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The feasibility of mudstone material as a natural landfill liner

Chyi Sheu [a,*], Tzong-Tzeng Lin [a], Juu-En Chang [b], Chih-Hung Cheng [b]

[a] *Department of Civil Engineering, National Kaohsiung Institute of Technology, 415 Chien Kung Road, Kaohsiung 80782, Taiwan*

[b] *Department of Environmental Engineering, National Cheng Kung University, Tainan, Taiwan*

Abstract

This paper presents the results of a series of laboratory tests investigating on physical properties and hydraulic conductive behaviors of a mudstone material obtained from southwestern Taiwan. The Atterberg limits and particle-size distribution examinations showed the liquid limit = 34.1%, the plasticity index = 15.2%, the percentage fines (< No. 200 sieve) ≥ 95.1%, the percentage of clay (< 2 μm) ≥ 30%, and the activity = 0.5. These characteristics perfectly satisfied the essential requirements for soil properties of landfill liner. Based on the column experiments using two different grain sizes of beads to simulate the mudstone liner constructed on the gravel and the sandy soil, the hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s could be achieved if the hydraulic gradient is less than 13.9 (gravel) and 17.8 (sand), respectively. However, the hydraulic conductivity rose with an increase in hydraulic gradient. It was attributed to the fine granular mudstone penetrated through the simulated beads and led to the fine granular mudstone that could not fill up the void of beads. Moreover, the results of permeability tests performed using the rigid-wall and flexible-wall permeameters revealed that all of the hydraulic conductivities were less than 1×10^{-7} cm/s for the mudstone with water contents from 17% to 37% (rigid-wall) and 14% to 29% (flexible-wall). Thus, it was confidently expected that this mudstone material could be applied on landfill soil liner. © 1998 Elsevier Science B.V.

Keywords: Landfill; Plasticity index; Rigid-wall; Flexible-wall

* Corresponding author.

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1. Introduction

In recent years, the geomembranes have usually been considered for the utilization in design and construction of landfill liner in Taiwan. Such landfill may cause the leachant leaking out of the bottom due to improper construction and management. As a result, the so-called secondary pollution will happen. However, the synthetic flexible membrane liner is still used in the sanitary landfill in Taiwan because it is difficult to obtain a lot of clay materials. Therefore, it is very important to search for a natural material for replacing the clay material as a natural landfill liner. Fortunately, the mudstone is widely and deeply distributed over southwestern Taiwan. According to the results of research reports [1–3] concerning mudstone materials from the standpoint of civil engineering for provision against natural disasters, the rain infiltrated mudstone can be in possession of the slaking, swelling, and eroding characteristics (as shown in Fig. 1). However, these characteristics of mudstone are highly detrimental to construction. Conversely, they are obviously advantageous to make mudstone material possess mobility and slit filling characteristics, which in fact is helpful us in this research.

Many researchers had been devoted to study the issues related to landfill liners, particularly the compacted clayey soils. Lambe [4] stated that the factors which influencing hydraulic conductivity include: (1) soil composition; (2) permeant characteristics; (3) void ratio; (4) structure; and (5) degree of saturation during permeation. Lambe also suggested that the hydraulic conductivity of a clay compacted optimum wet is less than the hydraulic conductivity of a clay compacted optimum dry because the clay with a flocculated particle structure has large voids than the clay with a dispersed structure [5]. According to Mitchell et al. [6], the lowest hydraulic conductivity occurs at water content slightly (2–4%) wet of optimum water content. Benson et al. [7] used the

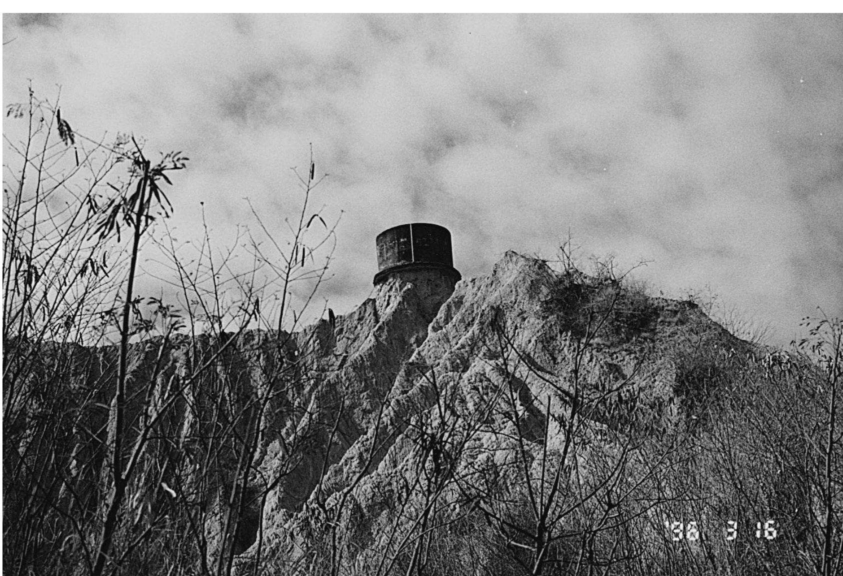

Fig. 1. Photograph of erosion on the surface of the mudstone mountain.

database measured from 67 landfills in North America to yield a geometric mean of hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s if the liquid limit $\geq 20\%$, the plasticity index $\geq 7\%$, the percentage fines (< No. 200 sieve) $\geq 30\%$, the percentage of clay (< 2 mm) $\geq 15\%$, and the activity ≥ 0.3. Recently, several investigators have studied on hydraulic conductivity of compacted soils [8–11].

Up to now, very few studies had been performed to disclose the feasibility of mudstone materials applied on landfill soil liner. The mudstone has slaking, swelling, and eroding characteristics while met with water due to the mudstone that belongs to marine deposit, it remains an unsolved puzzle whether the mudstone is suitable for the landfill liner. Therefore, the aim of this study was to explore the physical properties and hydraulic conductive behaviors of mudstone. This study employed general characteristic analysis, the simulated column test, and compaction permeability tests with rigid-wall and flexible-wall cells to evaluate whether the mudstone material could be designed for replacing the clayey soil as a natural landfill liner.

2. Materials and methods

2.1. Mudstone material

The specimen used in this work was a dry, lumpish mudstone obtained from Chi-shan area, Kaohsiung county, Taiwan. The mudstone is widely and deeply spread out in southwestern Taiwan. The distributed area of mudstone is about 1040 km^2, and the mudstone land approximately reaches a depth of 5000 m [12]. The qualitative X-ray diffraction test on the raw mudstone indicated large amounts of quartz and illite, minor calcium aluminate hydrate ($CaO–Al_2O_3–10H_2O$, CAH_{10}) and calcium silicate hydrate ($1.5CaO–SiO_2–xH_2O$, CSH), and small amounts of unidentifiable peaks [13]. Yao [14] found that the mudstone can be categorized as sand, silt, and clay according to textural fractions and can be in possession of high uniaxial compressive strength at low water content. Thus, Cheng [13] suggested that the compressive strength of the raw mudstone is probably attributed to the cementation among sand, silt, and clay formed by pozzolanic hydrates.

2.2. General characteristic tests

The basic property tests included such items as water content, specific gravity, Atterberg limits, and grain-size distribution. All tests were measured following American Society of Testing Materials (ASTM) Standard D2216, D854, D4318 and D427, and D452 and D422, respectively.

2.3. Simulated column tests

The main objective of this test was to simulate the permeate behaviors with water between two different geological strata below the bottom of the landfill and four various thick mudstone liners. The beads were packed into the simulated cells with a diameter of 1 cm and 2 mm and a height of 10 cm is used to represent the gravel stratum and the sandy soil, respectively. The simulated column as presented in Fig. 2 is a bright acrylic cylinder with an internal diameter of 9.3 cm and a height of 50 cm. The crushed

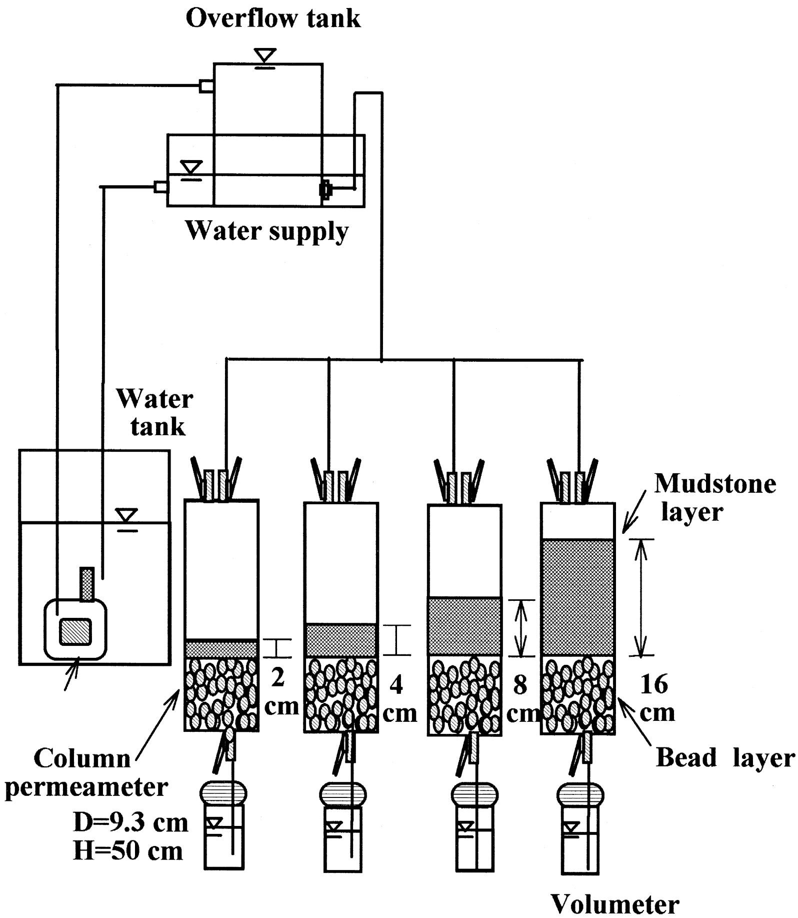

Fig. 2. Apparatus for the simulated column tests.

mudstone samples, passed through a No. 10 (2 mm) sieve, packed up to a maximum of 2 cm, 4 cm, 8 cm, and 16 cm in height, respectively, were tested in the columns. The simulated column tests were performed on the crushed mudstone using the pure water under different gradients and 180 cm in constant-head height for 30 days. The gradients were 90, 45, 22.5, and 11.25. During the testing period, the permeated waters was measured at various times. For understanding the particle-size change of mudstone, the permeated mudstone samples were carried out the measurement of grain-size distribution after the end of this test.

2.4. Compaction and permeability tests

The main purpose of this test was to simulate the constructive characteristics of the natural landfill liner. The air-dried mudstones were crushed and passed through a No. 4 (4.75 mm) sieve. Pure water was added to the crushed mudstones to provide different water contents (5%, 12.5%, 20%, 27.5%, and 35%, respectively). The moistened

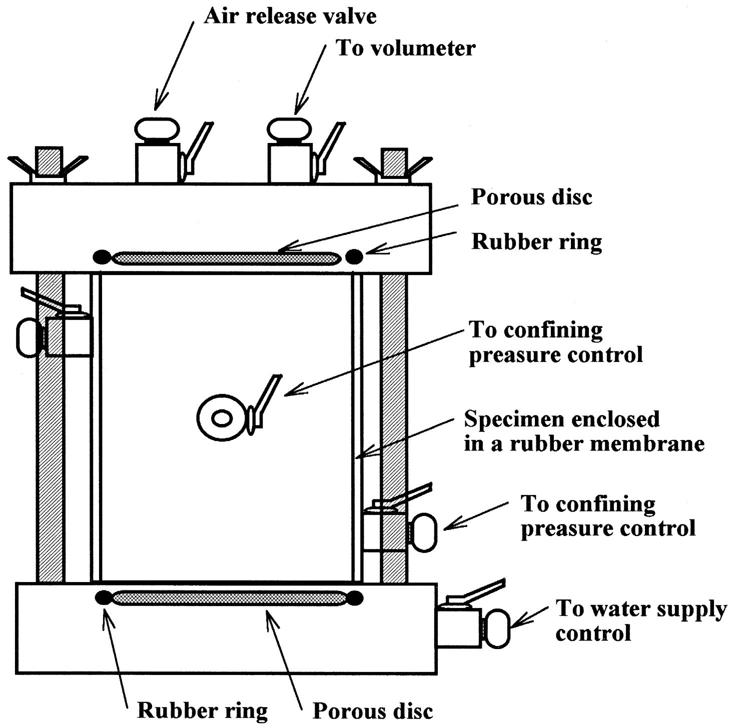

Fig. 3. Rigid-wall and flexible-wall cells used for permeability tests.

samples were placed in a plastic bag and stored for at least 3 days to allow moisture equilibration and hydration, and then compacted in standard Proctor molds according to ASTM D698.

The compacted mudstones were tested in rigid-wall and flexible-wall permeameters (as shown in Fig. 3). The rigid-wall specimens measured 10.1 cm in diameter and 11.65 cm in height. After being set up in the compaction frame, the mudstone was permeated with pure water applied with 3 kg/cm^2 pressure until steady state was reached. The flexible-wall permeameters were still equipped for testing with 10.1 cm diameter specimens. The mudstone was first encased in a rubbery membrane, then in the compaction mold. The test specimens were also permeated with 3 kg/cm^2 water pressure from the bottom of the cells. To avoid the side seepage which arise between the mudstone and membrane, a confining pressure of 3.2 kg/cm^2 was applied to the outside of the rubbery membrane until the testing was over.

3. Results and discussion

3.1. General geotechnical characteristics

The basic properties of the raw mudstone are summarized in Table 1. The result of grain-size analysis shows that the raw mudstone contains 95.1% fines (< 0.074 mm),

Table 1
General geotechnical properties of raw mudstone

Property	
Water content (%)	2.12
Specific gravity	2.73
Void ratio	0.27
Dry unit weight (g/cm^3)	2.14
Liquid limit (%)	34.1
Plastic limit (%)	18.9
Plasticity index (%)	15.2
Activity	0.5
Grain size	
Sand (> 0.06 mm)	6.2%
Silt (0.06–0.002 mm)	63.4%
Clay (< 0.002 mm)	30.4%
Fine (< 0.074 mm)	95.1%

30% clay, 64% silt, 6% sand, and an activity of 0.5. This clearly illustrates that the grain size of raw mudstone is very fine. Moreover, the results of Atterberg limits reveal the liquid limit (LL) = 34.1%, the plasticity limit (PL) = 18.9%, and the plasticity index (PI) = 15.2%. Obviously, the mudstone is classified as a low plasticity (liquid limit less than 50%) clay (CL) according to the US unified soil classification system.

Benson et al. [7] stressed that basic soil properties and compaction conditions normally monitored during construction quality control of soil liners were related to hydraulic conductivity. They also found that the geometric mean of hydraulic conductivity was correlated to the Atterberg limits, the percentage of fines and clay, and activity. Based on the results of their analyses, it was suggested that a geometric mean of hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s could be achieved if the liquid limit $\geq 20\%$, the plasticity index $\geq 7\%$, the percentage fines (< No. 200 sieve) $\geq 30\%$, the percentage of clay (< 2 μm) $\geq 15\%$, and the activity ≥ 0.3. For the comparison between the basic properties of the raw mudstone and the soil index as suggested by Benson et al., it proves a good performance of the former.

3.2. Simulated gravel and sandy soil column tests

It is an important step towards success to select a good geological site for a new landfill. Unfortunately, there are many landfill sites located on the permeable stratum (gravel or sandy soil) in Taiwan. Therefore, this test is to estimate whether the mudstone can restore the permeable stratum to decrease permeability.

The results of simulated column tests as shown in Table 2 indicate that the thickness of the mudstone liner has a decisive influence on hydraulic conductivity under constant-head condition. For 1 cm round bead, the hydraulic conductivity for 4 cm and 8 cm thick liner columns is approximately 8.39×10^{-5} cm/s and 7.40×10^{-8} cm/s, respectively. However, the hydraulic conductivity of 1-cm round bead is about 1.60×10^{-3} cm/s. Thus, it is clear that the mudstone material possesses a clogging ability for small openings.

Table 2
Results of the simulated gravel and sandy soil column tests

Thickness (cm)	Permeability (cm/s)	
	Simulated gravel stratum	Simulated sandy soil
0	6.55×10^{-3}	1.60×10^{-2}
2	3.27×10^{-3}	3.35×10^{-3}
4	1.10×10^{-6}	8.39×10^{-5}
8	9.60×10^{-8}	7.40×10^{-8}
16	7.30×10^{-8}	7.30×10^{-8}

Results of grain-size distribution analysis on the permeated mudstone sample were presented in Fig. 4. For the comparison between the permeated and raw mudstone samples passed through the 20-μm grain size, the weight percentage is about a range of 50 to 65% and 80%, respectively. It obviously illustrates that the fine grained particles in mudstone will flow out of the column with the leachate. In addition, the percentage of fines in the permeated mudstone is on the downward trend with the increase in thickness of the mudstone liner. According to Cheng [13], the formation of the fine particles in the leachate was attributed to the slaking and swelling production after mudstone absorbed moisture from the permeant. Although the fine particle in mudstone will be eroded with the permeant, the simulated bead is exactly coated with fine grain-size mudstone. Thus, the decrease in hydraulic conductivity for the simulated bead may be attributed to coating and clogging behaviors of fine particle-size mudstone.

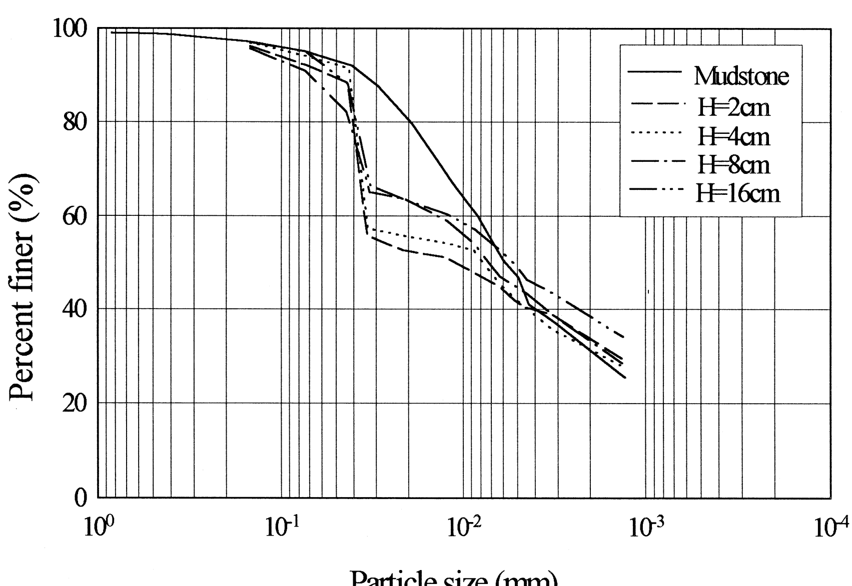

Fig. 4. Particle-size distribution curves of raw mudstone and the permeated mudstones obtained from four different thick liners, respectively.

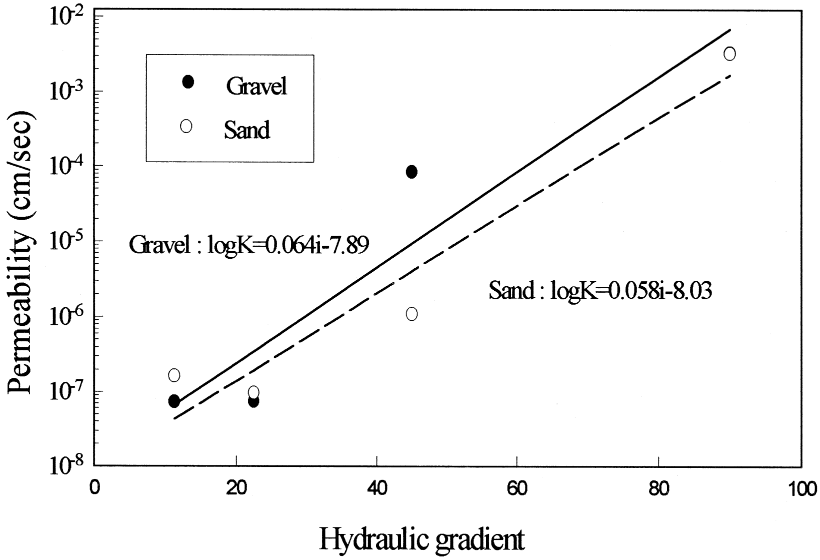

Fig. 5. Hydraulic conductivity vs. hydraulic gradient for mudstone permeated with water using rigid-wall and flexible-wall permeameters.

Fig. 5 shows the relationship between permeability and hydraulic gradient on the simulated column tests. It reveals that the permeability is on the upward trend as there was an increase in hydraulic gradient on both simulated columns. Based on the above result (Fig. 4), it clearly infers that the fine grains can be taken out of the mudstone under a high hydraulic gradient to lead to an increase of porosity in the mudstone liner. Therefore, the change of porosity in the mudstone might play an important role in the relationship between hydraulic conductivity and hydraulic gradient. Moreover, the variation of hydraulic conductivity (k) as a function of hydraulic gradient (i) for both simulated columns is carried on linear regression analysis. As can be seen, two different straight lines are obtained, whose regression equations are: (●) simulated gravel stratum, $\log\ k = 0.064i - 7.89$; (○) simulated sandy soil, $\log\ k = 0.058i - 8.03$. The hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s can be reached in simulated gravel and sandy soil columns, and the hydraulic gradients calculated from both regression equations must be less than 13.9 (gravel) and 17.8 (sandy soil), respectively. According to Darcy's law, the hydraulic conductivity will be less than 1×10^{-7} cm/s if the mudstone liner is respectively more than 2.33 cm (gravel) and 1.79 cm (sandy soil) in thickness and operates at a 30-cm constant gradient.

3.3. Compaction and permeability tests

The compaction curves performed using rigid-wall and flexible-wall permeameters for the mudstone are shown in Fig. 6. The corresponding hydraulic conductivities are presented in Fig. 7. Obviously, the shape and maximum dry unit weight of the two curves are almost identical, but the optimum moisture contents are different. For

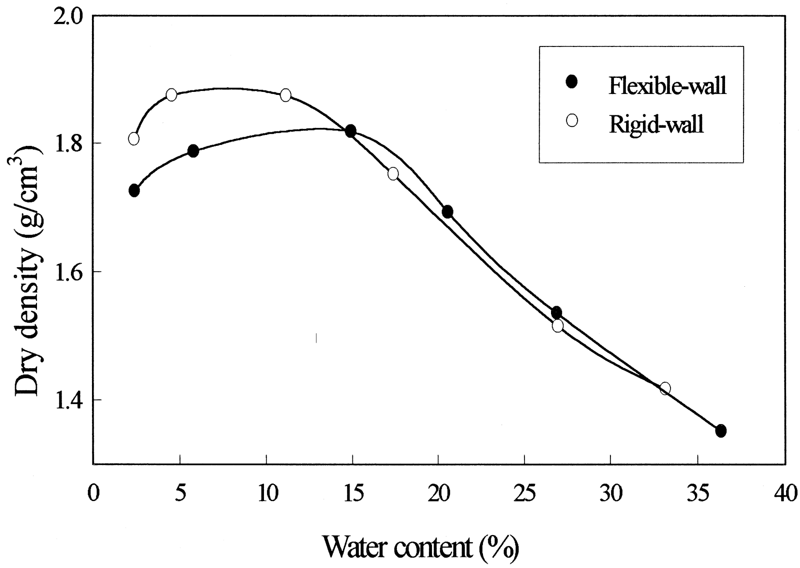

Fig. 6. Standard proctor compaction curves for both rigid-wall and flexible-wall cells.

rigid-wall test, the maximum dry unit weight is about 1.90 g/cm^3 as 8% water content of optimum; the maximum dry unit weight is about 1.84 g/cm^3 as 15% water content of optimum for flexible-wall cell. Moreover, the permeability curves are significantly influenced by water content in both cells. The hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s

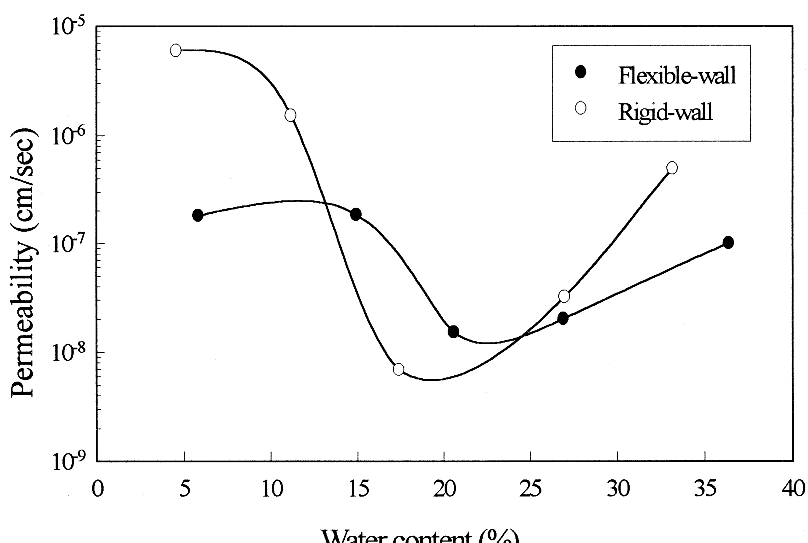

Fig. 7. Hydraulic conductivity vs. molding water content for rigid-wall and flexible-wall cells.

can be achieved with rigid-wall and flexible-wall cells for a range of 14 to 28% and 17 to 37% water contents, respectively, and the optimum moisture content is separately about 18% and 22% for the lowest hydraulic conductivity.

For comparing both water contents dry and wet of optimum from Figs. 5 and 6, respectively, the lowest hydraulic conductivities occur at water contents slightly (7–10%) wet of optimum water content. The lowest hydraulic conductivity of compacted clay occurs at water contents slightly (2–4%) wet of optimum water content [6,15–17]. At the macroscopic viewpoint, increasing water content generally results in an increased ability to break down clay and to eliminate interparticle pores [16]; at the microscopic standpoint, increase in water content result in reorientation of clay particles and reduction in the size of interparticle pores [17]. The result of Cheng [13] verified that the mudstone absorbed water will cause the slaking and swelling phenomena due to destruction of cementation, then lead to the fine particle-size erosion. Thus, the change in hydraulic conductivity for compacted mudstone that occurs when the molding water content is varied is possibly attributed to the slaking and swelling properties of the moistened mudstone and the changes in mudstone fabric.

In most geotechnical works, the 90 to 95% maximum dry unit weight has actually been used to field compacted soil for controlling the construction quality. For such requirement, the water content dry of optimum with rigid-wall cell ranges from 2.5% to 15.5%, and with flexible-wall cell is a range of 4 to 19%. The optimum range in field compacted case is different from the range in wet water content for hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s. Therefore, the construction of landfill liner using mudstone material must carefully control the addition of water because that adding more or less water will be to lead to an increase in hydraulic conductivity of mudstone liner.

4. Conclusion

Based on the above results, the following conclusions can be made: (1) The mudstone is possessed of the liquid limit = 34.1%, the plasticity index = 15.2%, the percentage fines (< No. 200 sieve) $\geq$ 95.1%, the percentage of clay (< 2 μm) $\geq$ 30%, and the activity = 0.5, and its physical characteristics perfectly satisfy the essential requirements in United States for soil properties of landfill. (2) Not only the fine particle in mudstone will be eroded with the permeate, but also the simulated bead is exactly coated with fine grain-size mudstone. Thus, the decrease in hydraulic conductivity for the simulated bead may be attributed to coating and clogging behaviors of fine particle-size mudstone. The hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s in simulated gravel and sandy soil columns will be reached if the hydraulic gradients can be controlled less than 13.9 (gravel) and 17.8 (sandy soil), respectively. In other words, the hydraulic conductivity will be less than 1×10^{-7} cm/s when the mudstone liner is respectively more than 2.33 cm (gravel) and 1.79 cm (sandy soil) in thickness and operates at a 30-cm constant gradient. (3) The hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s can be achieved with rigid-wall and flexible-wall cells for a range of 14 to 28% and 17 to 37% water contents, respectively, and the optimum moisture contents are separately about 18 and 22% for the lowest hydraulic conductivity. The construction of landfill liner using mudstone material must carefully control the addition of water because that adding more or less water will lead to an increase in hydraulic conductivity of mudstone liner. (4) Finally, it is possible that mudstone material can be applied as landfill soil liner.

Acknowledgements

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