ภาคผนวก 二

ผลงานตีพิมพ์

ภาคผนวก ก

Compacted sand-bentonite mixtures for hydraulic containment liners

ORIGINAL ARTICLE

Compacted sand-bentonite mixtures for hydraulic containment liners

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Abstract

Chalermyanont, T. and Arrykul, S.

Compacted sand-bentonite mixtures for hydraulic containment liners

Songklanakarin J. Sci. Technol., 2005, 27(2) : 313-323

Sand is a pervious material in nature. Mixing sand with appropriate bentonite contents yields sand-bentonite mixtures having low hydraulic conductivity that can be used as hydraulic containment liners. In this study, compaction tests were conducted to determine the optimum water content and maximum dry unit weight of compacted sand-bentonite mixtures. Direct shear and hydraulic conductivity tests were conducted to assess the shear strength parameters and hydraulic conductivity of compacted sand-bentonite mixtures. Test results indicate that hydraulic conductivity of mixtures decreases about four orders of magnitude when mixed with 5% bentonite or more. Mixing sand with bentonite, however, results in a decreased shear strength of the mixtures due to the swell of bentonite when soaked with water. For the mixtures with bentonite content varying from 0 to 9%, the hydraulic conductivity of the mixtures decreases from 3.60×10^{-5} to 4.13×10^{-9} cm/s; while the corresponding friction angle and swell ranges from 49 to 22 degrees and 0.85 to 10.32%, respectively. In addition, the compacted sand-bentonite mixture with 3% bentonite content could achieve low hydraulic conductivity of 1×10^{-7} cm/s which is a regular requirement for hydraulic containment liners, while still having relatively high shear strength.

Key words : sand-bentonite mixture, hydraulic conductivity, liners

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Received, 17 June 2004 Accepted, 26 August 2004

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ทรายผสมเบนโทไนต์บดอัดสำหรับชั้นกันซึมในสถานที่เก็บน้ำ

ว. สงขลานครินทร์ วทท. 2548 27(2) : 313-323

ทรายเป็นวัสดุที่น้ำซึมผ่านได้ง่ายตามธรรมชาติ การผสมทรายกับเบนโทไนท์ในสัดส่วนที่เหมาะสมแล้วนำไปบดอัด จะทำให้ได้วัสดุผสมที่มีค่าสัมประสิทธิการยอมให้น้ำซึมผ่านต่ำ และสามารถนำไปใช้เป็นชั้นกันซึมในสถานที่กักเก็บน้ำและสถานที่ฝังกลบมูลฝอยได้ ในการศึกษาครั้งนี้ได้มีการทดสอบการบดอัดเพื่อหาค่าปริมาณความชื้นที่เหมาะสมและค่าหน่วยน้ำหนักแห้งสูงสุดของทรายผสมเบนโทไนท์ รวมทั้งการทดสอบแรงเฉือนโดยตรงเพื่อหาค่ากำลังของดิน และการทดสอบหาค่าสัมประสิทธิการยอมให้น้ำซึมผ่าน ผลการทดสอบพบว่าค่าสัมประสิทธิ์การยอมให้น้ำซึมผ่านลดลงถึง 10,000 เท่าเมื่อผสมทรายกับเบนโทไนท์ปริมาณตั้งแต่ 5% โดยน้ำหนัก อย่างไรก็ตามการผสมทรายกับเบนโทไนท์จะทำให้กำลังของวัสดุผสมลดลง เนื่องจากการบวมตัวของวัสดุผสมจากการขยายตัวของเบนโทไนท์เมื่อสัมผัสกับน้ำ เมื่อบดอัดทรายผสมเบนโทไนท์ปริมาณจาก 0% ถึง 9% แล้วทดสอบค่าสัมประสิทธิ์การยอมให้น้ำซึมผ่านลดลงจาก 3.60×10^{-4} เป็น 4.13×10^{-8} ซม./วินาที ค่ามุมเสียดทานลดลงจาก 49 องศา เป็น 22 องศา และการบวมตัวเพิ่มจาก 0.85% เป็น 10.32% การใช้ทรายผสมเบนโทไนท์เพียง 3% ก็เพียงพอที่จะให้ค่าสัมประสิทธิ์การยอมให้น้ำซึมผ่านน้อยกว่า 1×10^{-7} ซม./วินาที ซึ่งเป็นค่าที่ต้องการในการสร้างชั้นกันซึมและยังคงมีค่ากำลังเฉือนที่สูง

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Hydraulic containments such as reservoirs and waste containment such as landfill are required to have appropriate liners in order to prevent leaks. Compacted clays are usually used as the liners because they are very impervious. Hydraulic conductivity of compacted clays is usually less than 1×10^{-7} cm/s. To build the liners with sand is difficult because, naturally, sand is a pervious material. Hydraulic conductivity of sand ranges from 1 to 1×10^{-3} cm/s (Freeze and Cherry, 1979). The hydraulic conductivity of sand can be reduced if sand is mixed with a very impervious material such as bentonite.

Bentonite refers to any material that is primarily composed of the montmorillonite group of minerals and whose physical properties are dictated by the montmorillonite minerals (Grim and Guven, 1978). Characteristics of montmorillonite minerals include large cation exchange capacity, large specific surface area, high swelling potential, and low hydraulic conductivity to water (Gleason *et al.*, 1997).

Properties of bentonite are greatly affected by interactions between its particles and the surrounding pore fluid. The net electrical charge on bentonite particles is negative (Mitchell, 1993), which causes dissolved cations in the pore water to be attracted to the surfaces of the bentonite. The layer of water and absorbed ions that surrounds a bentonite particle is referred to as the diffuse double layer (DDL) (Mitchell, 1993; Shackelford, 1994). The size of the DDL is dominated by ionic strength, dielectric constant, and temperature (Gleason, 1997). The overlapping of DDLs of bentonite makes it difficult for water and electrolytes to flow through (Hunter, 1981; Dukhin and Derjaguin ,1974).

In this study, tests were conducted to determine appropriate sand-bentonite mixtures that could yield a hydraulic conductivity below 1×10^{-7} cm/s, which is a regular requirement for water containment and waste containment liners. Compaction tests were carried out to find out the optimum water contents and maximum dry unit weight of sand-bentonite mixtures. Direct shear tests and hydraulic conductivity tests were carried out to determine, respectively, shear strength parameters and hydraulic conductivities of sand-bentonite mixtures compacted at 2% wet of optimum water content obtained from compaction tests. Several standard tests were also performed to obtain properties of the sand and the bentonite. Based on the test results, a suitable sand-bentonite mixture that yields low hydraulic conductivity while maintaining relatively high shear strength is recommended for use as liner in hydraulic containment applications.

Materials and Methods

Materials

The bentonite used in this study was powdered sodium bentonite manufactured by Wyo-Ben, Inc. This bentonite is generally used as drilling mud in boring activities. Sand used in this study was local sand within Songkhla Province which is typically used as a construction material. Standard tests were conducted with these two materials in order to determine their properties. The tests included: Atterberg limits, sieve analysis, specific gravity, x-ray diffraction, x-ray fluorescence spectrometry, and scanning electron micrograph.

Compaction Test

Compaction tests were carried out to assess the optimum water contents and maximum dry unit weights of sand-bentonite mixtures. Sand-bentoninte mixtures were prepared by mixing 3 kg of oven-dry Songkhla sand with air-dry bentonite. The bentonite contents used were 0%, 3%, 5%, 7%, and 9% by weight. For each sand-bentonite mixture, the optimum water content and the maximum dry unit weight were determined using standard Proctor compaction method (ASTM D698). Five samples of the soil-bentonite mixture were prepared with different water contents ranging from 3 to 17%. Tap water was added to the sand-bentonite mixtures to obtain the desired water contents. The sand-bentonite mixtures were allowed to hydrate for at least 24 hours prior to compaction. An ELE automatic compactor with a 5.5-lb hammer was used in compacting the sand-bentonite mixture into the 4-in mold (inside diameter) with 4.5-in in height in order to ensure the uniform compaction for each layer. Total of 3 layers of soil-bentonite mixture were compacted for each mold. After compaction, the weight of the compacted sand-bentonite mixtures was determined along with their water contents. Correspondingly, the maximum dry unit weight and optimum water content of compacted soil-bentonite mixtures were determined from a compaction curve.

Measurement of Shear Strength Parameters

Shear strength parameters (i.e., cohesion and friction angle) of the compacted sand-bentonite mixtures which are significant parameters in stability analysis, were determined by conducting a series of direct shear tests (ASTM D3080). The sand-bentonite mixtures were compacted in a shear box of 6×6 cm^2 with the thickness of 4.1 cm to achieve the dry unit weight of at least 95% of maximum dry unit weight obtained previously from the compaction tests. Tap water was added to the sand-bentonite mixtures to obtain the desired water contents. The sand-bentonite mixtures were allowed to hydrate for at least 24 hours prior to compaction. Specimen water contents were set to 2% wet of optimum water content to ensure that the hydraulic conductivities of the specimens were low, as recommended by Gleason *et al.* (1997) and Daniel (1994). Two sets of direct shear tests were performed. For the first set, conventional procedures were followed. The compacted sand-bentonite mixture specimens were sheared immediately after compaction. For the second set, in order to simulate field condition of liners, the specimens were inundated for one week prior to shearing. For each direct shear test, three normal stresses were used. The normal stresses used were 17.17, 29.57, and 41.94 kPa. The strain rate of 0.5 mm/min was used for all tests and the time required for shearing the samples to fail was about 4 to 8 min.

Measurement of Hydraulic Conductivity

The hydraulic conductivity tests were performed on compacted sand-bentonite mixtures in rigid-wall permeameters. The rigid wall permeameters used in this study is shown schematically in Figure 1. A rigid wall permeameter is a compaction-mold used in compaction test, made of stainless steel tube, and mounted on top and bottom with stainless steel plates. A collar was mounted between the top plate and the permeameter in order to obtain 1-D flow through the specimen. The specimens were allowed to swell vertically at the upper end into the collar that was filled with deionized water which was boiled prior to use. Stainless steel was used in order to minimize the chemical reaction to permeant liquids. Deionized water was permeated through the specimens from the top of permeameter via a Teflon tube that connected the top plate to the burette. Water level observed from the scale on the burette was used to identify the hydraulic gradient. The hydraulic gradient used was 10 to 15 as recommended in ASTM D5084. The graduated cylinders were used to collect the effluents at the bottom of the specimens. After the tests were completed, the final heights of samples were measured and reported in terms of percent swell, which is defined by ratio of thickness of swell in the collar to the original height of the specimen. For specimens with 5% swell or higher, the specimens were trimmed to their original height and hydraulic conductivity tests were continued until steady hydraulic conductivities of the specimens were obtained.

To ensure that the hydraulic conductivities obtained were reliable, a technique recommended

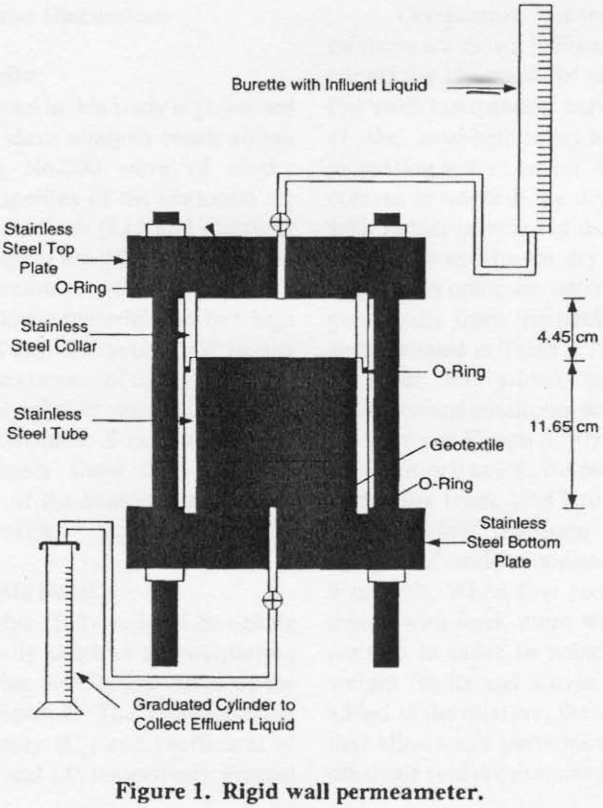


Figure 1. Rigid wall permeameter.

Table 1. Properties of sodium bentonite.

Property	Value
Liquid limit (%)	487
Plasticity index (%)	450
Percent Passing #200 Sieve	65
Specific Gravity	2.55
SiO_2 (%)	63.97
Al_2O_3 (%)	15.66
MgO (%)	4.51
Na_2O (%)	3.46
CaO (%)	2.62

Table 2. Maximum dry unit weight and optimum water content of compacted-sand bentonite mixtures.

Bentonite Content (%)	Maximum Dry Unit Weight (kN/m^3)	Optimum Water Content (%)
0	19.47	9.0
3	19.35	10.0
5	19.10	10.5
7	18.68	11.2
9	18.56	12.0

by Daniel (1994) was used. Following this technique, the deionized water was permeated until 1) inflow and outflow rates were reasonably equal and 2) the computed hydraulic conductivities were steady.

Results and Discussions

Properties of Bentonite

The bentonite used in this study is powdered sodium bentonite. A sieve analysis result shows that percent passing No.200 sieve of air-dry bentonite is 65%. Properties of the bentonite are listed in Table 1. Liquid limit (LL) and plasticity index (PI) of the bentonite are 487 and 450% respectively. The PI of bentonite indicates that bentonite is very highly plastic material and has high swelling potential. X-ray diffraction test results show that the bentonite consists of montmorillonite which is a very highly plastic material and consistent with PI value obtained. X-ray fluorescence spectrometry test results show that the main chemical compounds of the bentonite are silicon oxide and aluminum oxide.

Properties of Songkhla Sand

Sand used in this study is local Songkhla sand which is typically used as a construction material. The grain size distribution curve of the sand is shown in Figure 2. The corresponding coefficient of uniformity (C_u) and coefficient of curvature (C_c) are 11.7 and 1.0, respectively. Percent passing No. 200 sieve is 6.5% and fine content of the sand is found to be nonplastic. Thus, the sand is classified as SW-SM according to the Unified Soil Classification System (USCS).

Compaction Test Results

Compaction test results of sand-bentonite mixtures are shown in Figure 3. Typical compaction curves are observed for sand-bentonite mixtures. For each compaction curve, the dry unit weight of the sand-bentonite mixture increases with increasing water content. After the optimum water content is reached, the dry unit weight decreases with further increase of water content.

The maximum dry unit weights and corresponding optimum water contents were obtained graphically from the peak of compaction curves and tabulated in Table 2. As expected, when more bentonite was added, optimum water content increased and maximum dry unit weight decreased. As shown in Figure 3, when the bentonite content varies from 0 to 9%, the maximum dry unit weight decreases from 19.47 to 18.56 kN/m^3 and the corresponding optimum water content of the compacted sand-bentonite mixtures increases from 9 to 12%. When fine content (i.e., bentonite) is mixed with sand, more water is required in compaction in order to achieve maximum dry unit weight (Holtz and Kovac 1981). When water is added to the mixture, the water acts like lubricant that allows soil particles to move closer to each other, air void is minimized, and higher unit weight

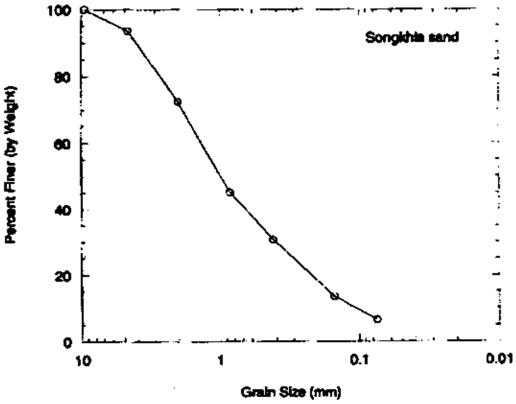


Figure 2. Grain size distribution of Songkhla sand.

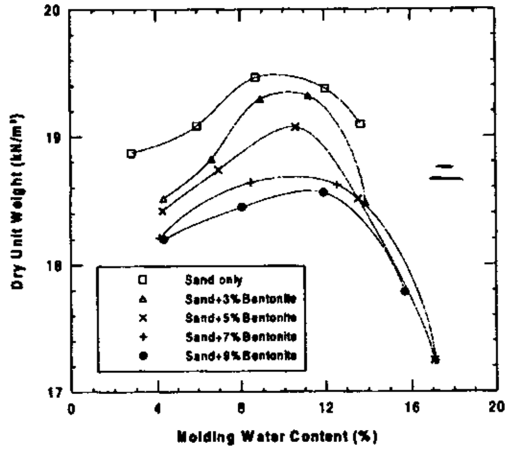


Figure 3. Compaction curves of sand-bentonite mixtures.

can be achieved.

When additional water was added after optimum water content, the dry unit weight of the compacted sand-bentonite mixtures drastically decreased particularly at high bentonite contents (i.e., 5%, 7%, and 9%) as shown in Figure 3. The bentonite swelled further when more additional water was added. At this stage, the additional water and swelled bentonite which was lighter than sand, occupied more space in the compaction mold resulting in decreasing of the dry unit weight of the mixtures.

Shear Strength Parameters

For all bentonite contents, the direct shear test results showed that maximum shear stress of sand-bentonite mixtures increases with increasing normal stress. The corresponding horizontal strain that yielded the maximum shear stress was as low as 2% for low bentonite content mixtures and up to 6% or more for high bentonite content mixtures. As expected the smaller horizontal strain was observed for stiffer material (i.e., mixtures with low bentonite content) and higher horizontal strain was observed for softer material (i.e., mixtures with high bentonite content). Relationships between shear stress and horizontal strain of mixture with 3% bentonite content tested as molded condition are shown in Figure 4.

The Mohr-Colomb failure envelopes, obtained by conducting linear regression of maximum shear stresses and corresponding normal stresses are shown in Figure 5. The corresponding shear strength parameters are tabulated in Table 3.

For the first set of tests, the specimens of sand-bentonite mixtures were sheared immediately after compaction. As shown in Table 3 and Figure 5a, friction angle of compacted sand-bentonite mixtures decreases with increasing bentonite content. The friction angle of the sand-bentonite mixtures decreases drastically from 56 to 37 degrees with increasing bentonite content from 0 to 5% and gradually decreases from 37 to 33 degrees with increasing bentonite content from 5 to 9%.

In contrast, the cohesion increases with increasing bentonite content. Cohesion of the sand-bentonite mixtures increases drastically from approximately 0 to 21.47 kPa with increasing bentonite content from 0 to 5% and gradually increases from 21.47 to 24.90 kPa with increasing bentonite content from 5 to 9%. The results of the direct shear tests have shown that with only 5% of bentonite added to Songkhla sand, the properties of the sand changes from sand-like materials (e.g., high friction angle and low cohesion) to be more clay-like materials (e.g., low friction angle and high cohesion).

For the second set of tests, the compacted specimens were inundated for one week prior to shearing. Inundating specimens in the water is analogous to the soil liners in the field which are normally soaked with water. Shear strength parameters obtained from this set of test should be used in design because they closely represent field condition. The inundated specimens swelled and became looser than those tested under molded condition. The swelling of the inundated specimens was due to the increase of the thickness of diffuse double layer of the bentonite particles. Since the inundated specimens were loose, their shear strengths were less than those tested under molded condition. As shown in Table 3 and Figure 5b, the friction angle of the inundated specimens decreases with increasing bentonite content. The friction angle of the sand-bentonite mixtures decreases from 49 to 22 degrees while the bentonite content varies from 0 to 9%. Only the mixtures with 0 to 3% are still having relatively high friction angle

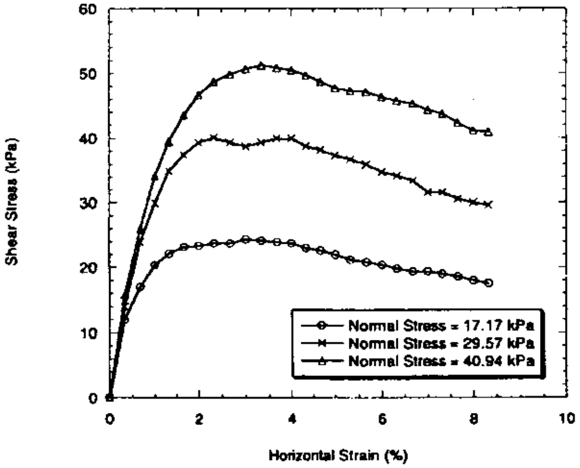
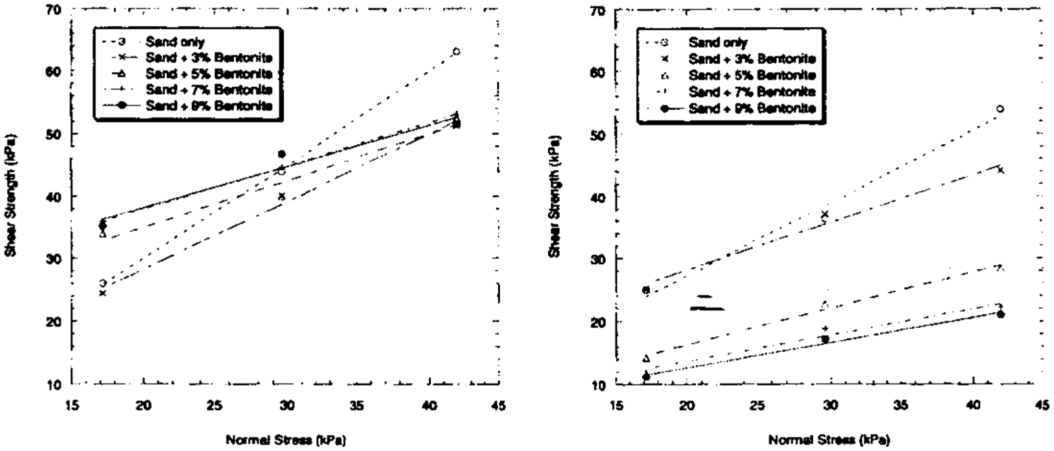


Figure 4. Stress-strain behavior of sand with 3% bentonite mixture obtained from direct shear test.

Table 3. Shear strength parameters of compacted-sand bentonite mixtures.

Bentonite Content (%)	As Molded Specimen		Inundated Specimen	
	Friction Angle (Degrees)	Cohesion (kPa)	Friction Angle (Degrees)	Cohesion (kPa)
0	56	0	49	2.85
3	47	6.43	38	12.65
5	37	21.47	30	4.84
7	35	24.11	22	5.50
9	33	24.90	22	4.72



(a)

(b)

Figure 5. Mohr-Coulomb failure envelopes obtained from direct shear tests: a)as molded specimens, and b) inundated specimens.

of 49 and 38 degrees respectively; whereas, the friction angle of mixtures with high bentonite content of 7 and 9% are low because of the loosening of the mixtures due to swelling bentonite. Cohesion of the mixtures is low comparing to those tested under molded condition. The mixtures lost their cohesion because of the swell of the bentonite particles particularly at bentonite content of 5 to 9%.

Hydraulic conductivity

The hydraulic conductivity tests were conducted using rigid-wall permeameters following procedures recommended by Daniel (1994). For all sand-bentonite mixtures, the testing process was continued until the hydraulic conductivities were reasonably constant and the rate of inflow to rate of outflow ratios were close to unity. Hydraulic conductivity test results for mixture with 3% bentonite content as a function of time are demonstrated in Figure 6. Within the first two weeks, the hydraulic conductivity and rate of inflow to rate of outflow ratio were fluctuated. After two weeks, these two values were reasonably constant which indicated that the constant flow was reached and reliable hydraulic conductivity had been achieved. For higher bentonite contents, the time to reach constant flow was longer. For a mixture with 9% bentonite, time required to reach constant flow was about 12 weeks.

Relationship between hydraulic conductivity of sand-bentonite mixtures and percent bentonite content is shown in Figure 7. The hydraulic conductivity of sand is 3.6×10^{-3} cm/s. The hydraulic conductivity of sand-bentonite mixtures decreases with increasing bentonite content. The hydraulic conductivity reduces about four orders of magnitude with the bentonite content of 5% or more. For bentonite contents of 3 and 5%, the hydraulic conductivity of the mixtures decreases significantly to 5.13×10^{-8} and 5.15×10^{-9} cm/s, respectively. Further increase of bentonite content above 5% does not make significant reduction of hydraulic conductivity. For mixtures with 7 to 9% bentonite content, as shown in Figure 7, the hydraulic conductivities of sand-bentonite mixtures were 4.89×10^{-9} and 4.13×10^{-9} cm/s, respectively. The common regulatory requirement for compacted soil liners states that the hydraulic conductivity should be less than 1×10^{-7} cm/s. Thus, the compacted sand-bentonite mixtures with only 3% bentonite or more are adequate to use as liners.

Relationship between swell and bentonite content is shown in Figure 7. For sand without bentonite, very small swell of 0.85% was observed. The swell of sand-bentonite mixtures significantly increases with increasing the bentonite content from 0 to 5%. The swells of mixtures with 3 and 5% bentonite were 4.30 and 9.46%, respectively. Addition of bentonite content above 5% did not increase swell of the mixtures. As shown in Figure 7, the swells of mixtures with 7 and 9% bentonite content are approximately the same at 10.32%.

The hydraulic conductivities of sand-bentonite mixtures are significantly related to their swell. As shown in Figure 7, for bentonite content up to 5%, the hydraulic conductivity significantly decreases whereas, the swell significantly increases. For bentonite content greater than 5%, the swell nearly ceases to increase and so does hydraulic conductivity.

The hydraulic conductivity of sand-bentonite mixtures was less than that of the sand without bentonite. Sand particles with bentonite adhered on their surface filled up the voids between particles resulting in smaller water flow path and decreased hydraulic conductivity. Scanning Electron Microscope (SEM) pictures with 1500 times magnifica-

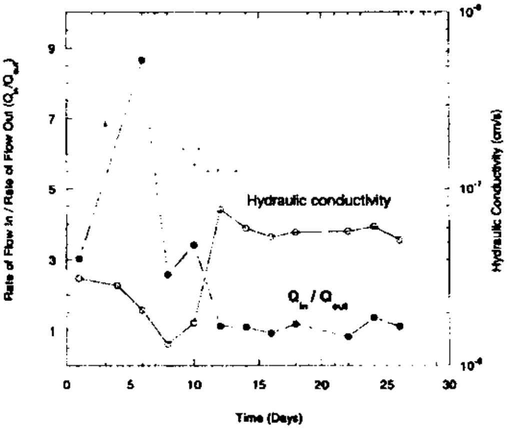


Figure 6. Ratio of inflow to outflow and hydraulic conductivity vs. time of sand with 3% bentonite mixture.

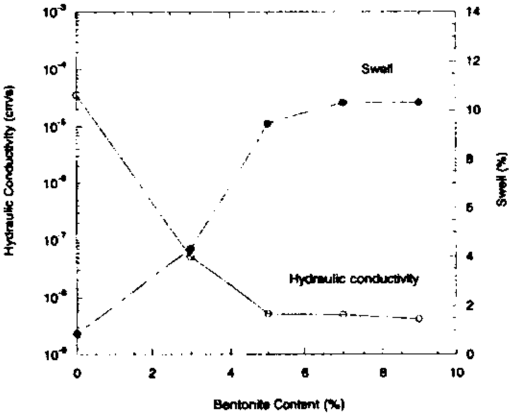


Figure 7. Hydraulic conductivity and swell vs. bentonite content of sand-bentonite mixtures.

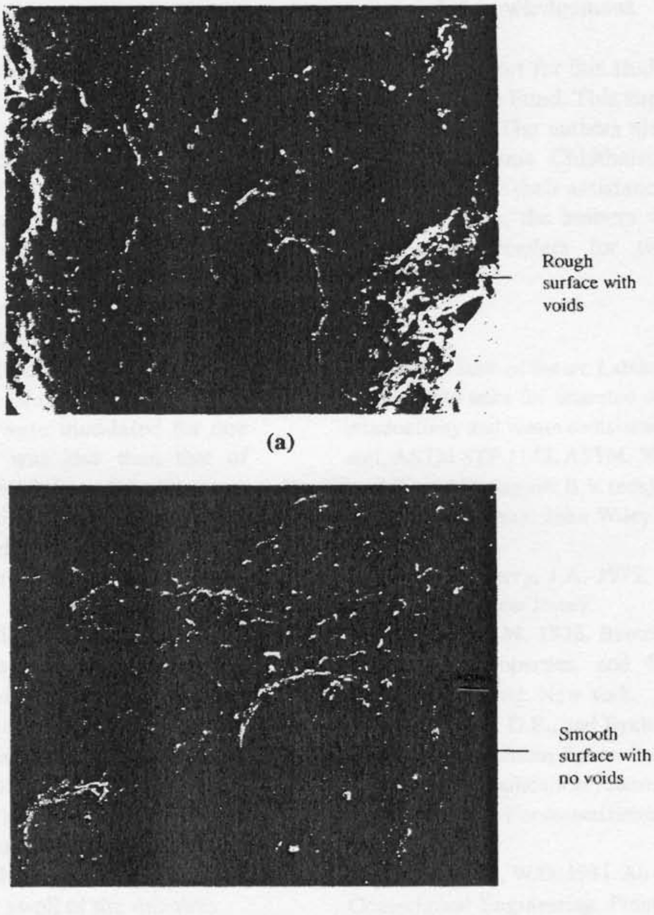


Figure 8. Scanning electron microscopy pictures with 1500 times magnification: (a) sand surface (b) sand surface with bentonite.

tion of sand surface (Figure 8a) and sand surface with the adhered bentonite (Figure 8b) shows that the sand surface was rough and full of voids. On the other hand, sand surface with the adhered bentonite was smooth and voids were filled.

Chemical resistance of the sand-bentonite mixtures was not considered in this study. Permeating sand-bentonite mixtures with high concentration solutions may results in increasing hydraulic conductivity of the mixtures. In addition, solute transport through sand-bentonite mixtures was not included in this study. Additional tests are being conducted to cover these issues in order to assess the suitability of using sand-bentonite mixtures in liners that might face with many kinds of solutions such as landfill liners.

Conclusions

The properties of compacted sand-bentonite mixtures were assessed by conducting a series of tests. From these tests, the following conclusions can be drawn.

1. Maximum dry unit weight decreases and optimum water content decreases with increasing bentonite content of the compacted sand-bentonite mixtures. Compaction test results show that when bentonite content varied from 0 to 9%, the maximum dry unit weight decreases from 19.47 to 18.56 kN/m^3 and the corresponding optimum water content increases from 9 to 12%.

2. When varying bentonite content from 0 to 9%, the friction angle of the sand-bentonite mixtures of the inundated specimen decreases drastically from 49 (very dense) to 22 degrees (very loose). The friction angle of the compacted sand-bentonite mixtures that were inundated for one week prior to shearing was less than that of specimens tested under molded condition because of the swell of the bentonite.

3. Hydraulic conductivity of the sand-bentonite mixtures decreases with increasing bentonite content. The hydraulic conductivity decreases approximately four orders of magnitude when 5% bentonite content or more are used.

4. Hydraulic conductivity of the sand-bentonite mixtures is related to the swell of the mixtures. As swell increases, the hydraulic conductivity decreases. Use of bentonite content more than 5% does not significantly decrease hydraulic conductivity of the mixtures. In contrast, adding bentonite content more than 5% results in lower shear strength and higher swell of the mixtures.

5. The common regulatory requirement for compacted soil liners states that the hydraulic conductivity should be less than 1×10^{-7} cm/s. Thus, compacted sand-bentonite mixtures with 3% bentonite content compacted at about 2% wet of optimum water contents are qualified for use as liners in hydraulic containment applications with relatively high friction angle of 38 degrees.

Acknowledgement

Financial support for this study is provided by Thailand Research Fund. This support is gratefully acknowledged. The authors also would like to thank Ms. Nantanit Chidthaisong and Mr. Pholwat Kongsom for their assistance in conducting tests. In addition, the authors would like to thank anonymous readers for their valuable comments.

References

Daniel, D.E. 1994. State of the art: Laboratory hydraulic conductivity tests for saturated soils, Hydraulic conductivity and waste containment transport in soil, ASTM STP 1142, ASTM, 30-78.

Dunkhin, S.S., and Derjaguin, B.V. (eds) 1974. Electrokinetic Phenomena, John Wiley & Sons, New York.

Freeze, R.A., and Cherry, J.A. 1979. Groundwater, Prentice Hall, New Jersey.

Grim, R., and Guven, N. 1978. Bentonite: Geology, Mineralogy, Properties, and Uses, Elsevier Science Publishing, New York.

Gleason, M.H., Daniel, D.E., and Eykholt, G.R. 1997. Calcuim and Sodium Bentonite for Hydraulic Containment Applications, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 123(5):438-445.

Holtz, R.D., and Kovac, W.D. 1981. An Introduction to Geotechnical Engineering, Prentice Hall, New Jersey.

Hunter, R.J. 1981. Zeta Potential in Colloid Science, Academic Press, Inc., New York.

Mitchell, J.K. 1993. Fundamental of Soil Behavior, 2nd ed., John Wiley & Sons, New York.

Shackelford, C.D. 1994. Waste Soil Interactions that Alter Hydraulic Conductivity, Hydraulic Conductivity and Waste Containment Transport, ASTM STP 1142, D.E. Daniel and S.J. Trautwein, eds., ASTM, West Conshohocken, Pa., 111-168.