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Effect of Bentonite Admixture Content on Effective Porosity and Hydraulic Conductivity of Clay-based Barrier Backfill Materials

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Clay-based barrier wall has been diffusely employed as vertical barriers. Nevertheless, there were few project practices of these walls in China. And few research have been performed to study the impact on the permeability of the addition of domestic bentonites. To solve this problem, the influences of bentonite level on hydraulic conductivity, porosity and clay-bound water of soil-bentonite admixtures have been assessed employing a flexible-wall test and water centrifugal dewatering experiment with various bentonites. The outcomes revealed that as barrier walls are constructed by blending bentonite and Fujian standard sandy soil, there is a critical bentonite level of the smallest porosity. If the bentonite level is less than the critical bentonite content, hydraulic conductivity is reduced quickly, while if the bentonite level is greater than the critical bentonite content, hydraulic conductivity is reduced gently. Additionally, as the bentonite level grew, the clay-bound water centage of the admixtures continually improved. Supposing that the clay-bound water enclosed the clay grains, a near computation approach of the effective porosity is put forward and showed that the effective porosity decreased with bentonite content. Additionally, an exponential relationship was found between the effective porosity and the permeability.

Keywords: landfill, barrier walls, sand-bentonite mixture, permeability, effective porosity.

1. INTRODUCTION

As the Chinese economy continues to develop rapidly and the process of urbanisation accelerates, the production of garbage increases commensurately, and thus the number of landfills has continued to increase. For example, 13 landfills including informal landfills have been running in Beijing, and there were also almost three thousand garbage disposal sites without seepage control systems. The innocent treatment extent of solid waste is about 60 % [1]. These landfills are without rigorous programming and building, especially the simple waste landfills that have no horizontal seepage-control barrier, consequently, would get main ambient harms. In the coming years, pollution governance projects for these landfills would gradually grow; however, it is tough and expensive to reconstruct the horizontal seepage control scheme at the base of landfills. Thus, vertical barrier becomes a usual way of enclosure. The Rocky Mountain Arsenal reconstruction location (the manufacture of barren land of chymic armament and insecticide) utilized a clay-based barrier to stem pollution of soil and underground water [2]. In the absence of or a failure of a horizontal seepage control system, vertical barrier walls have been methods to mitigate these risks. Specific examples of the existing landfills in China constructed by vertical barrier wall are rarely reported, but vertical barrier walls are usually applied to new landfills. Yao and Bao [3] indicated the quartus Shanghai Lao-gang plain type landfill site. The Tangshan centre area plain-type landfill and Taizhou Gangyang plain type landfill site also combined aclinic and perpendicular anti-seepage ways as they summarised vertical seepage control technology. Moreover, level and perpendicular synthetic leaking governance schemes have been directed at the expansion program in the Qi-zi Rise landfill [4].

In terms of the vertical seepage control material, Jing et al. [5] believed that because seepage control material and construction techniques have started late, especially grouting antiseepage technology, these methods have effectively borrowed methods from hydraulic engineering; however, as clay-based barrier wall possess mair engineering performances, the anti-seepage and anti-fouling property of clay-based barrier wall are a wide concern abroad. The general building method is to dig a sulcus as synchronously freighting the sulcus with about 5 % bentonite slurry to sustain sulcus stability. The freighted soils would be mixed with bentonite powder and then mixed with the bentonite slurry to form a conspecific soil-bentonite backfill material with the fluidity of 113 mm ~ 138 mm [6]. And the backfills are taken into sulcus, making for a cutoff wall with small permeability: generally $< 1.0 \times 10^{-7}$ cm/s [7, 8]. Devlin and Parker [9] studied the anti-fouling property of clay-based barriers. They reported that according to a theoretical calculation, these types of walls could effectively control the hydraulic migration of a contaminant, and the pollutants migrated by slow molecular diffusion with the permeability of lower than 5.0×10^{-10} m/s as the thickness of soil-bentonite

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vertical barrier is 1 m. Therefore, how to make a soil-bentonite backfill with a permeability lower than 5.0×10^{-10} m/s becomes the primary engineering problem. To reduce hydraulic conductivity after the growth of bentonite content, Yeo et al. [10] carried out falling-head permeability tests on sand-bentonite/clay mixtures. These indicated that hydraulic conductivity tended to decrease with increasing fines content or bentonite content, and a fines content of greater than 40 % might be lacking in soil-bentonite backfill material to obtain a permeability $\leq 1.0\times10^{-9}$ m/s as the backfill material just contains low plasticity fines.

The model used for predicting the hydraulic conductivity of a sand-bentonite admixture generally assumed that it is the ideal admixture in which hydrated bentonite pads the pores between soil grains uniformly and completely. Sivapullaiah et al. [11] studied the role of the size of coarser fraction in controlling the hydraulic conductivity of soil-bentonite mixtures by running one dimensional consolidation experiments and found four different methods of predicting the hydraulic conductivity of admixtures investing the pore and an invariable connected with liquid limit wL. Sallfors et al. [12] researched that the weight of bentonite and the dry density of sand-bentonite admixture might influence hydraulic conductivity by carrying out falling-head permeability experiments. Then, using the weight of bentonite and the dry density of admixture, they derived a new parameter k_1. Castelbaum and Shackelford [13] carried out rigid-wall permeability experiments on samples provided by blending sand with bentonite slurry. Their results showed that hydraulic conductivity related weakly with the pore of mixtures as a result of the complex influence of the bentonite in the admixtures; but permeability was found to be more correlated with the void ratio of the bentonites. Using this information, they created an empirical formula relating permeability and the pore of bentonites. Tripathi [14] advanced in the patterns of forecasting the hydraulic conductivity of saturated sand-bentonite admixtures ground on for research and calculated the hydraulic conductivity of these mixtures by estimating the free swell pore of the bentonite, according to their models.

The research showed that variations in the void spaces had critical influences on the hydraulic conductivity of the model formation due to the addition of bentonite, and the approaches of forecasting the hydraulic conductivity of soil-bentonite mixtures were exploited. Moreover, it was found that varying styles of bentonite would result in a non-uniform change of hydraulic conductivity. Bentonite obviously not only varies the amount of formation void spaces, which prohibit the flow of water, but also hydrates and expands upon touch with water and has a prominent capacity to integrate with water; these might be the primary characteristic that differentiates bentonite from other clays. Accordingly, it is necessary to investigate different bentonites to know the property effects on hydraulic conductivity. This study conducted laboratory tests using three common bentonites from China.

2. EXPERIMENTAL DETAILS

2.1. Sand

Because the formation might change with sites, disadvantageous conditions of the in-situ stratum would be imitated. The model formation was made up of Fujian standard sand (FSS) which is a silica sand with bad graduation. The properties of the FSS are shown in Table 1.

Table 1. Geotechnical properties of Fujian standard sand

Specific gravity	2.64
Non-uniform coefficient	5.99
Maximum dry density, g/cm^3	1.74
Minimum dry density, g/cm^3	1.43
Maximum void ratio	0.85
Minimum void ratio	0.52

2.2. Bentonite

The bentonites used were commercial grade and in powdered form. Three types were used and included: the bentonite from Anji of Zhejiang Province (AJ bentonite); the bentonite from Fanchang of Anhui Province (YD bentonite); and the bentonite from Lingshou of Hebei Province (HB bentonite). The geotechnical property of FSS and the three kinds of bentonites were measured in conformity to the Soil Test Method Standard GB/T 50123-2019 [15] and Bentonite GB/T20973-2007 [16] as illustrated in Table 2. Bentonites and the FSS were kiln-dried for 5 days at 66 °C.

Table 2. Geotechnical property of bentonites

Bentonite	AJ	YD	HB
Specific gravity	2.70	2.71	2.75
Liquid limit, %	301	247	181
Plastic limit, %	56	59	53
Swell index, mL/2g	38.5	29.5	17.0

2.3. Experimental method

2.3.1. Particle size layout

Particle size layout curve was measured respectively for bentonites and sand. A screen analysis experiment was performed for sand. Particle measurement distributions of bentonites were obtained by wet analysis employed in a hydrometer way. And the particle measurement layout curve of bentonites and sand adopted in tests were shown in Fig. 1. On the basis of USCS, FSS is uniformly graded sand (SP) and AJ, YD and HB are high plasticity clay.

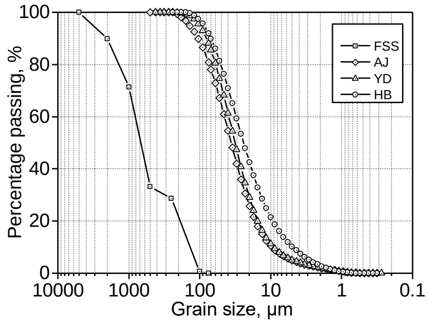

Fig. 1. Particle size layout curve of the sand and bentonites adopted in research

2.3.2. Specimen provision

FSS would be combined equably with a specified mass of bentonite dust and with 5 % bentonite muld intended to produce soil samples for placement [8]. To imitate the backfill material in actual engineering, the slump of the samples employed for the penetration test was produced with a slump of 112.5 mm ~ 137.5 mm [6].

2.3.3. Flexible wall penetration test

On account of the vulnerable self-reliance capability of the samples, the conventional flexible wall permeameter was ameliorated via augmenting the cutting ring with plentiful pores having a diameter of 3 mm to the boundary of the specimens [17]. As illustrated in Fig. 2, the specimens not only can be self-supporting fine, but also the ambient stress can be imposed around the specimens. The comparison with rigid wall permeameter, amelioration of flexible wall permeameter can impede it from sidewall giveaway effectively, to model after the pressure level of the barrier in engineering. The confining pressure of permeability experiments is 100 kPa. The permeant fluid used the DI water and the gradient imposed in the test was 35. The diameter and height of the specimens were 7 cm and 4 cm separately. The flexible wall penetration test refers to ASTM D5084 [18]. The test was performed at about 25 °C.

Fig. 2. The reformative flexible wall permeameter

2.3.4. The water content exodic dehydration experiments

To know shifts of clay-bound water percentage Pbw of samples after permeability experiments as a result of the adding of bentonites, the centrifugal approach was employed [19]. The pF is stated as –log(h) where h is the hydraulic head. In soil science, Lebedev [20] suggested that the pF of 3.8 can be employed to differentiate between the clay-bound water and freedom water. The commercially acquirable centrifugal separator, shown in Fig. 3, which has a radius of 9.8 cm was adopted in this research. The height and diameter of the sample box were 51 and 50 mm separately. The detail of the principle was depicted by Zhu et al. [21]. The large centrifugal force is exerted the specimen in the test. Gardner [19] suggested Eq. 1 to work out the suction in the sample in the centrifugal separator:

$$\psi = \frac{\rho\omega^2}{2}\left(r_1^2 - r_2^2\right), \quad (1)$$

where ψ is the suction of sample in N/m^2, r_1 is the actinomorphic interval to mid-position of sample in m, r_2 is the actinomorphic interval to free-water face in m, w is the angular velocity in s^{-1}, ρ is the density of the void liquid in kg/m^3. The equation indicates that exerted soil suction is the function of angular velocity.

In experiments, each specimen was rotated for 20 hours to obtain an equilibrium condition. The experiments were performed at the set temperature of 25 °C. Once finish permeability experiments, 4 samples of every mixture were applied for centrifuge experiments. The samples in the centrifuge suffered to angular velocity of 5000 ~ 9000 rpm consistent with *pF* of 3.5 ~ 4 separately. P_{bw} at the *pF* of 3.8 was got by the straight cut.

Fig. 3. The small centrifuge used in this study

3. RESULTS

3.1. Impact of bentonite content on the permeability of sand-bentonite backfill material

As illustrated in the figure, when bentonite content achieved a certain degree, the bentonite content had little impact on permeability. The figure also shows that hydraulic conductivity was smaller than 1.00×10^{-7} cm/s when the bentonite content of the AJ, YD and HB bentonites reached 3%, 4% and 5%, respectively. A barrier wall with antifouling performance with a hydraulic conductivity of less than 5.00×10^{-10} m/s, as suggested by Devlin and Parker [9], can be achieved with the three types of bentonites by changing the bentonite content. It is self-evident that the AJ bentonite has preferable properties in reducing the permeability of sand-bentonite backfills compared with the performance of the YD and HB bentonites.

Varying bentonite content of 3 sorts of bentonites was contradistinguished with hydraulic conductivity acquired in the experiments, as shown in Fig. 4.

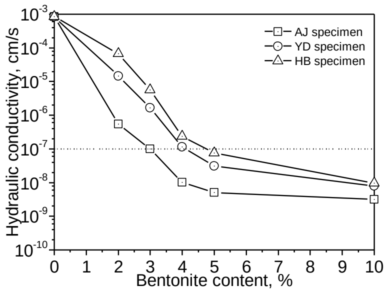

Fig. 4. Variations in hydraulic conductivity as the function of bentonite content

With increasing bentonite content, the hydraulic conductivity of backfill fell at a varying rate, but the reduction of hydraulic conductivity verged to slow down as bentonite content was more than 5%. Especially for the AJ bentonite, hydraulic conductivity only declined from 4.99×10^{-9} cm/s to 3.17×10^{-9} cm/s when the bentonite content increased from 5 % to 10 %.

3.2. Impact of bentonite content on porosity *n* of the mixtures

Previously, changes of *k* were analysed from the perspective of pore changes. Therefore the relationship between bentonite content and porosity was determined by testing and calculating the porosity of admixtures made with 3 kinds of bentonite after a flexible wall permeability test was performed, as shown in Fig. 5.

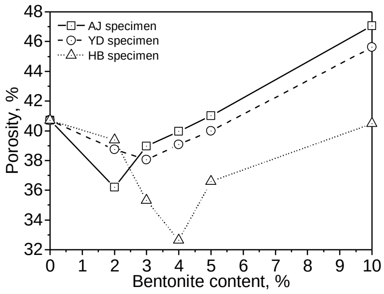

Fig. 5. Impact of bentonite content on porosity of backfill

Fig. 5 indicates that add of bentonite might not make for a loss in porosity. And porosity of admixtures consisted of 3 kinds of bentonite initially decrease and afterwards increase. There was a bentonite content with n_{min}, which could be regarded as critical bentonite content C_{cr} of the n_{min}, when the bentonite content of HB, YD and AJ was 4 %, 3 % and 2 %, respectively. However, with the same bentonite content, the HB bentonite most significantly decreases *n*, while the AJ bentonite has the smallest impact.

The *n* of FSS without bentonite is 40.69 %. And porosity of a sand-bentonite mixture can decrease to 32.62 % when bentonite content is equal to the C_{cr}. Nevertheless, porosity might gain again if bentonite content surpasses C_{cr}, rising up to a maximum of 47.07 %, which is greater than the porosity of FSS without bentonite. It shall be looked forward that as bentonite content is smaller than C_{cr}, the soil mixture is organized as though sand particles were skeleton and the pore was full of bentonite particles. With the further addition of bentonite, bentonite grains would become part of the entire structure and the soil would in turn become weaker.

According to the declining trend of *k* shown in Fig. 4, the addition of bentonite can impact permeability by changing the pores which is not unique way. Additionally, there are certain differences in the hydraulic conductivity of newly produced pore and initial pore. As a result, it is not enough to assess permeability variations just from *n*.

3.3. Impact of bentonite content on P_{bw} of mixtures

Because the pores are the same and yet there are differences in the permeability performance, more investigation is warranted. This phenomenon may have a relation to form of water present in pores. Liang et al. [22] found that clay-bound water round soil particle face may affect hydraulic conductivity by influencing the mutual effect of the clay, water and electrolyte system in a time of the progress of studying micro electric field effect of hydraulic conductivity in tiny-grain clay. Out of considerations about the impact of bound water on the permeability, moisture centrifugal dewatering tests were carried out for specimens after the flexible wall permeability test. Then, the combined potential *pF*s of the porewater were tested.

Water content with $pF > 3.8$ could be acquired via the water content exodic dehydration experiment. Then P_{bw} in admixture could be tested. In Fig. 6, the relation between bentonite content and P_{bw} is shown. According to the data, up until the bentonite content is lower than 5 %, the P_{bw} of the mixtures grows linearly, and after the bentonite content is greater than 5 %, the growth of P_{bw} declines gradually. The AJ bentonite makes the most significant contributions to the P_{bw} in the porewater, followed by the YD bentonite and then the HB bentonite. This is a reflection of the differences in the water combining capacity of different types of bentonite.

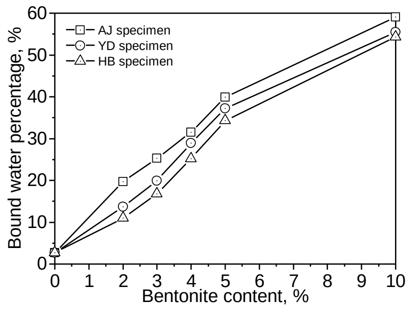

Fig. 6. Impact of bentonite content on clay-bound water percentage of soil mixture

4. DISCUSSION

Fig. 4 and Fig. 5 reveal that as bentonite content is lower than C_{cr}, the hydraulic conductivity of the mixture would decrease observably. Nevertheless, when bentonite content surpasses C_{cr}, hydraulic conductivity initiates reduction tardily, but the porosity of sand-bentonite mixtures keeps increasing. It's distinguished from ordinary phenomenon where a larger *n* in clay a larger *k* [23], for the changes in the skeleton of sand-bentonite mixtures. In theory, the sand grains are load-bearing and sand pores are full of bentonite grains. And porosity of the mixture reduces with adding bentonite content as bentonite content is less than C_{cr}. Yet as bentonite content is better than C_{cr}, add of bentonite can be accomplished by expanding sand particles and sand and bentonite constituents are both load bearing. Sand particles are dangling in bentonite and *n* of the soil mixture enhances with raising bentonite as a result of substitute of sand particles with bentonite (Fig. 7). Similar phenomena were noted in sand-kaolinite soil mixture at different confining stresses.

Besides, the P_{bw} in the porewater of the mixture increases faster than *n* as the bentonite content becomes greater than C_{cr}. This might narrow the channels available for flow in the mixtures, resulting in a decrease of *k*. The *k* of the mixture is not only influenced by *n*. When compared to ordinary clay, there is a higher P_{bw} in the porewater of the sand-bentonite mixture. Therefore, the bound water in the mixture cannot be neglected as analysing changes in the k of a sand-bentonite mixture.

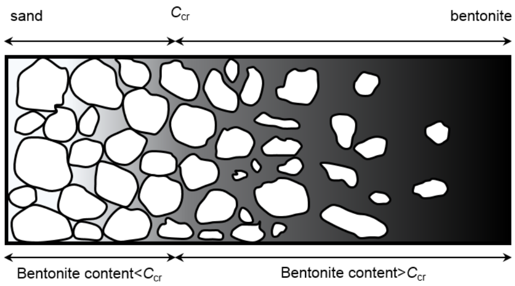

Fig. 7. Geometry of sand-bentonite soil mixtures

Following the analysis above, it is likely that in moving progress via sand-bentonite mixtures, water would not move as combinative potential *pF* between pore water and bentonite grains surpasses 3.8, making for a distinct pattern of matter between solid and fluid states with regard to physical property, notably viscosity [24]. That is, it is assumed that bound water in the soil mixture is believed the un-mobile pore water, which may be in the stern-layer of the electrical double layer [25]. When there is no bentonite, the combining capacity between FSS and water is very weak, and there is nearly no bound water around sand particles. However, after the addition of bentonite, the combining capacity of the mixture increases, and the bound water thickens gradually as illustrated in Fig. 8.

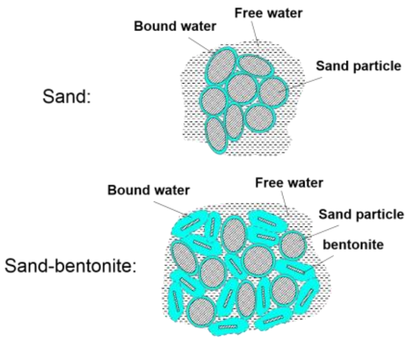

Fig. 8. Principle scheme of sand and sand-bentonite soil admixture

From differences in the permeability and the combining capacity with water of the three types of bentonite, the clay-bound water percentage in pore water of soil admixture enhanced with liquid limit w_L and swell index of bentonite, then k decreased. Mishra et al. [26] found that w_L and swell index of bentonite might markedly affect the hydraulic conductivity of soil-bentonite soil mixtures and that there is a plus correlation between liquid limit and swell index, feeling that swell of the bentonite would prevent movement channels of fluid in admixture. Consequently, in the application of soil-bentonite vertical barrier, the swell index shall be considered primarily during the selection of a type of bentonite.

Basis on conception and analysis hereinabove, an approximative approach of computational valid porosity n_{eff} [27] is raised as follows.

$$n_{eff} = n \times \left(1 - P_{bw}\right), \qquad (2)$$

where n is the porosity of sand-bentonite mixtures and P_{bw} is the clay-bound water percentage in the pore water of soil mixtures.

The correlation between bentonite content and n_{eff} of the sand-bentonite mixture is built, as shown in Fig. 9. This can also explain that the porosity of the mixture goes on improving and that even n is larger than that of the FSS without the addition of any bentonite as bentonite content is larger than C_{cr} but hydraulic conductivity continues to decrease, arising from the continuously decreasing n_{eff} of the mixture. Furthermore, the trend of n_{eff} is quite similar to that of k in Fig. 4 with the increasing bentonite content.

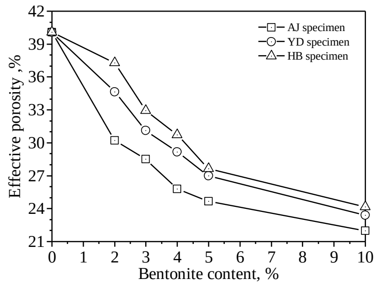

Fig. 9. Impact of bentonite content on effective porosity of admixture

To understand better the quantitative relationship between n_{eff} and k of a sand-bentonite mixture, fitting is conducted between the n_{eff} and k of the soil mixture as illustrated in Fig. 10, including the data from the test and the literature. Without considering the bentonite content and the type of bentonite, there is an exponential relationship between k and n_{eff}. The best fit line (R = 0.830) is:

$$\log k = 0.288 n_{eff} - 15.647, \qquad (3)$$

where the coefficient of determination r^2 is 0.676 and the units of k and n_{eff} is cm/s and %, respectively. As could be expected from various sources of data, fitting isn't very well. It doesn't appear to have a relation to the intrinsic diversity in bentonite and thus shall represent diversities in a method of evaluating effective porosity n_{eff}, testing technique and random change in microstructure.

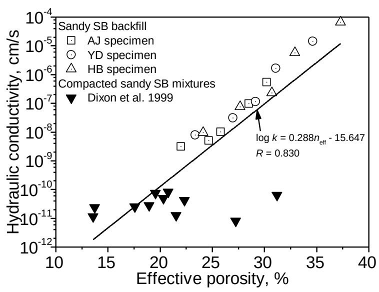

Fig. 10. Permeability as a function of effective porosity of sand-bentonite mixtures

Castelbaum and Shackelford [13] established the prediction equation $k = ae_b^c$ in form of a power function, in which a and c are invariable, e_b is the corresponding void ratio of the bentonite in sand-bentonite soil mixtures when the hydraulic conductivity of soil mixture is k. In this equation, the e_b can be obtained from the test, but an increasing e_b yields a smaller coefficient of determination

r^2 of the equation and thus a worse fitting. Compared to the equation above, the prediction equation in this paper considers the interaction between bentonite and porewater. However, obtaining n_{eff} requires a test to determine the P_{bw}. Consequently, in our future works, we will focus on the methods of determining the n_{eff} of sand-bentonite mixtures.

In conclusion, when bentonite is added the FSS, changes in n_{eff} is the primary cause for changes in the k of the sand-bentonite mixture. In addition, there is a quantitative empirical relationship between n_{eff} and k, which is of significant importance for the prediction of the k of soil-bentonite vertical barrier in a landfill.

5. CONCLUSIONS

As bentonite produces a barrier with Fujian standard sand, there is a critical bentonite content with a homologous lowest porosity. As bentonite content is less than critical bentonite content, hydraulic conductivity reduces quickly; contrary, hydraulic conductivity reduces tardily as bentonite content is more than critical bentonite content. With the increase of the bentonite content, clay-bound water percentage in pore water of admixture goes on improving. An approximative approach of computational valid porosity is raised and reveals that effective porosity reduces with adding bentonite content. After the bound water was investigated, an exponential correlation between effective porosity and permeability was discovered. This empirical equation between effective porosity and permeability allows for the prediction of the permeability of the soil-bentonite vertical barrier used at a landfill. Additionally, it is concluded that the addition of bentonite alters effective porosity, which is the primary cause for the ultimate variations of permeability of the mixture.

Acknowledgments

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