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Research paper

Studies on hydraulic conductivity and compressibility of backfills for soil-bentonite cutoff walls

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ABSTRACT

Fujian standard sand (Sand-F) was used to simulate a sandy soil layer. Hebei bentonite (Bent-H) and Jiangning clay (Clay-J) were served as additives for studying the hydraulic conductivity and compressibility of sand-bentonite/clay mixture backfills. The results indicate that there is an optimum mixing content (C_{opt}) when Bent-H or Clay-J is mixed with the Sand-F. If the content of bentonite/clay is less than C_{opt}, hydraulic conductivity $k > 1.0 \times 10^{-7}$ cm/s and porosity and coefficient of compressibility decrease with the increase of the content of bentonite/clay. While the content of bentonite/clay are greater than C_{opt}, hydraulic conductivity $k \leq 1.0 \times 10^{-7}$ cm/s and porosity and coefficient of compressibility increase with the increase of the content of bentonite/clay. As the content of bentonite/clay is less than C_{opt}, clay minerals only fill the sand pore space without influencing the sand skeleton and porosity decreases with the increase of the content of bentonite/clay. While the content of bentonite/clay becomes greater than C_{opt}, sand particles become disconnected and porosity increases with the increase of the content of bentonite/clay. A porosity model of sand-bentonite/clay mixtures was derived based on a micro-geometrical principle. Another equation was also developed to calculate hydraulic conductivity values with the changes of the content of bentonite/clay.

1. Introduction

In China, nearly 90% of municipal solid waste (MSW) is disposed to landfills. The first-generation landfills in China were mostly built in 1980s. Those landfills generally do not have either liner system or leachate collection and removal system. They mainly depend on natural stratum to prevent pollution migration. In order to prevent groundwater pollution around the landfills, it is increasingly important to construct downstream cutoff walls (China Ministry of Environmental Protection, 2010). In addition, the cutoff walls have been widely used in the remediation projects for various old landfills and contaminated sites in the world (Qian et al., 2002; Spooner et al., 1984). There are many types of cutoff walls by using various site remediation projects for different countries. The soil-bentonite slurry-trench cutoff wall is first used in the United States (D'Appolonia, 1980). The cement-bentonite cutoff wall is preferred in European countries such as Germany and Britain (Joshi et al., 2010). The soil-bentonite mixture cutoff wall is constructed by deep mixing method (Takai et al., 2014) and the steel sheet pile wall is widely used in Japan (Inazumi et al., 2006). The plastic concrete cutoff wall is generally adopted in China. Because the poured homogeneity of the cement-bentonite cutoff wall is hard to guarantee during the construction process, which will reduce its ability of preventing contaminants and change the original engineering properties (Garvin and Hayles, 1999), the soil-bentonite cutoff wall attracts general attention for its low hydraulic conductivity and low construction cost (Lee and Benson, 2000; Sharma and Reddy, 2004).

The hydraulic conductivity of soil-bentonite backfill is the most important parameter affecting the hydraulic performance of soil-bentonite cutoff wall (Devlin and Parker, 1996; Filz et al., 2001; Malusis and McKeehan, 2013; Mishra et al., 2009; Rumer and Ryan, 1995). But it is also necessary to study the compressibility of soil-bentonite backfill because it can significantly influence the lateral displacement of the trench sidewalls (Ruffing et al., 2010; Sreedharan and Puvvadi, 2013). The effects of the content of bentonite, the content of fines, the gradation of sandy particles, and the type and content of amendment agents (e.g., zeolites and activated carbon) on the hydraulic conductivity and compressibility of soil-bentonite backfills have been extensively studied

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0169-1317/

(Castelbaum and Shackelford, 2009; Du et al., 2015; Fan et al., 2014; Hong et al., 2011; Kaya et al., 2006; Malusis et al., 2009; Yeo et al., 2005; Yukselen-Aksoy, 2010).

Devlin and Parker (1996) investigated the antifouling performance of soil-bentonite cutoff walls in an inward gradient condition. Based on theoretical calculations, it was found that when the thickness of the soil-bentonite cutoff wall ≤1.0 m and its hydraulic conductivity $\leq 1.0 \times 10^{-7}$ cm/s, the molecular diffusion becomes the dominant transport process. Malusis and McKeehan (2013) and Mishra et al. (2009) used salt solutions to conduct permeability tests to measure the hydraulic conductivities of soil-bentonite backfills and evaluated the chemical compatibility for various types of sand-bentonite backfills. Yeo et al. (2005) performed one-dimensional consolidation tests and falling head permeability tests for nine different types of soil-bentonite backfills. It was found that the compression index, swelling index, coefficient of consolidation and barrier property increased linearly with the increase of the content of bentonite or clayey fines (Yeo et al., 2005). Malusis et al. (2009) suggested that it was necessary to investigate the effects of amendment agents on the engineering properties of soil-bentonite backfills and study the hydraulic conductivity and compressibility of sand-bentonite backfills after adding powdered and granular activated carbons. Du et al. (2015) and Hong et al. (2011) conducted consolidation and permeability tests by using zeolite-amended soil-bentonite backfills. The test results showed that the compressibility and hydraulic conductivity of the backfills was not significantly affected by adding zeolite powder. Thus, the optimization of the content of bentonite and estimation of the hydraulic conductivity and compressibility of soil-bentonite backfills become the items of common concerns in engineering practice.

The objectives of this study are to investigate the hydraulic conductivity and compressibility of sand-bentonite and sand-clay cutoff wall backfills, establish the quantitative relationship between the content of bentonite or clay and the porosity of backfills based on a micro-geometrical principle, and develop a calculation equation to estimate the hydraulic conductivity of backfills with the changes of the content of bentonite or clay. The results obtained from this study can help to improve the design and construction of soil-bentonite cutoff walls.

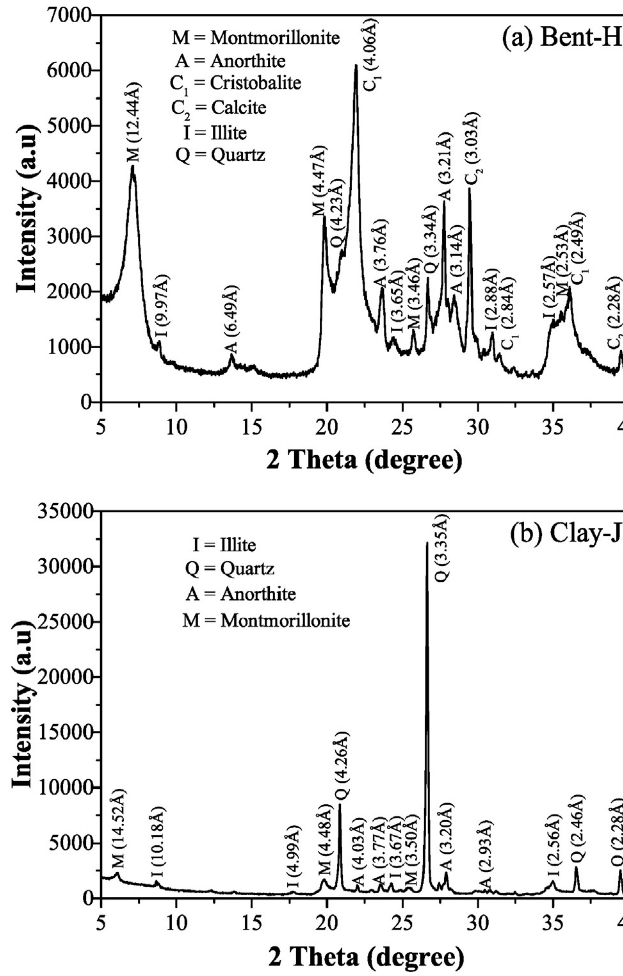

Fig. 1. X-ray diffraction patterns for Bent-H and Clay-J.

2. Experimental studies

2.1. Materials

Since the soil formations vary due to site conditions, China's Fujian standard sand (called as Sand-F) was used to simulate a sandy soil layer at site. The basic physical properties of Sand-F are listed in Table 1.

Two types of clays were used in this study. They were Hebei Bentonite produced in Hebei Province, China (call as Bent-H) and Jiangning Clay produced in Jiangning District of Nanjing, China (called as Clay-J). X-ray diffraction analysis of Bent-H and Clay-J was conducted by a Rigaku D/max-rC rotating anode X-ray powder diffractometer. Air-dried powdered samples (particle size <75 μm) of Bent-H and Clay-J were used. The X-ray source was a Cu anode operating at 40 kV and 100 mA using Cu $K\alpha$ radiation ($\lambda = 1.5406$ Å). The run speed was 3°/min. Data were collected between 5° and 40° in 2θ increments (Mitchell and Soga, 2005). Mineralogical analysis of X-ray diffraction pattern of Bent-H and Clay-J was conducted by comparing with the X-ray powder diffraction standard files (Joint Committee for Powder Diffraction Standards, 1995). The mineralogical characterizations by X-ray diffraction of the Bent-H and Clay-J are shown in Fig. 1.

The basic physical index tests were conducted per GB/T 50123-1999 method (China MOC, 1999). The zeta potential of the Bent-H or Clay-J disperse system containing 0.5% solid in distilled water was determined by micro electrophoresis using a Malvern Zetasizer Nano zeta potential analyzer. Measurement of the interchangeable Calcium and Magnesium was tested by the ammonium acetate exchange-EDTA complexometric titration method. The interchangeable Kalium and Sodium was tested by the ammonium acetate exchange-flame photometry rule. The geotechnical properties of Bent-H and Clay-J are listed in Table 2. All soils were oven-dried at 105 °C for 24 to 48 h as pretreatment before used in tests.

The particle size distribution curves for all three soils are shown in Fig. 2. Sand-F was tested by using sieve analysis. The particle size distributions of Bent-H and Clay-J were measured by using a laser particle size analyzer Mastersizer 2000. According to Unified Soil Classification System (ASTM, 2011b), the Sand-F is a poorly graded sand (SP) and Bent-H and Clay-J are classified as high-plasticity clay (CH) and low-

Table 1
Physical properties of Fujian standard sand.

Specific gravity G_s	Non-uniform coefficient C_u	Maximum dry density ρ_{dmax} (g/cm^3)	Minimum dry density ρ_{dmin} (g/cm^3)	Maximum void ratio e_{max}	Minimum void ratio e_{min}
2.64	5.99	1.74	1.43	0.85	0.52

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Table 2
Geotechnical properties of Bent-H and Clay-J.

Property	Bent-H	Clay-J
Specific gravity G_s	2.75	2.72
Initial water content w_0 (%)	1.39	0.45
Liquid limit w_L (%)	181	48
Plastic limit w_p (%)	53	24
Plasticity index I_p (%)	128	24
Classification	CH	CL
Swell index (mL/2 g)	17.0	1.6
Zeta potential ζ (mV)	−34.1	−18.3
Exchangeable cations (cmol/kg)		
Na^+	78.93	4.96
K^+	1.32	2.11
Ca^{2+}	32.82	17.15
Mg^{2+}	0.59	0.11
Sum	113.66	24.33

plasticity clay (CL), respectively. The hydraulic conductivities of Bent-H and Clay-J are 6.3×10^{-10} cm/s and 2.3×10^{-8} cm/s under a confining pressure of 50 kPa. The coefficients of compressibility are 1.90 MPa^{-1} and 0.88 MPa^{-1} within the vertical consolidation stress applied from 100 kPa to 200 kPa.

2.2. Sample preparation

Sand-F were uniformly mixed with a certain amount of Bent-H or Clay-J and then stirred well with 5% concentration slurry to form as similar to concrete pouring mortar-like sample. In order to simulate the backfills in the practical projects, the slump and density of the test samples were controlled at a range from 7.5 to 12 cm and from 1.45 to 1.80 g/cm^3, respectively (Malusis et al., 2009; Rumer and Ryan, 1995). Note that the content of bentonite/clay means the dry weight percentage of bentonite/clay to sand-bentonite/clay mixture.

2.3. Improved flexible wall permeability test

Due to the poor self-supporting characteristics of the samples, a flexible wall permeameter was improved, namely a cutting ring with a lot of opened pores having a diameter of 3 mm was added at the periphery of the samples (Zhu et al., 2014). The samples could be made not only well self-reliance, but also applied confining pressure around the samples, as shown in Fig. 3. Compared to the rigid wall permeameter, the improved flexible wall permeameter can effectively prevent leakage of the side walls and in turn be able to simulate the stress conditions of the cutoff wall in the actual projects. The diameter and height of the samples were 7 cm and 4 cm, respectively. The deionized water was used as the permeant liquid in the tests. The applied hydraulic gradient was 50 during the tests. The flexible wall permeability tests were referred to ASTM D5084 (ASTM, 2010). All tests were conducted at a constant temperature of 25 °C.

Fig. 3. An improved flexible-wall permeameter.

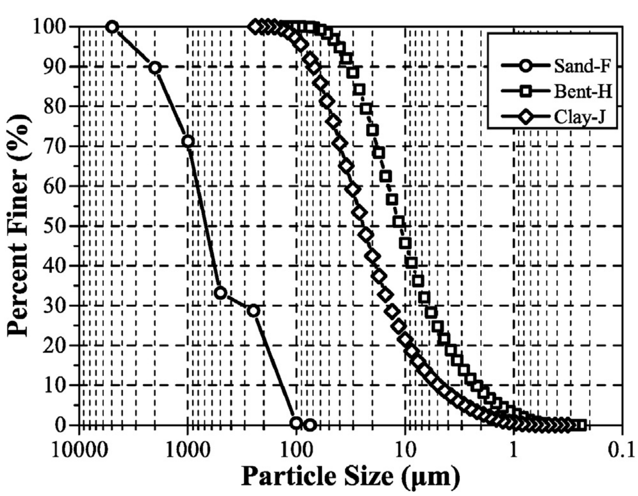

Fig. 2. Particle-size distributions for three soils used in this study.

2.4. Consolidation test

The compressibility of the prepared backfills was measured in accordance with traditional consolidation test procedure ASTM D2435 (ASTM, 2011a). The samples were applied at an initial stress of 3.125 kPa for 24 h, which can prevent the sample extruded from the gap between the ring and porous stone. Thereafter, the consolidation of the samples started immediately by stepwise loading. Each subsequent load was twice of the previous load until the maximum applied stress of 800 kPa. The time for each stage of loading was 24 h.

3. Test results

3.1. Hydraulic conductivity of sand-bentonite/clay mixtures vs. content of bentonite/clay

Fig. 4 shows the changes of the hydraulic conductivity of sand-bentonite and sand-clay mixtures with the added content of Bent-H and Clay-J under a confining pressure of 50 kPa. With the increase of bentonite/clay content, the hydraulic conductivities of the soil mixtures are reduced to different extents. But when content of bentonite/clay was added to a certain amount, the hydraulic conductivity tended to decline slowly. When the contents of Bent-H and Clay-J were >5% and 25% in the mixtures, respectively, the hydraulic conductivity still reduced but the downward trend had slowed down significantly. This means that

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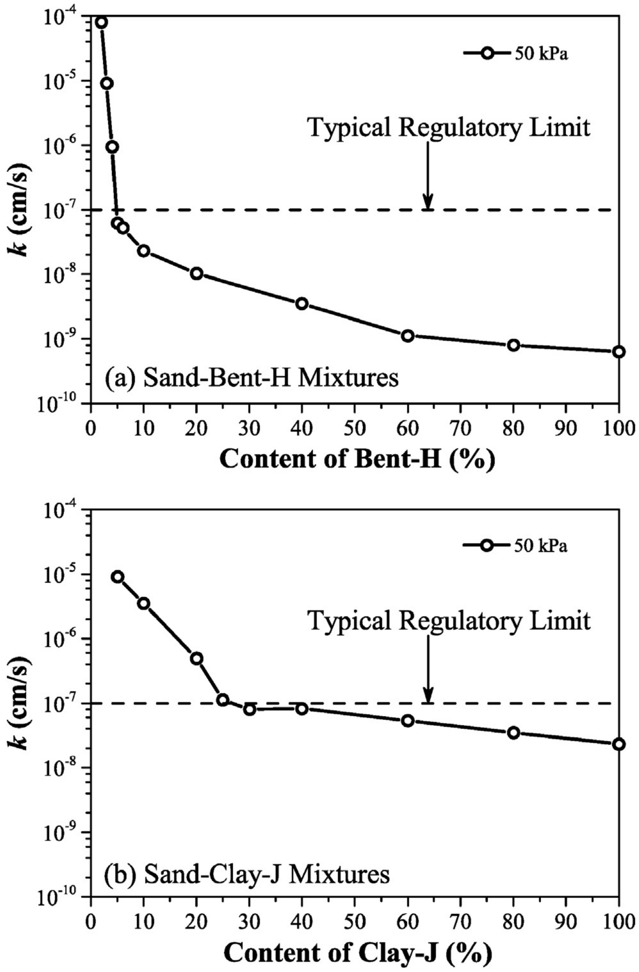

Fig. 4. Hydraulic conductivity k versus content of bentonite/clay for soil mixtures.

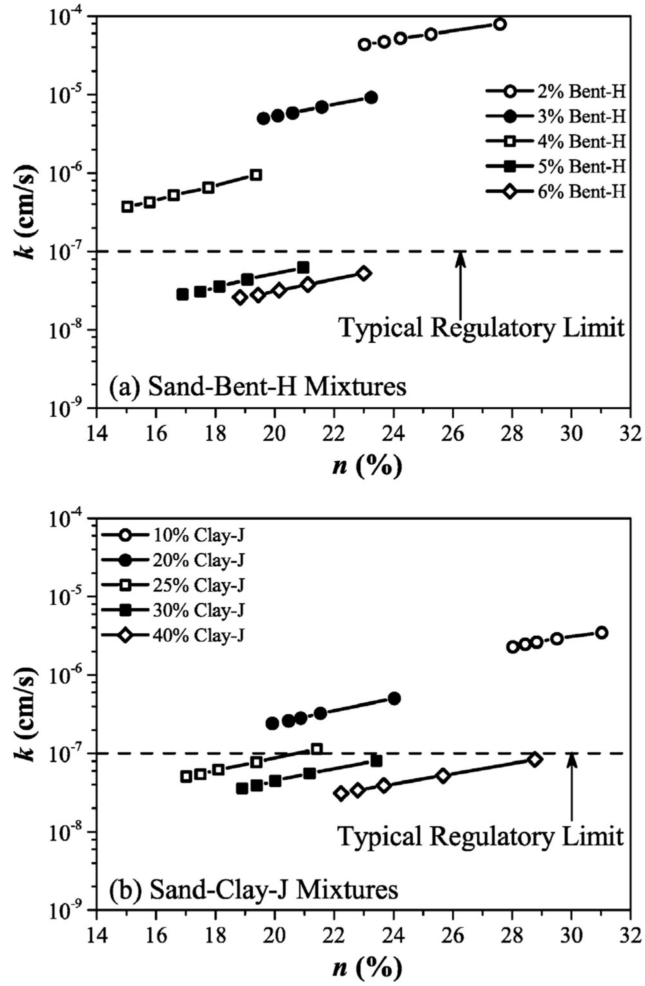

Fig. 5. Hydraulic conductivity k versus porosity n for soil mixtures.

the subsequent incorporation of the content of Bent-H or Clay-J only plays a very limited effect on reducing the hydraulic conductivity. In addition, Devlin and Parker (1996) proposed that the soil-bentonite cutoff walls might have better antifouling properties if the hydraulic conductivity was $<5.0 \times 10^{-8}$ cm/s. It can be achieved by increasing the content of Bent-H or Clay-J. Clearly, the effect of reducing the hydraulic conductivity for adding Bent-H is much better than that for adding Clay-J (see Fig. 4).

3.2. Hydraulic conductivity of sand-bentonite/clay mixtures vs. porosity

Based on the different subjected stresses of the soil-bentonite cutoff walls at different depths, the contents of Bent-H of 2%, 3%, 4%, 5%, and 6% and the contents of Clay-J of 10%, 20%, 25%, 30%, and 40% were used in the study. The confining pressures used in the improved flexible wall permeability tests were 50 kPa, 100 kPa, 200 kPa, 400 kPa, and 800 kPa. The relationships between hydraulic conductivity of sand-bentonite/clay mixtures and porosity are shown in Fig. 5.

When the porosity decreases, the logarithm values of the hydraulic conductivity for the same type of sand-bentonite/clay mixtures generally present a linear downward trend, which can be clearly presented in Fig. 5.

In addition, the hydraulic conductivities of the mixtures for the contents of Bent-H of 2%, 3%, and 4% or the contents of Clay-J of 10% and 20% are all $>1.0 \times 10^{-7}$ cm/s when the porosity varies at the confining pressure ranging from 50 kPa to 800 kPa. However, the hydraulic conductivities of the mixtures for the contents of Bent-H of 5% and 6% were $<1.0 \times 10^{-7}$ cm/s when the porosity changes with the confining pressure. The hydraulic conductivities of the mixtures for the contents of Clay-J of 25%, 30%, and 40% can be mostly $<1.0 \times 10^{-7}$ cm/s when the porosity changes with the confining pressure. This is consistent with the recommendation by Ryan (1987), which is that at least 15 to 20% fines content must be required in soil-bentonite backfills when the backfills contains only low-plasticity fines. Because the fines contents of the mixtures for the contents of Clay-J of 25%, 30%, and 40% are 22.96%, 27.55% and 36.73%, respectively, which are >20%, the values of the hydraulic conductivity of these mixtures are lower.

3.3. Porosity of sand-bentonite/clay mixtures vs. content of bentonite/clay

Fig. 6 shows the relationships between the porosity and the contents of Bent-H and Clay-J under the consolidation stress of 25 kPa, 100 kPa, and 800 kPa.

As shown in Fig. 6, the increases of adding Bent-H or Clay-J do not always result in the decrease of the porosity. With the increase of the contents of Bent-H and Clay-J, the porosities for both mixtures tend to decline, and then begin to rise again. The porosities of sand-bentonite and sand-clay mixtures reach their minimum when the contents of Bent-H and Clay-J are 5% and 25%, respectively. In contrast, the effect of Bent-H on reducing porosity is more significant than that of Clay-J. Marion et al. (1992) investigated the porosities of various sand-kaolin mixtures at different confining pressures and also found a phenomenon of the minimum porosity. It was observed that the minimum porosity occurred not only in montmorillonite-type and illite-type clays, but also in kaolinite-type clay. That indicates that this phenomenon is universal in clay minerals.

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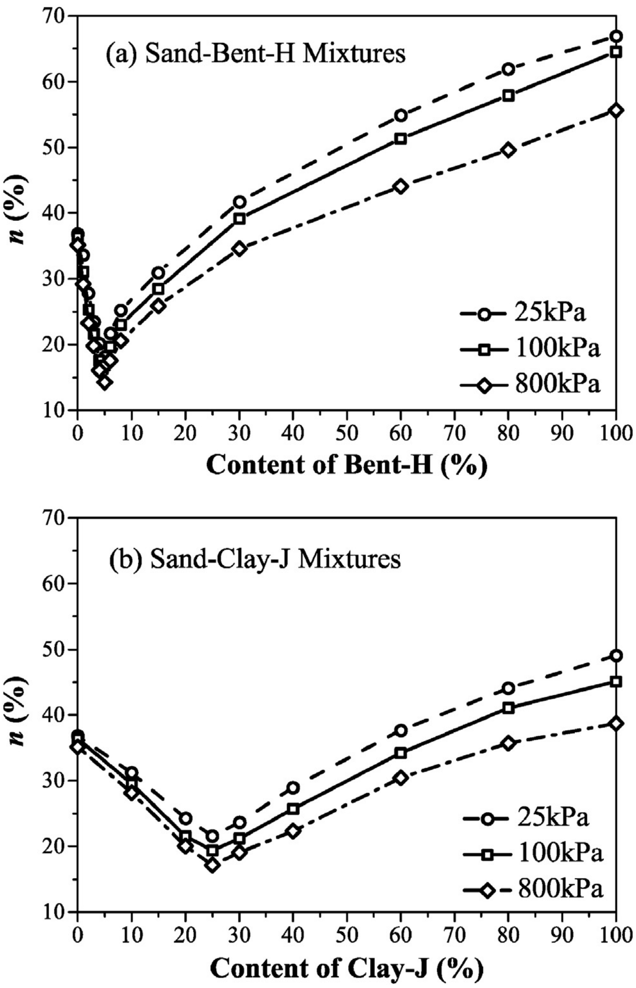

Fig. 6. Porosity n versus content of bentonite/clay for soil mixtures.

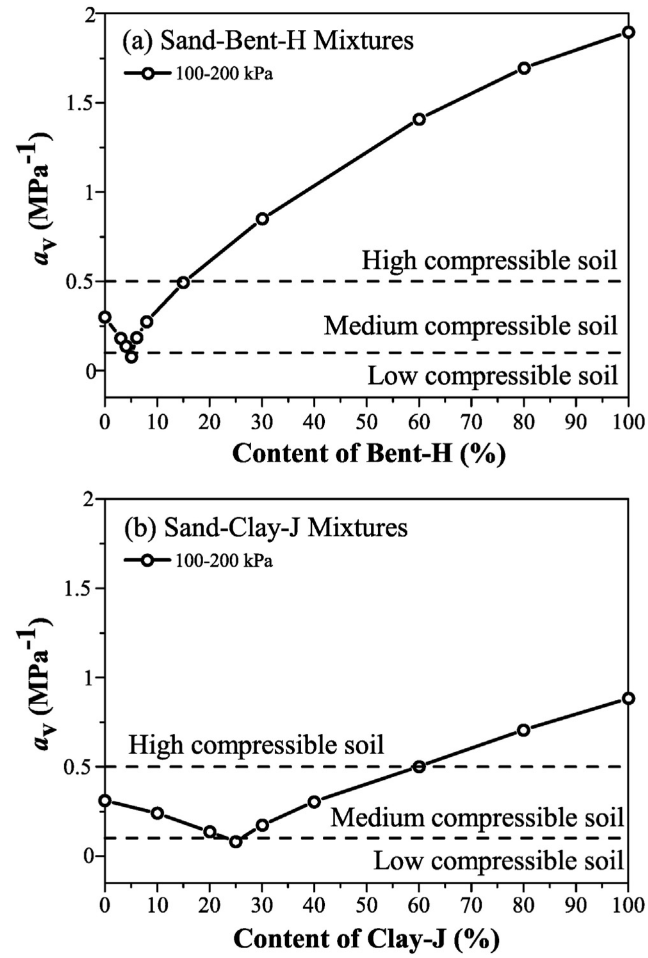

Fig. 7. Coefficient of compressibility $a_{v.}$ versus content of bentonite/clay for soil mixtures.

Table 3
Evaluation criterion for the compressibility of soil (GB 50007-2011).

Soil type	Coefficient of compressibility $a_{v.}$ (MPa^{-1})
Low compressible soil	$a_v < 0.1$ MPa^{-1}
Medium compressible soil	0.1 MPa^{-1} $\le a_{v.} <$ 0.5 MPa^{-1}
High compressible soil	$a_v \ge 0.5$ MPa^{-1}

Note: Coefficient of compressibility $a_{v.}$ was obtained under the consolidation stress from 100 to 200 kPa.

3.4. Coefficient of compressibility of sand-bentonite/clay mixtures vs. content of bentonite/clay

The relationships between the coefficients of compressibility and the contents of Bent-H and Clay-J, which were obtained from the consolidation tests, are shown in Fig. 7. In order to facilitate unified comparison, the coefficient of compressibility obtained under the vertical consolidation stress from 100 to 200 kPa is used to evaluate the compressibility of soil-bentonite backfills in cutoff wall projects.

Fig. 7 shows that with the increase of the contents of Bent-H and Clay-J, the coefficients of compressibility for both mixtures tend to decline, and then begin to rise again, which is similar to Fig. 6. The coefficient of compressibility for the sand-bentonite mixture appears a minimum value of 0.077 MPa^{-1} when the content of Bent-H is 5%. However, when the content of Clay-J reaches 25%, the minimum coefficient of compressibility for the sand-clay mixture is just appeared, which is equal to 0.082 MPa^{-1}. Thus, compared to Clay-J, Bent-H can make the coefficient of compressibility of backfill reaches a minimum at a lesser mixing content.

The criterion for evaluating the compressibility of soil (GB 50007-2011, 2011) is presented in Table 3. When the contents of Bent-H and Clay-J are close to 5% or 25%, both of the sand-bentonite and sand-clay mixtures become low compressible soil. However when the contents of Bent-H and Clay-J are >15% and 60%, both of the mixtures become a high compressible soil. By overall comparisons of two mixtures, sand-Clay-J mixture usually has lower compressibility than sand-Bent-H mixture at the same mixing content.

4. Discussion

Combined with Figs. 4–7, when the content of Bent-H or Clay-J is <5% and 25%, the hydraulic conductivities of both sand-bentonite and sand-clay mixtures are $>1.0 \times 10^{-7}$ cm/s and the porosities and the coefficients of compressibility decrease with the increase of the content of Bent-H or Clay-J. However, when the content of Bent-H or Clay-J is >5% and 25%, the hydraulic conductivities of both sand-bentonite and sand-clay mixtures become

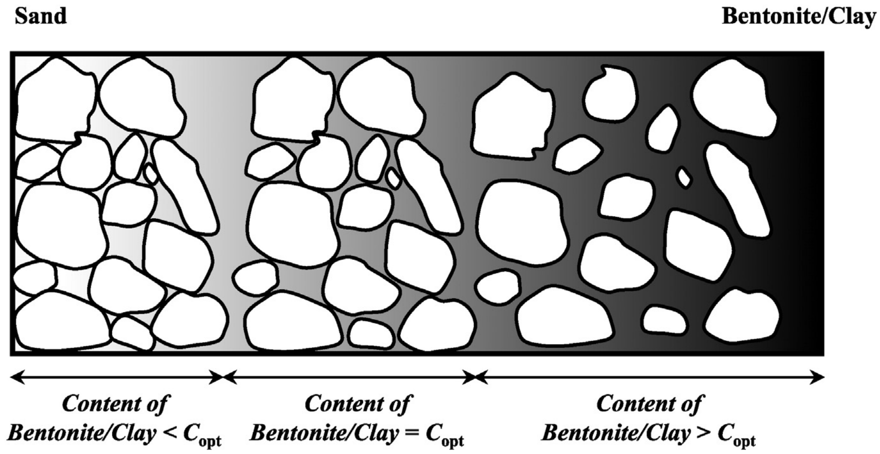

Fig. 8. Schematic diagram of geometry of sand-bentonite/clay mixture.

$<1.0\times10^{-7}$ cm/s and the porosities and the coefficients of compressibility are increased with the increase of the content of Bent-H or Clay-J. Thus, the contents of Bent-H or Clay-J corresponding to the minimum porosity and the minimum coefficient of compressibility are same (5% or 25%). It is reasonable that when a soil is in its minimum porosity condition, it should have the minimum compressibility. In addition, according to the swell index of clays shown in Table 2, it can be found that the higher the swell index, the smaller the content of clayey material is added to achieve the low hydraulic conductivity (i.e., 1.0×10^{-7} cm/s), the minimum porosity and the minimum coefficient of compressibility. It means that under the premise to ensure the performance of the cutoff walls, the amount of bentonite added in the soil-bentonite backfills can be optimized in actual projects.

Based on a micro-geometrical principle, when the contents of Bent-H and Clay-J are <5% or 25%, the external load is born by the sand particles in the mixture and the clay minerals are only filling the pore space between the sand particles without affecting the sand skeleton (see the left part of Fig. 8). Thus, the mixture has relatively higher hydraulic conductivity and the porosity and the coefficient of compressibility decrease with the increase of the content of Bent-H or Clay-J.

When the contents of Bent-H and Clay-J are >5% or 25%, the total volume of the clay minerals becomes greater than the pore space between the sand particles, so that achieving the increase of Bent-H or Clay-J only relies on the destruction of the sand skeleton. In this case, both sand and clay particles in Bent-H or Clay-J support the external load together and the sand particles are suspended among the clay particles (see the right part of Fig. 8). Thus, the hydraulic conductivity of the mixture is lower due to the low-permeability clay particles filled between the sand particles and the coefficient of compressibility and porosity increase with the increase of the content of Bent-H or Clay-J.

When the contents of Bent-H and Clay-J are equal to 5% or 25%, the clay particles are just completely filled the pore space between the sand particles without destroying sand skeleton and the mixtures are also in both minimum porosity and minimum compressibility status. Herein, the contents of Bent-H of 5% and the content of Clay-J of 25% are defined as the optimum mixing content, C_{opt}, where the hydraulic conductivities of the mixtures are also $<1.0\times10^{-7}$ cm/s. The schematic diagram of geometry for sand-bentonite/clay mixture is shown in Fig. 8. It is assumed that the bound water film of sand particles could be ignored and sand particles touch each other as the contents of Bent-H and Clay-J are less than and equal to 5% or 25%.

Firstly, the clay volume fraction (c) (Clarke, 1979) is defined as the volumetric ratio of the indoor dry clay (including to the clay minerals, associated bound water and its macro pores) to the indoor dry sand-clay mixture in this study. The volume expansion multiples of soil (s) is defined as the ratio of the volume of the soil after hydration to its indoor dry volume under the same stress. Considering unlike illite and kaolinite clay the volume expansion will happen after the bentonite is hydrated and based on the swell index of clays shown in Table 2, it is assumed that the volume expansion multiples of Clay-J and Bent-H are equal to 1.0 and 10.0, respectively. If the porosities of a pure sand (n_s) and a pure clay (n_c) under a certain stress level are known, the relationship between the porosity (n) of sand-clay mixture and the clay volume fraction (c) can be quantitatively expressed by a piecewise function, i.e., $n = f(c)$.

(1) When $s\cdot c < n_s$, the clay particles are filled in the sand pore space and the porosity of the mixture (n) decreases with the increase of the clay volume fraction (c),

$$n = n_s\text{-}sc(1-n_c) \tag{1}$$

In this geometrical model, Eq. 1 is applicable until clay particles are completely filled with the sand pore space (Fig. 8). Therefore, when $s\cdot c = n_s$, which means that the content of clay is equal to the optimum mixing content, C_{opt}, at this point the minimum porosity of the sand-clay mixture (n) is equal to the product of the sand porosity (n_s) and the clay porosity (n_c).

(2) When $s\cdot c > n_s$, the increase of clay only relies on the destruction of the sand skeleton. In this case, the sand particles are separated from each other. Because the clay particles occupy the sand pore space, the porosity of the mixture increases with the increase of the clay volume fraction (c). It is assumed when $s\cdot c > n_s$, the volume expansion multiples of the indoor dry clay is α times of the indoor dry sand-clay mixture in the case of the same clay minerals. Thus, α is a function of the mixing content and the volume expansion multiples of clay,

$$n = \alpha c n_c \tag{2}$$

In order to make the comparisons between the porosity model and the porosity data presented in Fig. 6, the clay volume fraction (c) must be converted to the clay weight fraction (C) (Marion et al., 1992) (i.e., the weight content of clay). The clay weight fraction (C) is defined as the weight ratio of the indoor dry clay to the indoor dry sand-clay mixture. An exponential function is then used to express α as follows:

$$\alpha = \alpha(C, s) = \frac{s\text{-}1}{s} e^{-5C} + 1 \tag{3}$$

When $s \cdot c \le n_s$,

$$C = \frac{\rho_c(1-n_c)c}{\rho_c(1-n_c)c + \rho_s(1-n_s)} \tag{4}$$

When $s \cdot c > n_s$,

$$C = \frac{\rho_c(1-n_c)c}{\rho_c(1-n_c)c + \rho_s(1-c)} \tag{5}$$

where ρ_c and ρ_s are the particle densities for clays and sand. The porosity (n_c) of pure clay does not include the bound water existing in the indoor dry clay mineral.

Therefore, when $C \le C_{opt}$,

$$c = \frac{\rho_s(1-n_s)C}{\rho_c(1-n_c)(1-C)} \tag{6}$$

and when $C > C_{opt}$,

$$c = \frac{\rho_s C}{\rho_c(1-n_c)(1-C) + \rho_s C} \tag{7}$$

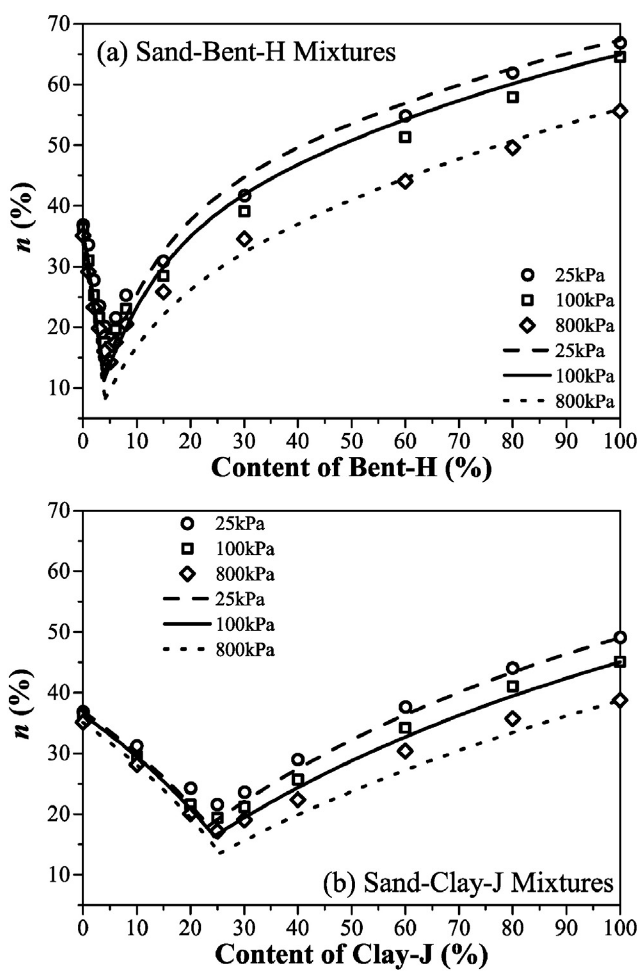

Fig. 9. Comparison between the tested porosity (points) and the porosity (lines) calculated from Eq. 8 and Eq. 9.

Table 4
The parameter values used in the Eq. 8 and Eq. 9 of sand-Bent-H/Clay-J mixtures.

Type	Pressure (kPa)	Particle density (g/cm^3)	Porosity (%)	*s*
Sand-F	25	2.64	36.83	–
	100		36.37	
	800		35.13	
Bent-H	25	2.75	66.87	10.0
	100		64.55	
	800		55.61	
Clay-J	25	2.72	49.07	1.0
	100		45.11	
	800		38.75	

The following equations can be obtained when Eqs. 6 and 7 are substituted into Eqs. 1 and 2, respectively:
When $C \le C_{\text{opt}}$,

$$n = n_s - \frac{s\rho_s(1-n_s)C}{\rho_c(1-C)} \tag{8}$$

When $C > C_{\text{opt}}$,

$$n = \frac{\alpha\rho_s C}{\rho_c(1-n_c)(1-C)+\rho_s C} n_c \tag{9}$$

The parameters of n_s and n_c are the porosities of pure sand and pure clay, which are measured at the corresponding pressures (Fig. 6). Fig. 9 shows the comparisons between the tested data (Fig. 6) and the data calculated from Eq. 8 and Eq. 9 for the Sand-Bent-H and Sand-Clay-J mixtures. The comparisons between the calculated and tested results show the following characteristics:

(1) Both the calculated and tested results have a similar minimum porosity and the changes of the porosities have the same trend with the changes of the contents of Bent-H and Clay-J.
(2) The porosities obtained from both calculations and tests decease with the increase of the confining pressures.
(3) In the vicinity of the optimum mixing content, there are differences in compressibility behavior of sand-Bent-H mixture or sand-Clay-J mixture, especially for the sand-Bent-H mixture, which is consistent with the results shown in Fig. 7.

The parameter values used in the Eq. 8 and Eq. 9 of sand-Bent-H and sand-Clay-J mixtures are listed in Table 4.

It can be shown from the above results that the quantitative relationship between the porosity of the sand-bentonite/clay mixture and the content of bentonite/clay can be established based on the micro-geometrical principle of sand-bentonite/clay mixture, which can well explain the hydraulic conductivity and compressibility of the sand-bentonite/clay mixture with the content of bentonite/clay.

The Kozeny-Carman Equation has been widely used to predict the hydraulic conductivity for most saturated soils including sandy soils and natural clays (Chapuis and Aubertin, 2003; Sanzeni et al. 2013; Shen and Xu, 2011). The relationship between the hydraulic conductivity, k and the clay weight fraction, C can be expressed by combining the porosity model of the mixtures with the Kozeny-Carman Equation, that is $k = f(C)$. The Kozeny-Carman Equation is expressed in terms of porosity n:

$$k = C_s \frac{\gamma_w}{\mu_w} \frac{n^3}{S_{eff}^2(1-n)^2} \tag{10}$$

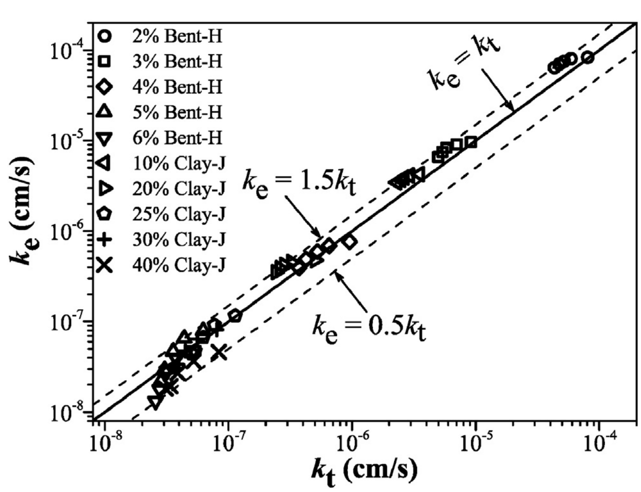

Fig. 10. Relationship between the estimated hydraulic conductivity k_e and the tested hydraulic conductivity k_t.

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Table 5
The parameter values used in the Eq. 12 and Eq. 13 of sand-Bent-H/Clay-J mixtures.

Type	Pressure (kPa)	Particle density (g/cm^3)	Porosity (%)	s	w_L (%)	α
Sand-F	50	2.64	36.58	–	–	–
	100		36.32			
	200		35.97			
	400		35.57			
	800		35.10			
Bent-H	50	2.75	65.95	10.0	–	–
	100		64.46			
	200		61.84			
	400		58.06			
	800		55.56			
Clay-J	50	2.72	47.19	1.0	–	–
	100		45.04			
	200		42.24			
	400		39.29			
	800		38.71			
2%Bent-H	–	–	–	–	3.18	–
3%Bent-H	–	–	–	–	3.80	–
4%Bent-H	–	–	–	–	4.50	–
5%Bent-H	–	–	–	–	7.83	1.7
6%Bent-H	–	–	–	–	9.45	1.7
10%Clay-J	–	–	–	–	6.04	–
20%Clay-J	–	–	–	–	7.98	–
25%Clay-J	–	–	–	–	8.30	1.0
30%Clay-J	–	–	–	–	9.60	1.0
40%Clay-J	–	–	–	–	12.10	1.0

where C_s is the shape factor having a relatively small range and generally accepted values (0.5 for circle, 0.33 for a strip, 0.56 for a square shaped pore structure), and Yong and Warkentin (1975) recommended to use an average C_s value of 0.4; γ_w is the unit weight of pore water, N/m^3; μ_w is the dynamic viscosity of pore water, Pa · s; n is the porosity; S_{eff} is the wetted surface area per unit volume of soil particles, m^2/m^3. The wetted surface area depends on the particle sizes and the soil structures and could be considered as an effective surface area per unit volume of particles. It is less than the total specific surface area of the soil since seepage will not occur adjacent to all particle surfaces (Mitchell and Soga, 2005). S_{eff} values for the sand-bentonite/clay mixtures are not available in previous researches. Sanzeni et al. (2013) found that the inaccurate S_{eff} values would cause the predicted hydraulic conductivity appears significant deviation. In order to solve these problems, Fan et al. (2014) proposed using a function of the liquid limit w_L to replace S_{eff} in the original Kozeny-Carman Equation. On this basis, an empirical equation is developed as follows:

$$\log_{10}k = 0.97\log_{10}\frac{n^3}{w_L^6(1-n)^2} - 11.23 \tag{11}$$

Substituting Eqs. 8 and 9 into Eq. 11 to obtain:
When $C \le C_{opt}$,

$$\log_{10}k = 0.97\log_{10}\frac{\{\rho_c n_s - [s\rho_s + (\rho_c - s\rho_s)n_s]C\}^3}{w_L^6\rho_c(1-n_s)^2[\rho_c - (\rho_c - s\rho_s)C]^2(1-C)} - 11.23 \tag{12}$$

When $C > C_{opt}$,

$$\log_{10}k = 0.97\log_{10}\frac{\alpha^3\rho_s^3 n_c^3 C^3}{w_L^6\{\rho_c(1-n_c) + [\rho_s(1-\alpha n_c) - \rho_c(1-n_c)]C\}^2\{\rho_c(1-n_c) + [\rho_s\text{-}\rho_c(1-n_c)]C\}} - 11.23 \tag{13}$$

where n_s and n_c are the porosities of pure sand and pure clay under same stress, %; ρ_s and ρ_c are the particle densities of pure sand and pure clay, g/cm^3; C is the clay weight fraction, %; s is the volume expansion multiples of clay; w_L is the liquid limit of the mixtures, %.

Fig. 10 shows the comparisons between the estimated values calculated from Eqs. 12 and 13 and the tested values obtained in the flexible wall permeability tests. It is indicated in Fig. 10 that the estimated values, k_e are generally in the range of 0.5 to 1.5 times the tested values, k_t. Thus, the estimated values of the hydraulic conductivity of sand-Bent-H mixtures and sand-Clay-J mixtures are 0.5 to 1.5 times of the tested values by using the porosity model of the mixtures and the improved Kozeny-Carman Equation. The parameter values used in the Eq. 12 and Eq. 13 of sand-Bent-H and sand-Clay-J mixtures are listed in Table 5.

5. Conclusions

Based on the discussions of the test results and further analysis, the following conclusions can be made:

(1) An optimum mixing content, C_{opt} was found for the sand-bentonite/clay mixture backfills when Sand-F was mixed with a certain content of Bent-H or Clay-J. When the content of bentonite/clay is less than the optimum mixing content, the hydraulic conductivities of the mixtures are $>1.0\times10^{-7}$ cm/s and the coefficients of compressibility and the porosities decrease with the increase of the content of bentonite/clay. As the content of bentonite/clay becomes greater than the optimum mixing content, the hydraulic conductivities becomes $<1.0\times10^{-7}$ cm/s and the porosities and the coefficients of compressibility gradually

increase with the increase of the content of bentonite/clay. That means that the hydraulic conductivity is $<1.0 \times 10^{-7}$ cm/s and the porosity and the coefficient of compressibility have a minimum value at the optimum mixing content for the mixtures.

(2) When the content of bentonite/clay is less than the optimum mixing content, the clay minerals only fill the pore space between the sand particles without affecting the sand skeleton. Thus the porosity of the mixture decreases with the increase of the content of bentonite/clay. As the content of bentonite/clay becomes greater than the optimum mixing content, the total volume of the clay minerals becomes greater than the pore space between the sand particles and the sand particles are suspended among the clay particles. Hence the porosity of the mixture increases with the increase of the content of bentonite/clay. A porosity model of sand-bentonite/clay mixtures has been established based on the micro-geometrical principle of sand-bentonite/clay mixture, which can explain the hydraulic conductivity and compressibility of the sand-bentonite/clay mixture with the content of bentonite/clay.

(3) Based on the porosity model of the mixtures and the improved Kozeny-Carman Equation, a calculation equation was developed to estimate the hydraulic conductivity of the mixtures with various content of bentonite/clay. The comparisons between the estimated and tested values indicate that the estimated values fall within the range of 0.5 to 1.5 times the tested values. The further improvement for the calculation equation is needed in future studies.

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