times 10^{-7}\text{cm/s}\right) \quad (4)$$

The values of the fitting parameters are shown in Table 2. The correlation coefficients are all greater than 0.96, and the fitting degree of the curve is higher. Figure 6. shows the fitting relationship cloud image.

| Test                  | R-Square | C1     | C2     | C3     | C4     | t1       | t2       |
|-----------------------|----------|--------|--------|--------|--------|----------|----------|
| 28d variable head test| 0.96161  | 0.00321| 0.87752| -0.00365| -0.96422| -3.34841 | -0.94918 |
| 60d variable head test| 0.96728  | 0.00646| 0.16779| -0.00036| 0.04159 | -2.44943 | -1.25803 |

It can be seen from Fig.6. that when the $R_{wb}$ is between 3.85 and 7.14, the permeability coefficient increases gradually with the increase of the $R_{wc}$, but the increase range is different. When the cement ratio is between 3.85 and 5, the permeability coefficient increases as the $R_{wb}$ increases. When the $R_{wc}$ is between 5 and 5.88, the permeability coefficient decreases first and then increases with the increase of $R_{wb}$. When the $R_{wc}$ is equal to 5.88 and the $R_{wb}$ is equal to 7.14, the seepage coefficient of the cut-off wall is the largest, and the permeability coefficients of 28d and 60d are $1.82 \times 10^{-6}\text{cm/s}$ and $1.62 \times 10^{-6}\text{cm/s}$, respectively.

4. Conclusion

(1) The unconfined compressive strength of cement-bentonite anti-seepage wall has a double
exponential function relationship with $R_{wc}$ and $R_{wb}$. The $R_{wb}$ is between 3.88 and 7.14, and the unconfined compressive strength of the cut-off wall is a single exponential function relationship with the $R_{wc}$. When cement ratio equals 5.0, 4.35 and 3.85, the relationship between the unconfined compressive strength of cut-off wall and $R_{wb}$ is a single exponential function.

(2) When the ratio of water to bentonite is constant, the modulus of deformation increases with the decrease of $R_{wc}$. When the $R_{wc}$ is constant, the effect of water-bentonite on the deformation modulus is not obvious. When the peaks of deformation modulus were reached in each group, the deformation modulus mostly decreased with the decrease of $R_{wb}$.

(3) The deformation modulus has a good linear relationship with the unconfined compressive strength, and the ratio between them is 45 to 60.

(4) The permeability coefficient of cement-bentonite anti-seepage wall has a double exponential function relationship with $R_{wc}$ and $R_{wb}$. The permeability coefficient of the mud-solidified body increases as the $R_{wc}$ increases. When the $R_{wc}$ is relatively high, the permeability coefficient first decreases with the increase of the $R_{wb}$, and then the increase is larger. When the $R_{wc}$ is relatively low, the permeability coefficient increases with the increase of the $R_{wb}$.

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