SELF-HEALING PROPERTIES OF CLAYMAX

As part of a comprehensive testing program on Claymax, Shan and Daniel (1991) evaluated shear strength, hydraulic conductivity (both to water and various chemicals), effects of wet/dry cycling, and effects of freeze/thaw cycling.

As part of the hydraulic conductivity testing, Claymax samples were punctured with holes ranging from 0.5 to 3 inches in diameter, and then hydrated and permeated to evaluate the effect of the punctures. The data, summarized below, indicates that the sodium bentonite swelled and effectively "healed" holes up to 1 inch in diameter:

Puncture Diameter	**Hydraulic Conductivity** (cm/sec)
No punctures	2×10^{-9}
12 mm (1/2-inch)	3×10^{-9}
25 mm (1 inch)	5×10^{-9}
75 mm (3 inches)	$> 2 \times 10^{-4}$

The researchers concluded that, "small holes or imperfections are of little consequence as long as the bentonite is not impeded from swelling to fill the holes once the material is hydrated." It is important to stress that this beneficial property of sodium bentonite should not be taken as a license to mishandle or deliberately puncture GCLs during installation. Instead, it should be seen as evidence that GCLs may be able to handle small, infrequent punctures that may occur incidentally during installation without experiencing a dramatic decrease in hydraulic performance.

Results of Laboratory Tests on a Geotextile/Bentonite Liner Material

Hsin-Yu Shan
University of Texas - Austin, USA
David E. Daniel
University of Texas - Austin, USA

ABSTRACT

Laboratory tests were performed to evaluate the hydraulic properties and shearing characteristics of a bentonitic blanket. The material investigated contains sodium bentonite sandwiched between two geotextiles. The material was found to have an angle of internal friction of about 10° when the bentonite was fully hydrated and sheared under drained conditions. The hydraulic conductivity to water was sensitive to the effective confining stress applied to the bentonite but was equal to approximately 2×10^{-11} m/s (2×10^{-9} cm/s) at a low confining stress and 2×10^{-12} m/s (2×10^{-10} cm/s) at a higher confining stress. The material was found to be somewhat self healing if punctured, desiccated, or frozen under controlled laboratory conditions. The material was attacked by some chemicals, but hydration with water prior to permeation by organic chemicals led to much lower hydraulic conductivity than permeation of unhydrated material directly by organic compounds. Tests show that the material must be hydrated with water, and not concentrated organic chemicals, in order to achieve low hydraulic conductivity.

INTRODUCTION

Compacted soil is widely used as a low-permeability component of liner and cover systems for waste-disposal units. Recently, thin bentonitic blankets have been suggested, and in some cases used, as an alternative material to compacted soil. To date, the main use of bentonitic blankets has been to back up a geomembrane so that the geomembrane and bentonitic blanket will function together as a composite liner (Schubert, 1987). The advantages of composite materials in minimizing leakage rates through liners are discussed by Giroud and Bonaparte (1989).

The research described in this paper was conducted to develop a base of scientific and engineering data on one bentonitic blanket material. Tests were performed to evaluate: (1) shear strength; (2) hydraulic conductivity to water; (3) hydraulic conductivity to chemicals; and (4) effect of wet/dry and freeze/thaw cycles upon hydraulic conductivity.

BENTONITIC BLANKET INVESTIGATED

The Material. The bentonitic blanket that was selected for testing was Claymax®, which is manufactured by the James Clem Corporation, Chicago, Illinois. This material was selected because more information and experience existed for it than other bentonitic blanket materials. Claymax® consists of approximately 1 lb/ft^2 (4.9 kg/m^2) of sodium bentonite sandwiched between a slit-film, woven, polypropylene geotextile containing nylon fibers needlepunched into the geotextile and a very light, open-weave, spun-lace polyester backing that helps to hold the bentonite in place. The primary polypropylene geotextile typically weighs 3 to 6 oz/yd^2 (102 to 204 g/m^2) while the backing weighs approximately 3/4 oz/yd^2 (25 g/m^2). Other geotextiles can be substituted for special designs. A non-toxic, water-soluble, sodium-enriched, organic adhesive is used to bond the bentonite to the geotextiles. Claymax® is manufactured in sheets that measure approximately 4 m in width and 30 m in length. The sheets are placed on rolls and stored at the factory prior to delivery.

To install this material in the field, the manufacturer recommends placing the bentonitic blanket on a smooth subgrade and overlapping adjacent sheets by at least 6 in. (152 mm). The material is said to be self sealing at the overlaps: the bentonite oozes out of the openings in the geotextiles when the bentonite is hydrated, and a seal forms.

Advantages and Disadvantages of Bentonitic Blankets. Bentonitic blankets have several potential advantages over compacted soil liners: installation is simpler; less space is occupied by the liner (leaving more space for waste); repair is simpler; installation can be accomplished with light-weight equipment (soil liners are compacted with heavy rollers, which can damage underlying geosynthetics); once a material is thoroughly characterized, there should be no need to re-characterize it (each compacted soil liner material is different and must be individually studied and characterized); bentonitic blankets are not as vulnerable to desiccation as wet, compacted clays during and immediately after installation; and the cost of a bentonite blanket is more predictable than the cost of a compacted soil liner.

The main disadvantages of bentonitic blankets are that the material must be properly covered before it hydrates (rainstorms during installation can prematurely hydrate the material before it is covered), experience with the material is limited, independent test data and analysis are limited, the shear strength of hydrated bentonite is low, the thinness of the blankets makes them vulnerable to damage by puncture, the bentonite may be attacked by chemicals, and the thin blankets may be vulnerable to damage if exposed to wet/dry or freeze/thaw cycles. Despite these concerns, the advantages of bentonite blankets are compelling, and the materials deserve careful testing and analysis by the scientific and engineering communities.

MATERIALS AND METHODS

Materials. Ordinary Claymax® supplied by the manufacturer was used in this research. The polypropylene geotextile weighed approximately 4 oz/yd^2 (136 g/m^2). Test specimens were cut from larger sheets at randomly-selected locations.

Methods. The shear strength of the bentonitic blanket was evaluated with the direct shear apparatus. Circular specimens with a diameter of 60 mm were sheared through the bentonite under different normal (vertical) loads. Dry test specimens were sheared at a strain rate of 16 mm/hr. Hydrated materials were soaked at the desired normal load until vertical deformation ceased (about 2 to 3 weeks) and were then sheared at a rate of 0.02 mm/hr, which produced failure in 3 to 5 days.

Hydraulic conductivity tests were performed using flexible-wall permeameters and the general procedures outlined by Daniel et al. (1984). The test specimens were cut out from larger pieces of the material with a sharp knife. Except for two tests, the specimens were all 152 mm (4 in.) in diameter. Two tests were performed on specimens that measured 305 mm (12 in.) in diameter. Rigid porous discs were placed above and below each test specimen, with a sheet of filter paper separating the test specimen from the porous disc. The specimens were confined with a latex membrane. In addition, the specimens that were permeated with chemicals other than water were wrapped in Teflon® tape prior to placement of the latex membrane over the Teflon®. The test specimens were permeated with either distilled water, tap water, or various chemicals. All tests with chemicals other than water were performed on test specimens that had first been fully hydrated at the applied compressive stress with tap water (the hydraulic conductivity to tap water was determined prior to introducing a chemical so that the hydraulic conductivity with the chemical could be compared directly with the hydraulic conductivity for water). Most test specimens were not back-pressure saturated (because the primary interest on this research project was use of bentonitic materials as a low-hydraulic-conductivity barrier material in covers, which are not likely to ever become 100 percent saturated with water). However, some comparative tests were performed with backpressure saturation. When backpressure was used, the backpressure was 275 kPa (40 psi). In all tests, with or without backpressure, permeation continued until rates of inflow and outflow were equal (within ± 5%) and the hydraulic conductivity ceased to change with time.

Tests were falling-head tests, although the drop in head was less than 10% of the original head. The tests were performed keeping the hydraulic gradient as small as possible, keeping in mind the need to utilize a hydraulic gradient that was large enough to produce sufficient flow so that the tests could be completed in a few months time. A hydraulic gradient of approximately 20 was used for tests with water, and a gradient of 80 to 100 was used for permeant liquids other than water. Hydraulic conductivity was calculated utilizing the final thickness of the specimen, which was determined by constantly monitoring the thickness of the bentonitic blanket with a cathetometer and by checking the thickness when the test was complete and the apparatus dismantled. Test specimens were permeated at different levels of effective stress. Unless otherwise noted, the effective stress was 14 kPa for tests with water and 35 kPa for tests with chemicals other than water.

Some test specimens were artificially "punctured" and then hydrated and permeated to evaluate the effect of the puncture. The circular punctures were made by cutting three holes in the pattern shown in Fig. 1 through the test specimen. Some test specimens were fully hydrated and then desiccated. Desiccation was accomplished by air drying the material with a vertical stress of about 1 kPa acting to keep the material from shrinking as a block. (Without the small vertical stress, the wet specimens shrank during drying as a block to a smaller, uncracked, circular specimen; with the small vertical stress, the diameter decreased only slightly during desiccation, and large cracks developed in the bentonite during drying).

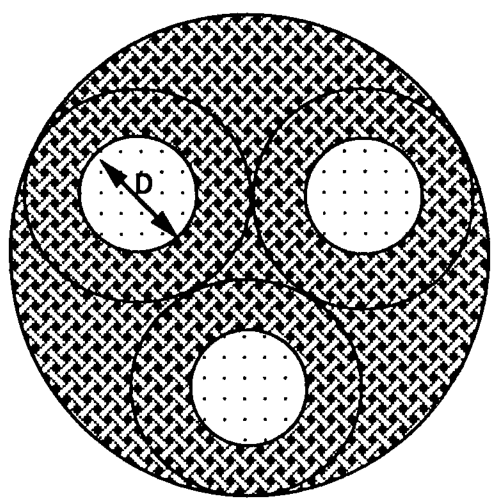

Figure 1. Pattern of the Holes Cut for Tests to Study the Effect of Punctures.

Some fully hydrated test specimens were permeated, then removed from the permeameter and frozen, and later thawed and repermeated. The specimens were frozen three-dimensionally by placing a disc-shaped test specimen in a freezer (-10° C) for approximately 24 hours. Thawing was accomplished by removing the specimen from the freezer and allowing it to thaw at room temperature (approximately 22° C).

Swelling tests were performed using a Wykam-Farrance back-loading oedometer. Each test specimen was cut to a diameter of 50 mm and the original thickness was measured. A constant vertical stress was applied to each test specimen. When the height of the specimen ceased to decrease after the vertical stress was applied (usually after just a few minutes), water was introduced into the cell and the specimen was allowed to compress or swell freely at the constant vertical stress. Changes in height were monitored continuously until the height ceased to change. The final swell or compression for a given vertical stress was recorded.

RESULTS OF SWELL TESTS

The results of swell tests are shown in Fig. 2. Under low overburden pressure, the thickness increased substantially when the bentonitic blanket was hydrated. No change in the thickness of the specimen occurred when the overburden pressure was approximately 140 kPa (3000 psf). At vertical stresses > 140 kPa, the material compressed when it was soaked. Normally, one would expect to measure a much higher swelling pressure for compacted or consolidated bentonite. However, this material is constructed from loosely placed bentonite granules. Hydration at a stress > 140 kPa evidently causes the granules to compact, which offsets swelling of the granules themselves.

RESULTS OF DIRECT SHEAR TESTS

The Mohr-Coulomb diagrams for dry and hydrated bentonitic blanket specimens are shown in Figs. 3 and 4, respectively. The failure envelopes were determined by linear regression. For dry specimens, the apparent cohesion was 26 kPa and the angle of friction was 28°. For hydrated specimens, the apparent cohesion was 4 kPa and the angle of friction was 9°. The failure envelope for hydrated specimens may be curved at low normal stress and the actual effective cohesion may be essentially zero. The manufacturer reports that unpublished test results typically indicate an angle of internal friction of about 10 to 15° for the hydrated material sheared under drained conditions.

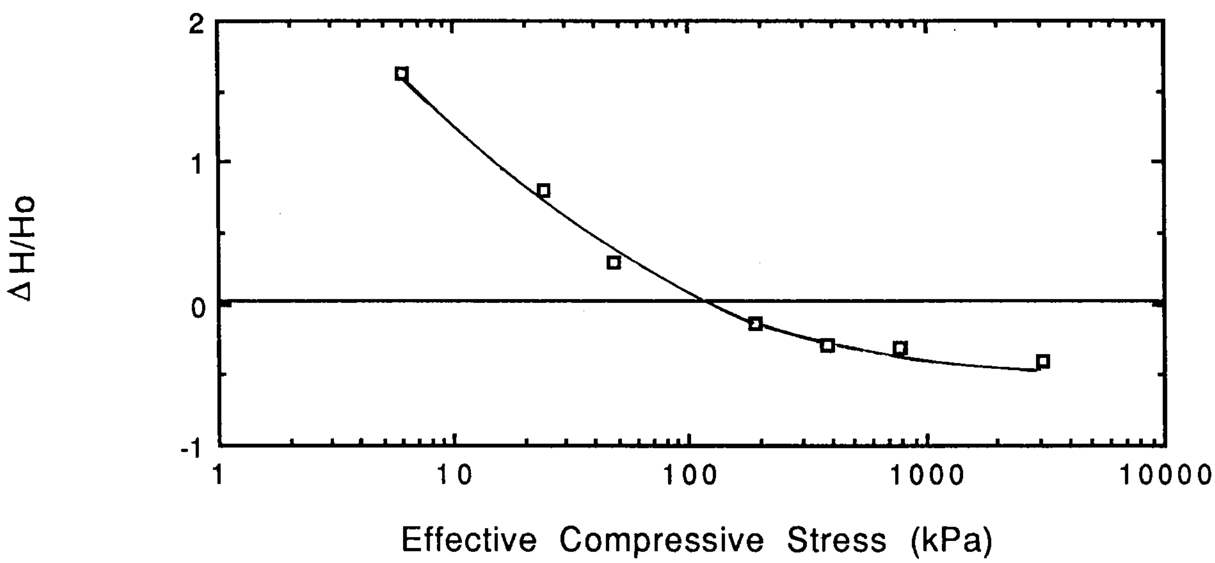

Figure 2. Height Change (ΔH) Vs. Effective Overburden Pressure from Swelling Tests (H_o = Height of Specimen before Testing)

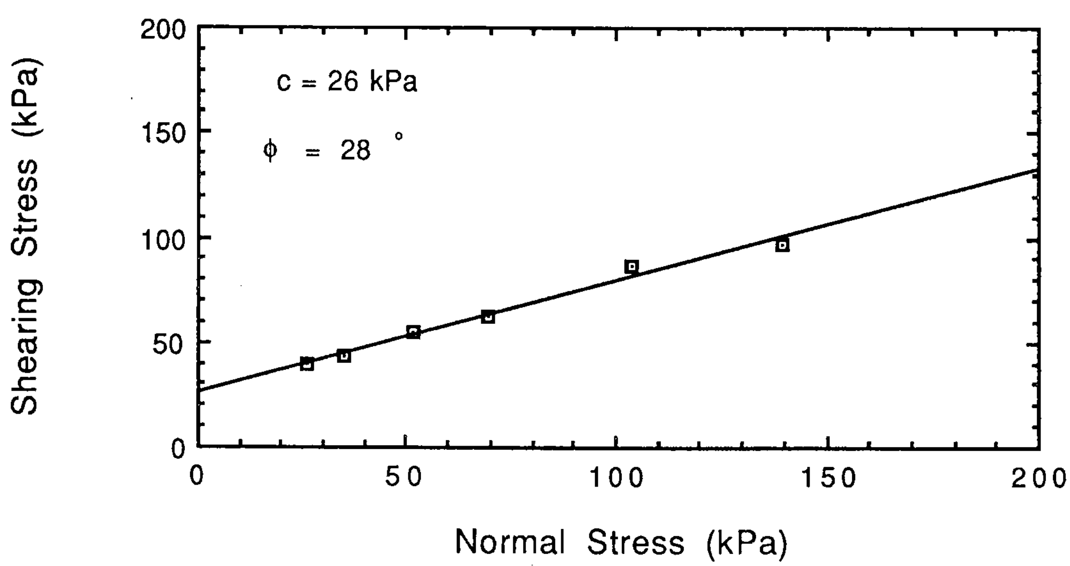

Figure 3. Mohr-Coulomb Diagram for Dry Test Specimens

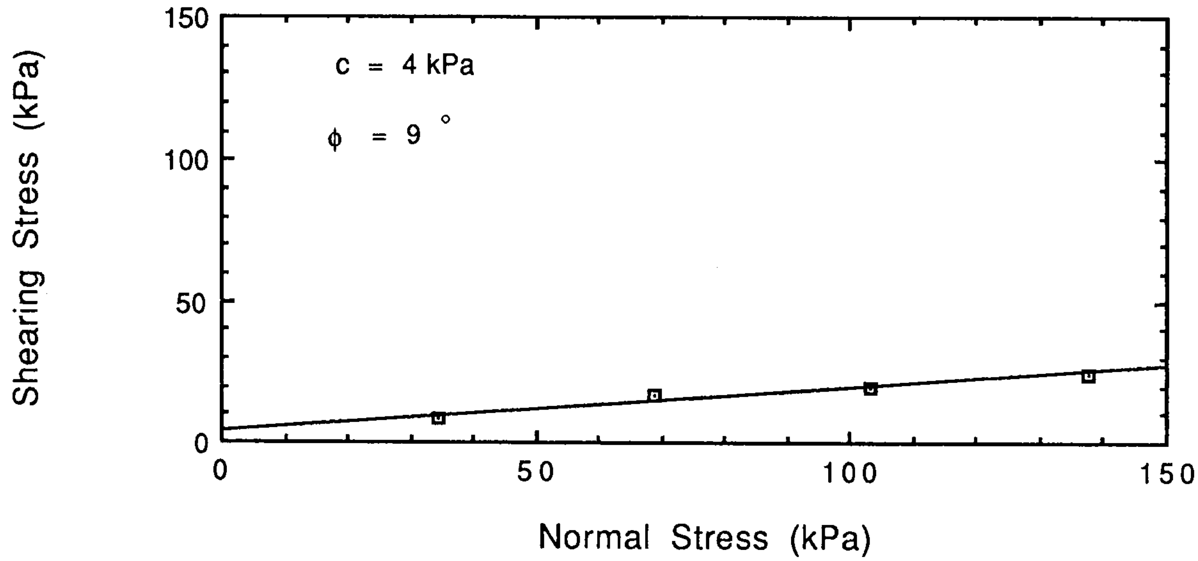

Figure 4. Mohr-Coulomb Diagram for Hydrated Test Specimens

The friction angle measured in this study is similar to the range of values reported by the manufacturer but near the low end of the range reported. An angle of internal friction of 9° is quite low, and the designer is cautioned to anchor properly this type of material when it is placed on slopes approaching or exceeding 9°.

RESULTS OF HYDRAULIC CONDUCTIVITY TESTS

Hydraulic Conductivity to Water. The relationship between hydraulic conductivity of the bentonitic blanket permeated with water and effective stress is shown in Fig. 5. At low effective stress, for example, 14 kPa (2 psi), the hydraulic conductivity was about 2×10^{-11} m/s (2×10^{-9} cm/s). When effective stress was increased to 138 kPa (20 psi), the hydraulic conductivity became as low as 3×10^{-12} m/s (3×10^{-10} cm/s). Given the order-of-magnitude variation in hydraulic conductivity shown in Fig. 5, it is very important that effective stress be reported along with the hydraulic conductivity value. This is especially true when one bentonitic blanket is compared with another; hydraulic conductivities measured at the same effective stress should be compared.

Effect of Punctures. The effects of punctures on the hydraulic conductivity of the bentonitic blanket are listed in Table 1. The test specimens were examined after dismantling the permeameters, and it was found that the bentonite had swelled and fully filled the holes that were initially 12 and 25 mm in diameter. The bentonite paste that occupied the holes was not as thick as elsewhere, and thus the overall hydraulic conductivity of the test specimens increased slightly as a result. Two out of three of the 75 mm-diameter holes did not seal themselves and were left with openings of about 12 mm diameter. The measured hydraulic conductivity fluctuated but was as high as 2 x 10^{-6} m/s. The actual hydraulic conductivity was probably much higher; the hydraulic-conductivity apparatus was not designed to measure high hydraulic conductivity accurately, and the flow rates were limited by head losses in tubings, porous discs, and the protective filter paper that separated the test specimens from the porous discs.

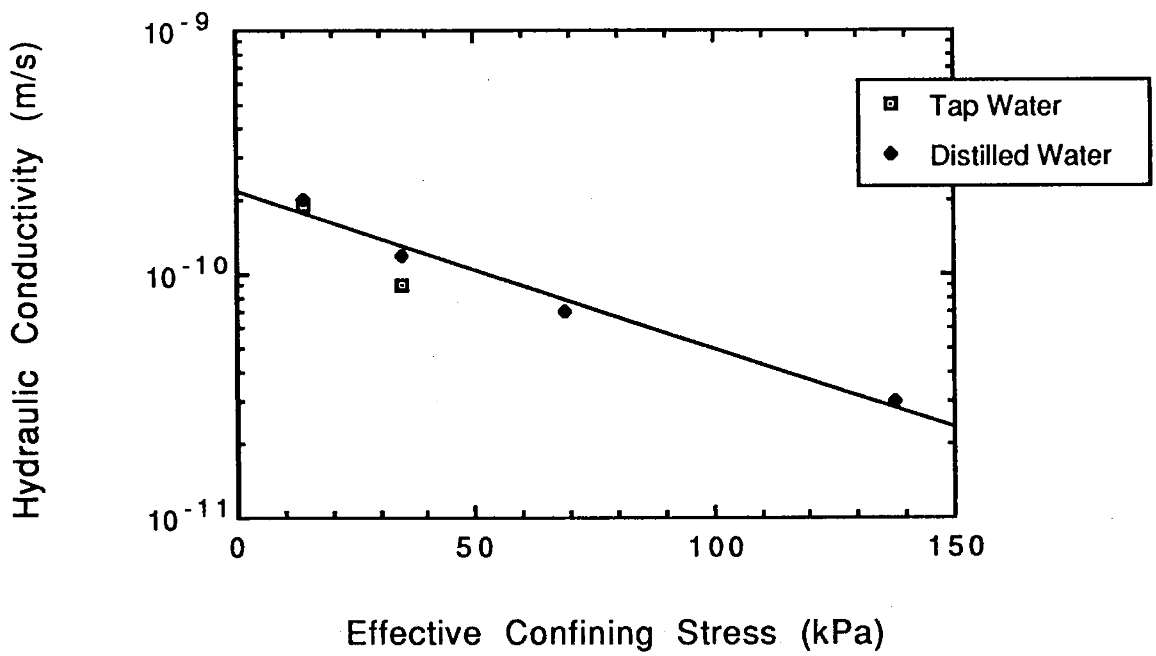

Figure 5. Relationship between Hydraulic Conductivity and Effective Confining Stress.

These tests demonstrate that under controlled laboratory test conditions, bentonitic blankets have some self-healing capability. Small holes or imperfections in the materials are probably of little consequence so long as the bentonite is not impeded from swelling to fill the holes once the material is hydrated.

Table 1 Effect of Punctures

Diameter of Punctures	Hydraulic Conductivity (m/s)
No punctures	2×10^{-11}
12 mm	3×10^{-11}
25 mm	5×10^{-11}
75 mm	$> 2 \times 10^{-6}$

Effect of Wet/Dry Cycles. The results of tests aimed at studying the effect of desiccation on hydraulic conductivity are summarized in Table 2. It was found that the hydraulic conductivity of the bentonitic blanket did not change after 3 wet/dry cycles. When the specimens had been desiccated, cracks as wide as about 2 mm were observed. A typical crack pattern is sketched in Fig. 6. The hydraulic conductivity was on the order of 1×10^{-6} m/s at the beginning of repermeation after drying. The cracks closed within a few hours and outflow stopped as bentonite hydrated. It was not until bentonite was fully hydrated that outflow started again.

Table 2 Effect of Wet/Dry Cycles

Specimen	Hydraulic Conductivity (m/s)			
	Original	After First Cycle	After Second Cycle	After Third Cycle
DS-1	1.7×10^{-11}	1.9×10^{-11}	1.7×10^{-11}	1.8×10^{-11}
DS-2	1.9×10^{-11}	1.7×10^{-11}	2.0×10^{-11}	-
DS-3	1.8×10^{-11}	1.7×10^{-11}	-	-

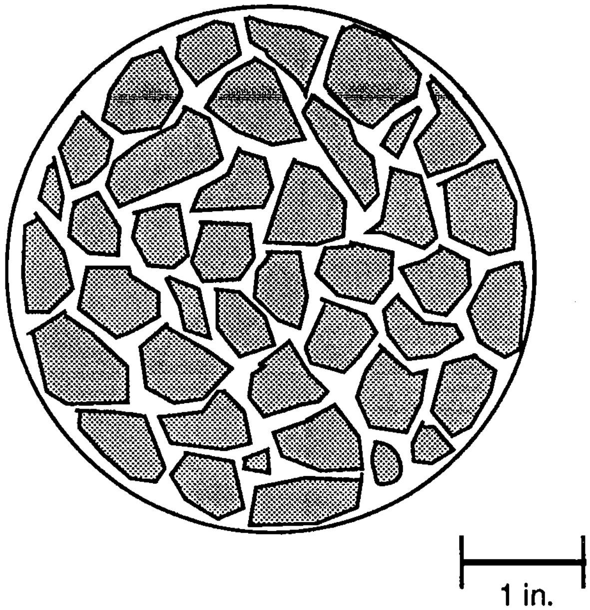

Figure 6. Typical Crack Pattern in Desiccated Specimens.

These tests, like the puncture tests described earlier, point to the self-healing capability of the bentonitic material. So long as small punctures or cracks did not fill with a permeable material, the bentonite self-healed when hydrated with water.

Effect of Freeze/Thaw Cycles. The hydraulic conductivity of the test specimen before freezing was 2×10^{-11} m/s. After five freeze/thaw cycles, the hydraulic conductivity of the specimen was found to still be 2×10^{-11} m/s. Under these conditions, freeze/thaw had no effect.

Hydraulic Conductivity to Chemicals. The results of hydraulic conductivity tests with various chemicals are summarized in Table 3. All of the test specimens were first permeated with tap water for about 1.5 months and were then permeated with the chemicals for about 6 months. The results of the control test with tap water as the permeant liquid are shown in Fig. 7. The hydraulic conductivity increased with time initially but stabilized at 7×10^{-11} m/s (7×10^{-9} cm/s) after 1 pore volume of flow. (A pore volume of flow is defined as the cumulative quantity of flow divided by the volume of water contained in the pores of the bentonitic material.)

Table 3 Results of Hydraulic Conductivity Tests with Different Chemicals

Liquids	Total Pore Volumes of Flow of Chemical	Hydraulic conductivity (m/s) To tap water	Final
Methanol	0.6	7×10^{-12}	3×10^{-12}
50% methanol	2.2	7×10^{-12}	9×10^{-12}
Heptane	0.2	7×10^{-12}	1×10^{-12}
Sulfuric acid	3.1	8×10^{-12}	6×10^{-13}
0.01 N $CaSO_4$	2.2	9×10^{-12}	1×10^{-11}
0.5 N $CaCl_2$	24.2	9×10^{-12}	8×10^{-11}
Tap water	2.7	-	7×10^{-12}

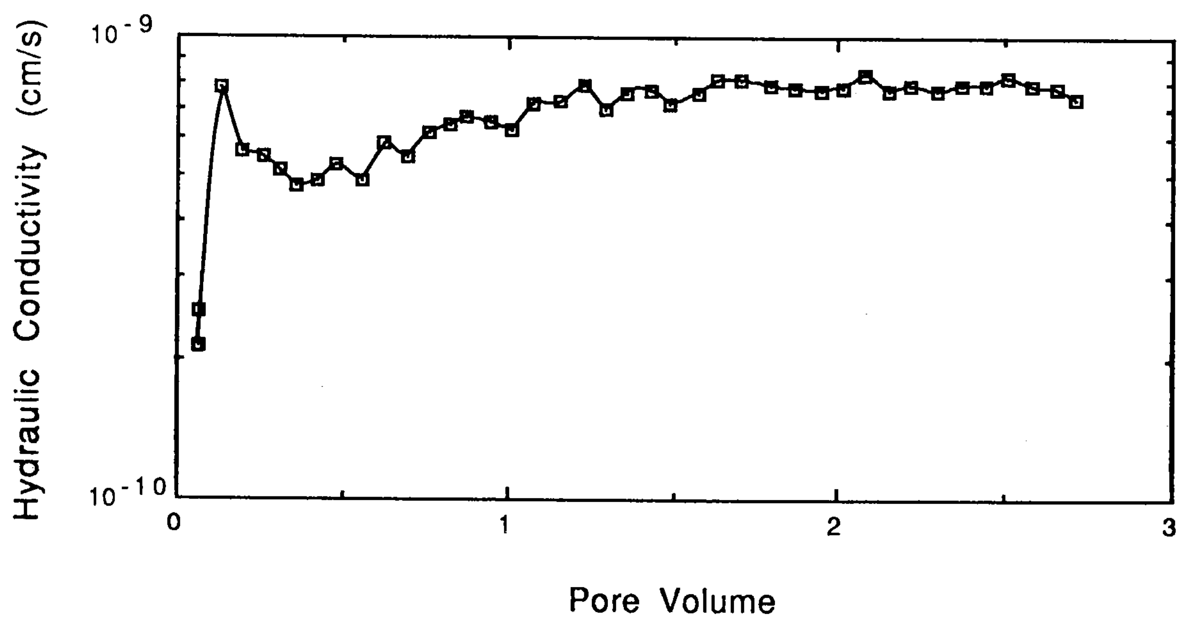

Figure 7. Hydraulic Conductivity to Tap Water

Pure methanol was chosen to represent a neutral, polar organic chemical. The hydraulic conductivity of the bentonitic blanket decreased to 3 x 10^{-12} m/s (3 x 10^{-10} cm/s) after 0.6 pore volumes of effluent fluid was collected (Fig. 8). The thickness of the specimen increased about 20% after the permeant liquid had been switched to pure methanol. The result was contradictory to the findings of most other investigators (Brown and Anderson, 1983; Foreman and Daniel, 1987; Uppot and Stephenson, 1989) who found that methanol increased the hydraulic conductivity of clayey soils. However, Fernandez and Quigley (1988) found that the hydraulic conductivity of their compacted clay sample decreased when permeated with pure methanol in flexible-wall permeameters. Uppot and Stephenson (1989) found that the hydraulic conductivity of kaolinite and Mg-montmorillonite decreased during the first pore volume of flow when permeated with pure methanol. Since less than 1 pore volume of methanol passed through the test specimen, it is possible that hydraulic conductivity of the bentonitic blanket would have increased had there been more flow.

The hydraulic conductivity of the bentonitic blanket to 50% methanol solution was found to be almost the same as that to water (Fig. 9). Bowders and Daniel (1987) observed the same results from kaolinite and illite-chlorite permeated with 50% methanol.

Heptane was selected as a representative neutral, nonpolar organic. As recommended by Foreman and Daniel (1986) the test specimen was permeated with pure methanol before introducing heptane into the specimen to avoid surface-tension exclusion of the heptane from soil. As shown in Fig. 10, heptane was introduced into the specimen after it had been permeated with 0.44 pore volumes of pure methanol. The hydraulic conductivity was as low as 1 x 10^{-12} m/s (1 x 10^{-10} cm/s) and only 0.22 pore volumes of effluent fluid was collected after 3 months of permeation with heptane.

The hydraulic conductivity of the bentonitic blanket to sulfuric acid went through changes that are typical for soils permeated with inorganic acids. After sulfuric acid was introduced into the specimen, the outflow rate, Q_{out}, became larger than the inflow rate, Q_{in} (Fig. 11). Water was being driven out of the material, and thickness of the specimen decreased. The hydraulic conductivity increased slightly to 2 x 10^{-11} m/s (2 x 10^{-9} cm/s) in the initial stages of acid permeation (Fig. 12). The effluent liquid was brownish yellow, and a small amount of solids was present, which provided evidence of dissolutioning. Later, probably because precipitates clogged the pores, the hydraulic conductivity decreased to as low as 6 x 10^{-13} m/s (6 x 10^{-11} cm/s). Also, the pH of the effluent liquid decreased continuously during the test (Fig. 13). Had the test continued to very high pore volumes of flow to exhaust the buffering capacity of the soil, the hydraulic conductivity probably would have eventually increased.

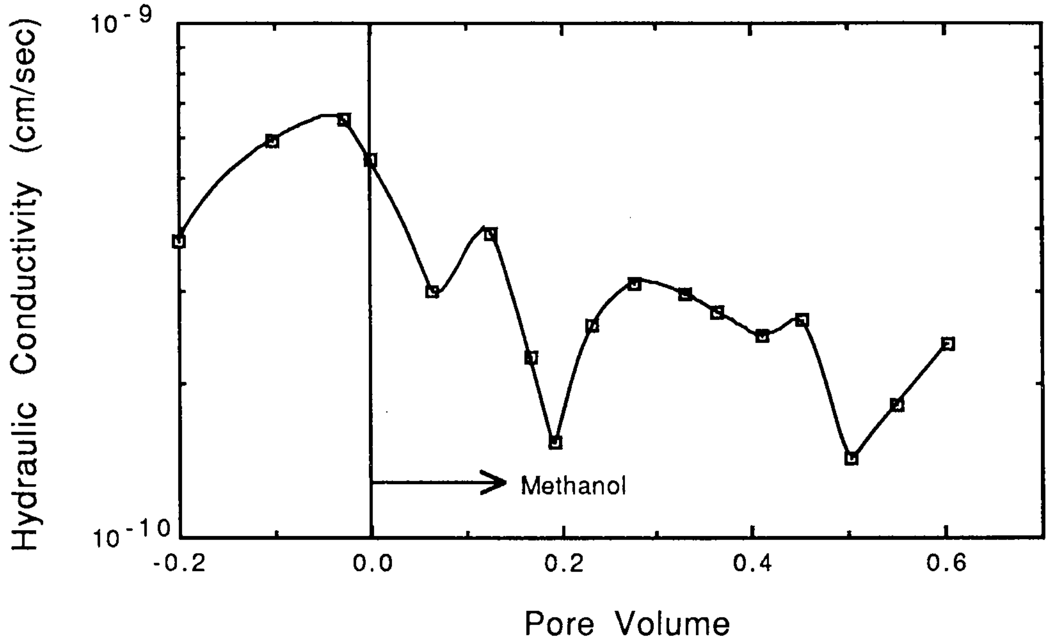

Figure 8. Hydraulic Conductivity to Pure Methanol

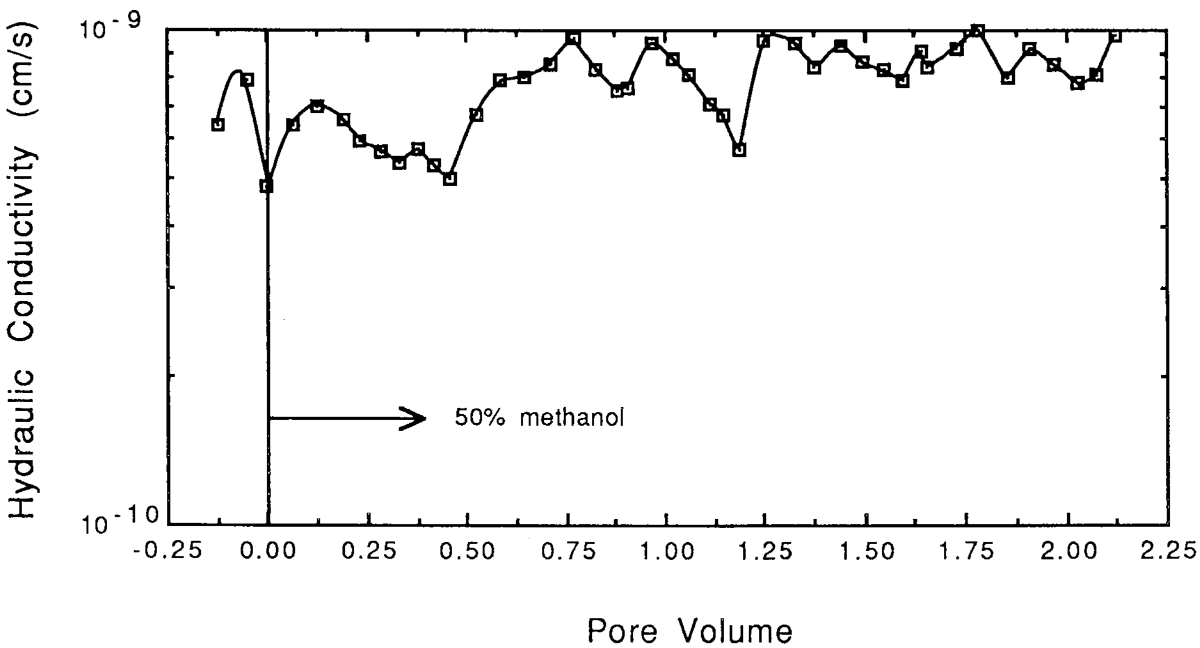

Figure 9. Hydraulic Conductivity to 50% Methanol/Water Solution

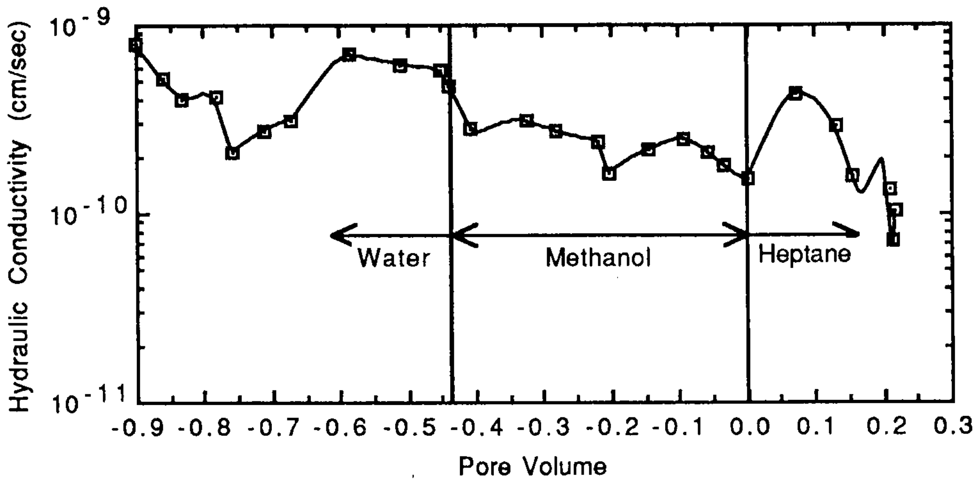

Figure 10. Hydraulic Conductivity to Heptane

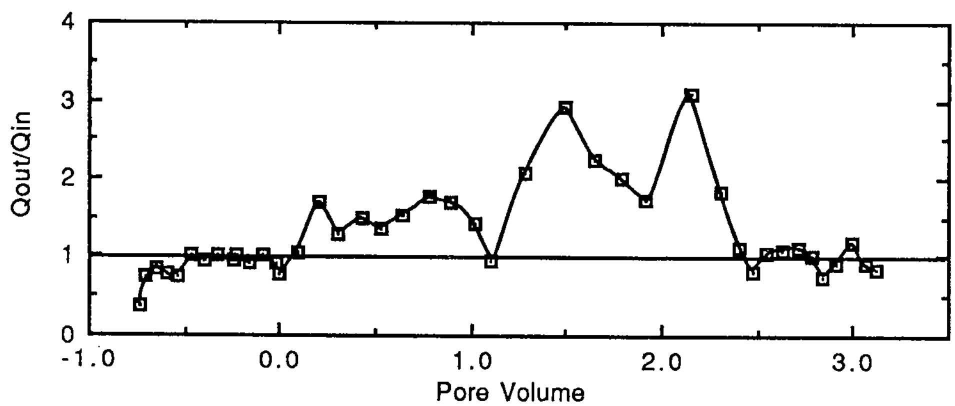

Figure 11. Variation of Outflow/Inflow Ratio from Test with Sulfuric Acid (pH=1.5)

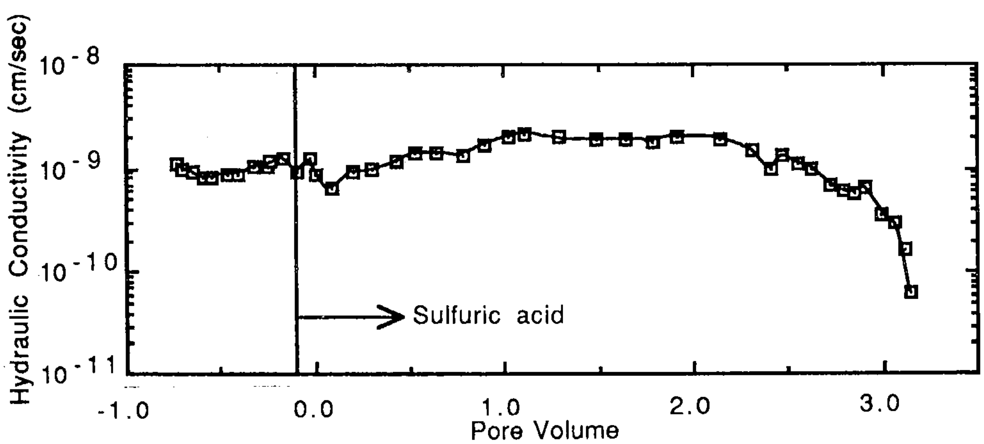

Figure 12. Hydraulic Conductivity to Sulfuric Acid (pH=1.5)

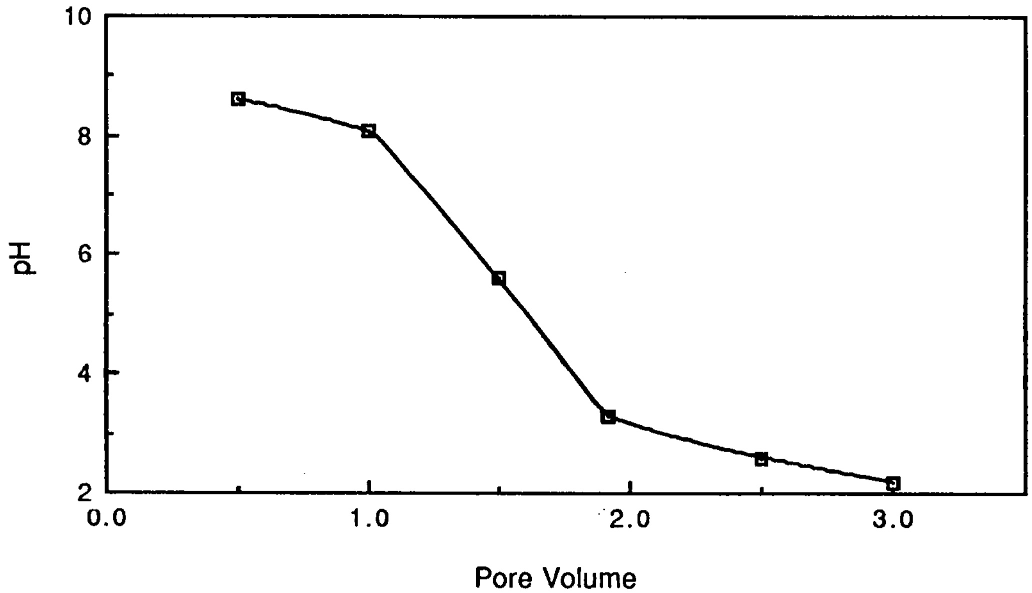

Figure 13. pH Value of Effluent Liquid from Test with Sulfuric Acid

The 0.01 N calcium sulfate solution had little influence on the hydraulic conductivity of the bentonitic blanket. The final value of hydraulic conductivity was found to be 1 x 10^{-11} m/s (Fig. 14) and there was little change over time. During the test period, a large amount of gas was produced, probably by anaerobic bacteria. Gas occupied the pore spaces of the porous disk at the effluent end and impeded the flow. The tubings were repeatedly flushed to drive to gas out. The permeant was switched to 0.01 N calcium chloride solution in an attempt to minimize the problem of the gas formation from the production of H_2S. However, the problem remained. The periodic generation and removal of gas was probably the cause of the fluctuations shown in Fig. 14.

The hydraulic conductivity of the test specimen permeated with 0.5 N calcium chloride solution increased about an order of magnitude to 8 x 10^{-11} m/s (Fig. 15). The outflow rate was larger than inflow rate throughout the test and especially between 0 and 2 pore volumes of flow (Fig. 16). The thickness of the specimen decreased 46%. It appears that calcium replaced sodium, which reduced the thickness of adsorbed water layer and caused the bentonite to shrink.

It should to be mentioned that during the period in which the specimens were permeated with water, although no backpressure was applied, the specimens took in water from both the influent and effluent ends. There was no outflow for approximately four weeks. The same phenomenon was also observed by Edil and Erickson (1985) when they permeated specimens of bentonite-sand mixture. They

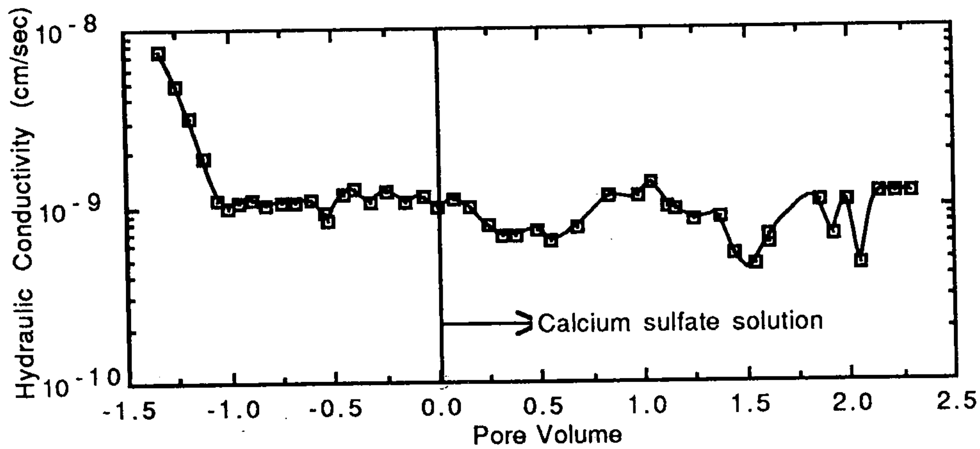

Figure 14. Hydraulic Conductivity to 0.01 N Calcium Sulfate Solution

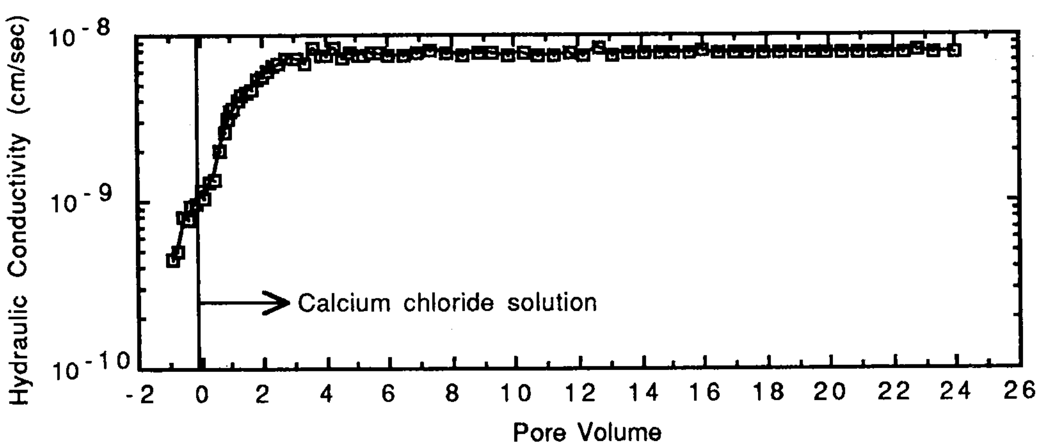

Figure 15. Hydraulic Conductivity to 0.5 N Calcium Chloride Solution

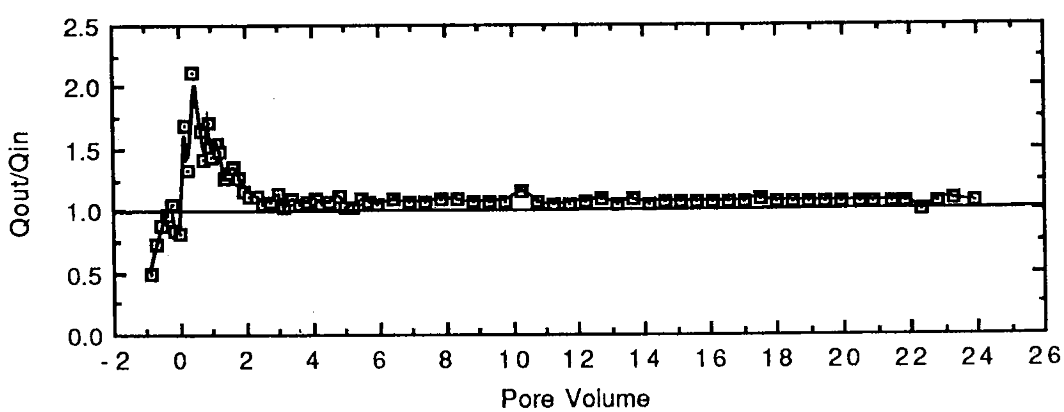

Figure 16. Variation of Outflow/Inflow Ratio from Test with 0.5 N Calcium Sulfate Solution

point out that highly active bentonite may have a threshold water content below which all water entering the specimen is absorbed.

It should also be mentioned that much different results were obtained when dry test specimens were permeated directly with concentrated organic chemicals, like methnaol and heptane, rather than prehydrated with water prior to permeation. When the bentonitic blanket was exposed directly to a concentrated organic chemical, the material did not attain a hydraulic conductivity below 1 x 10^{-7} m/s (1 x 10^{-5} cm/s) even after 10 pore volumes of flow. The bentonite must be hydrated with water prior to exposure to concentrated organic liquids in order to achieve low hydraulic conductivity. For bentonitic blankets used in liner systems, the ability of the material to hydrate and achieve low hydraulic conductivity when exposed to leachate should be evaluated.

CONCLUSIONS

In this study, several characteristics of a bentonitic blanket (Claymax®) were investigated. The hydraulic conductivity to water was found to be 2 x 10^{-11} m/s at low confining stress (14 kPa) and 3 x 10^{-12} m/s at a confining stress at 138 kPa.

The material swells at pressures ≤ 140 kPa. When fully hydrated and sheared under drained conditions, the angle of internal friction was found to be approximately 9°.

The material was found to be capable of sealing punctures of diameters up to 25 mm with only a slight increase in hydraulic conductivity. Desiccation cracks formed when saturated material was dried, but when the material was rewetted, the cracks closed and the hydraulic conductivity returned to the original, low value. Hydraulic conductivity of the material appeared to be not affected by freeze/thaw action.

Results from hydraulic conductivity tests with chemicals showed that a diluted organic chemical did not affect the hydraulic conductivity of the material. Pure organic chemicals and an inorganic acid caused decreases in hydraulic conductivities, but the period of testing was probably too short to allow observation of the potential long-term damaging effects of these chemicals. When the material was permeated with 0.5 N calcium chloride solution, an order of magnitude increase in hydraulic conductivity occurred and the material underwent shrinkage. The increase in hydraulic conductivity and bulk shrinkage were evidently caused by the replacement of sodium ions in the bentonite with calcium ions. All tests with chemicals were performed on test specimens that had been pre-soaked with tap water.

The tests described in this paper show that thin bentonitic blankets have low hydraulic conductivity to water, resist chemical attack when prehydrated with water, and have outstanding self-healing characteristics. Low shear strength of the hydrated material was observed. Clearly these types of materials have some desirable characteristics and warrant further testing and evaluation.

ACKNOWLEDGEMENTS

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