HYDRAULIC CONDUCTIVITY OF THREE GEOSYNTHETIC CLAY LINERS

The hydraulic conductivity of three geosynthetic clay liners (GCLs) was measured. The three GCLs investigated were: Bentomat® ST, a Claymax® GCL and a Paraseal/Gundseal GCL. Bentomat ST consists of sodium bentonite sandwiched between a woven and a nonwoven geotextile that are needlepunched together. The Claymax GCL tested consisted of sodium bentonite sandwiched between two woven geotextiles of which the lower geotextile was a lightweight, open-weave, spun-lace polyester with large openings. A water-soluble glue was mixed with the bentonite to hold the components together. The Paraseal/Gundseal GCL consisted of sodium bentonite mixed with adhesive attached to a 20-mil HDPE geomembrane.

Two types of tests were performed, laboratory flexible-wall hydraulic conductivity tests and bench-scale tank tests. Flexible-wall hydraulic conductivity tests were only performed on Bentomat ST GCL. These values were compared with other results reported in literature. Hydraulic conductivities for all three GCLs had a tendency to decrease with increasing effective stress.

Bench-scale tank tests were performed at low effective stress (1.3-1.5 psi) on individual sheets of the GCLs, on overlapping pieces of GCLs, and on composite liners consisting of a punctured geomembrane overlying a GCL. Hydraulic conductivities of Bentomat and Claymax GCLs were in the range of 10^{-10} to 10^{-8} cm/s. No flow was measured through the Paraseal/Gundseal GCL. The hydraulic conductivity of overlapping GCLs were about the same as those of the control samples with no overlap; an effective hydraulic seal developed along the overlaps in all the materials tested. Performance of the punctured geomembrane-GCL composites varied. Performance was best when the punctured geomembrane was directly placed against bentonite and no geotextile separated the punctured geomembrane from the bentonite. For those GCLs with geotextiles on both sides, problems with migration of bentonite into the underlying drainage layer were encountered when no separation geotextile was used between the GCL and drainage layer. However, with a 10.5 oz./sqyd. nonwoven geotextile separating the drainage layer from the GCL, problems with migration of bentonite were eliminated.

The Claymax GCL used in this experiment was redesigned in the mid 1990s when CETCO acquired Claymax from Clem Corporation. The current Claymax, called 200R, has replaced the open-weave polyester geotextile with a tighter polypropylene geotextile.

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Hydraulic Conductivity of Three Geosynthetic Clay Liners

By Paula Estornell[1] and David E. Daniel[2]

Abstract: The hydraulic conductivity of three 2.9 m^2 (32 sq ft) geosynthetic clay liners (GCLs) was measured. Tests were performed on individual sheets of the GCLs, on overlapped pieces of GCLs, and on composite liners consisting of a punctured geomembrane overlying a GCL. Hydraulic conductivities of two of the GCLs were in the range of 10^{-10} to 10^{-8} cm/s. No flow was measured through the third GCL, but the conductivity was obviously very low ($\ll 10^{-7}$ cm/s). The hydraulic conductivities of overlapped GCLs were about the same as those of the control samples with no overlap; an effective hydraulic seal developed along the overlaps in all of the materials tested. Performance of the punctured geomembrane-GCL composites varied—performance was best when the punctured geomembrane was placed directly against bentonite and no geotextile separated the punctured geomembrane from the bentonite. For those GCLs with geotextiles on both sides, problems with migration of bentonite into the underlying drainage layer were encountered when inadequate filtration was provided. However, with a suitable filtration layer separating the drainage layer from the GCL, problems with migration of bentonite were eliminated.

Introduction

A layer of low-hydraulic-conductivity compacted soil is a required component of most liner and cover systems at waste-containment facilities. In the past few years, several thin, prefabricated, clay blankets, called geosynthetic clay liners (GCLs), have been developed and proposed as an alternative to compacted clay in liner and cover systems. Geosynthetic clay liners may supplement required components in waste-containment units or, as proposed by some, replace part or all of the low-hydraulic-conductivity compacted-soil liner (Daniel and Koerner 1991). Daniel and Estornell (1990), Eith et al. (1990), Grube (1991), and Grube and Daniel (1991) review advantages and disadvantages of GCLs for various waste-containment applications.

The research described in this paper was performed to develop technical information on the engineering properties of GCLs, to determine the hydraulic properties of GCLs and the overlapped seams, and to evaluate the composite behavior of geomembrane-GCL composite liners.

Geosynthetic Clay Liners

Three geosynthetic clay liners (GCLs) were investigated: Bentomat, Claymax, and Paraseal/Gundseal. A fourth GCL, Bentofix (Scheu et al. 1990), manufactured in Germany, was not included in this study. The three GCLs investigated are shown in Fig. 1.

Bentomat is manufactured by the Colloid Environmental Technologies

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Note. Discussion open until March 1, 1993. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 20, 1991. This paper is part of the *Journal of Geotechnical Engineering*, Vol. 118, No. 10, October, 1992. ©ASCE, ISSN 0733-9410/92/0010-1592/$1.00 + $.15 per page. Paper No. 2605.

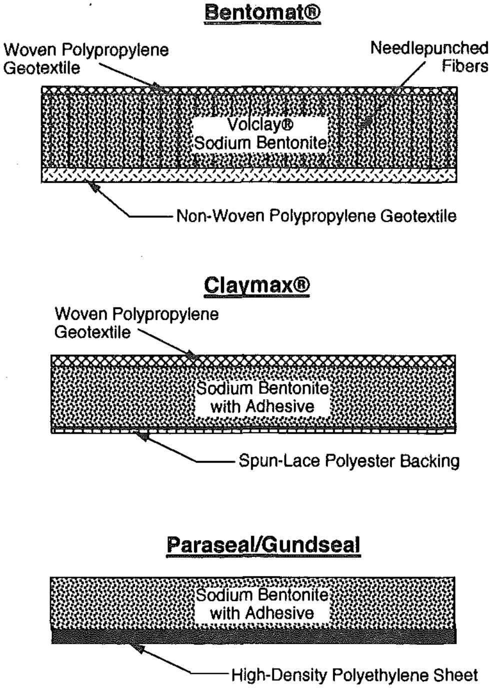

FIG. 1. Geosynthetic Clay Liners

Co. (CETCO) in Villa Rica, Georgia. The material that was tested consisted of 4.9 kg/m^2 (1 lb/sq ft) of untreated, Volclay sodium bentonite ("CS" grade) sandwiched between woven and nonwoven geotextiles that are needle punched together (Fig. 1) to contain the bentonite and to enhance in-plane shear strength.

Claymax is manufactured by the James Clem Corp. in Fairmont, Georgia. The material that was tested consisted by 4.9 kg/m^2 (1 lb/sq ft) of sodium bentonite sandwiched between two woven geotextiles (Fig. 1). The lower geotextile is a lightweight, open-weave, spun-lace polyester with large openings. A water-soluble glue is mixed with the bentonite to hold the components together until the GCL has been installed.

Paraseal/Gundseal is manufactured by Gundle Lining Systems, Inc., and Paramount Technical Products, Inc., (see Appendix I) in Spearfish, South Dakota. The material that was tested consisted of 4.9 kg/m^2 (1 lb/sq ft) of sodium bentonite mixed with an adhesive and attached to a 0.5 mm (20 mil) thick high-density polyethylene (HDPE) geomembrane (Fig. 1). Material tested in this study was Paraseal, but Paraseal and Gundseal are functionally identical.

Geosynthetic clay liners are manufactured in panels with widths of 4–5 m (13–17 ft) and lengths of 25–60 m (80–200 ft). The panels are placed on rolls at the factory and unrolled at the time of installation. The panels are overlapped 75–225 mm (3–9 in.) during installation and are said to be self-sealing at the overlap. Fig. 2 shows a sketch of the overlap zones. In the case of Bentomat, additional sodium bentonite is placed along the overlap at a rate of 0.4 kg/m (0.25 lb/ft). The bentonite penetrates the pores of the geotextiles, and the manufacturer says it causes the material to self-seam when the bentonite hydrates.

Claymax panels are normally placed with the open-weave, polyester backing facing downward (Fig. 2). When the bentonite hydrates, the manufacturer states that the bentonite oozes out through the openings in the geotextiles and causes the material to self-seal.

With Gundseal, the GCL can be placed with the bentonite facing upward or, as shown in Fig. 2, downward. The material is said to be self-sealing at the overlap. Although no mechanical joining of overlapped seams is necessary for any of the GCLs, the HDPE sheets in Gundseal can be welded together along the overlaps, if desired, but a thicker HDPE sheet than the usual 0.5-mm (20-mil) sheet would be required. Gundseal would be placed with the bentonite facing upward if a separate, conventional geomembrane lining is to be placed on top of the GCL.

More information about GCLs is available from the manufacturers and from Schubert (1987), Daniel and Estornell (1990), Shan (1990), Eith et al. (1990), Bruton (1991), Estornell (1991), Grube (1991), Grube and Daniel (1991), Shan and Daniel (1991), and Trauger (1991).

Experimental Methods

Steel tanks, shown schematically in Fig. 3, were fabricated for bench-scale hydraulic conductivity tests. The tanks measured 2.4 m (8 ft) long, 1.2 m (4 ft) wide, and 0.9 m (3 ft) tall. A 13 mm (0.5 in.) diameter drainage

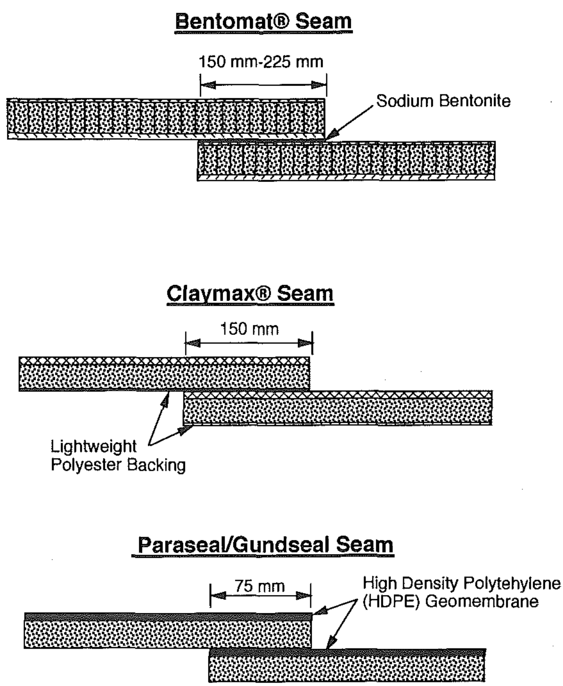

FIG. 2. Configuration of Overlapped Seams with Manufacturers' Minimum Recommended Overlap Width

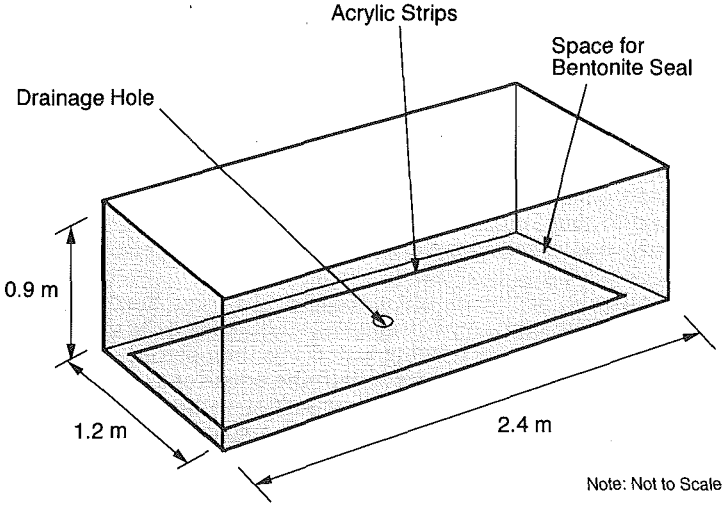

FIG. 3. Orthogonal View of Tank Used for Bench-Scale Hydraulic Conductivity Tests

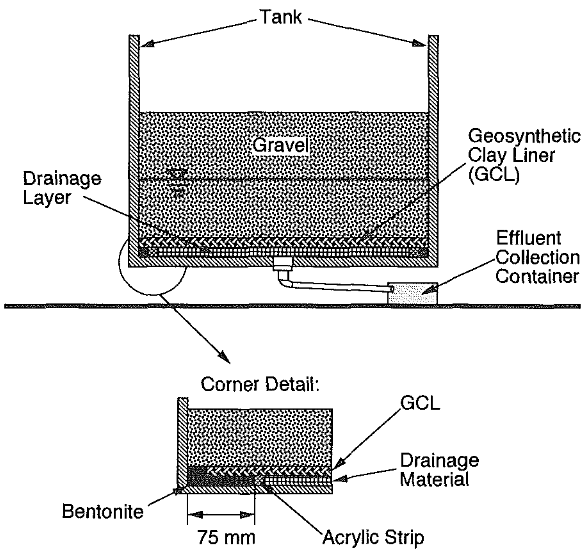

FIG. 4. Cross-Sectional View of Configuration of Materials in Tanks

hole was drilled in the center of the base (Fig. 3) of each tank. The inside walls of the tanks were coated with epoxy. The tanks were raised about 150 mm (6 in.) off the floor with wooden supports.

Acrylic fittings with PVC elbows and flexible plastic tubes were attached to the drainage holes at the bottom of each tank, as shown in Fig. 4. This outlet system provided a closed channel for effluent drainage. In addition, 6.4 mm by 6.4 mm (1/4 in. by 1/4 in.) acrylic strips were glued to the bottoms of the tanks in a rectangular pattern, as shown in Fig. 3. The acrylic strips provided a 75 mm (3 in.) wide space around the edges of the tanks to retain bentonite that was placed to seal the GCLs against the edges of the tanks.

To conduct a test, a 2.3 m (7.5 ft) long by 1.1 m (3.5 ft) wide sheet of geotextile/geonet/geotextile composite (Gundnet) was centered and placed on the bottom surface of the tank. The Gundnet was cut smaller than the area of the tank to create a 75 mm (3 in.) wide space between the drainage material and edge of the tank to accommodate a bentonite seal (Fig. 4). The geotextile that separated the geonet from the GCLs was a 200 g/cm^2 (6 oz/sq yd), nonwoven geotextile with an apparent opening size of 0.15–0.25 mm.

Next, dry bentonite was placed in the space between the drainage material and the walls of the tank. A photograph of the seal and the drainage material is shown in Fig. 5. The GCL being tested was then placed over the drainage composite and bentonite edge seal, with the edges of the GCL either going to the edges of the steel tank (first test set) or within 25 mm (1 in.) of the edge of the tank (subsequent test sets). The spaces between the edges of the GCLs and the walls of the tank were filled with dry bentonite.

Next, a 300 or 600 mm (1 or 2 ft) thick layer of gravel was placed over the GCL with a front-end loader. The gravel had dry and saturated unit weights of 15.4 and 19.3 kN/m^3 (98 and 123 pcf), respectively, and a hydraulic conductivity of 5 cm/s (Estornell 1991). The tank was then slowly filled with water over a period of several days. The depth of water was then kept constant. The first set of tests was performed with a 300 mm (1 ft) thick gravel layer and 600 mm (2 ft) of water ponded on the GCLs. These conditions produced a calculated vertical effective stress of 3 kPa (0.4 psi) at the top of the GCL and 9 kPa (1.3 psi) at the bottom. The vertical effective stress was increased in the second and subsequent series of tests by increasing the thickness of gravel to 600 mm (2 ft) and decreasing the water depth to 300 mm (1 ft); the calculated effective stress acting on the top and bottom surface of the GCLs was 8 kPa (1.1 psi) and 10 kPa (1.5 psi), respectively.

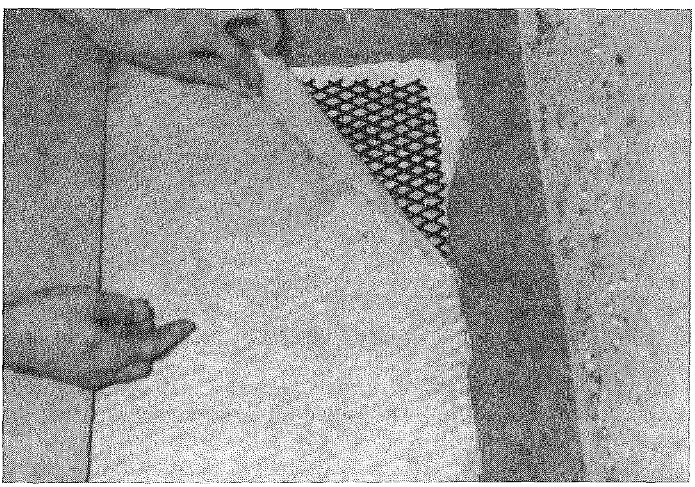

FIG. 5. Drainage Material (Geotextile/Geonet Composite) and 75 mm (3 in.) Wide Bentonitic Edge Seal

Effluent water passing through the drainage hole was collected and weighed to determine the flux of water. Corrections were made to account for evaporation of water from collection pans. Tests were continued until the flux was steady. Except for Gundseal, steady flow was achieved after one to two and a half months, at which point outflow readings varied by no more than $\pm 10\%$. For Gundseal, no outflow from any of the tanks occurred during more than five months of testing.

Hydraulic conductivity was calculated from Darcy's law for those GCLs that produced flow. It was assumed that the head loss was constant and that the pressure head was zero on the base of the GCL. The hydrated thicknesses of the GCLs (9.4 mm for Bentomat and 16–18 mm for Claymax), which were used to calculate hydraulic conductivity, were determined from laboratory swelling tests. Hydraulic gradient was typically in the range of 30–60.

Three types of tests were performed (Fig. 6). One type of test was a control test on individual sheets of GCL material that had no overlap. The second type of test was on overlapped sheets of GCL material. For Bentomat, sodium bentonite was placed along the overlap at the manufacturer's recommended rate, as shown in Fig. 7. Placement of Claymax overlaps is shown in Fig. 8. Placement of a Gundseal overlap is shown in Fig. 9 for the test with the HDPE facing upward.

At least one test was performed using the minimum overlap width rec-

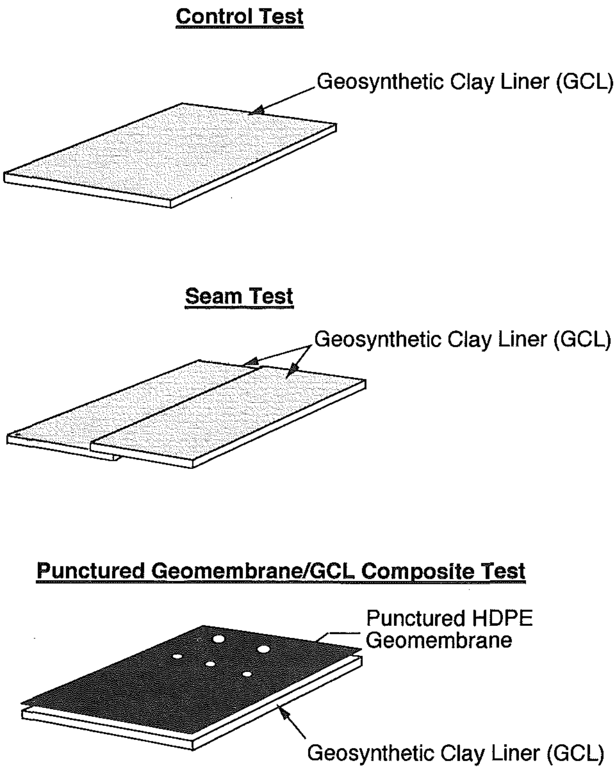

FIG. 6. Schematic Diagram of Types of Tests Performed in Tanks

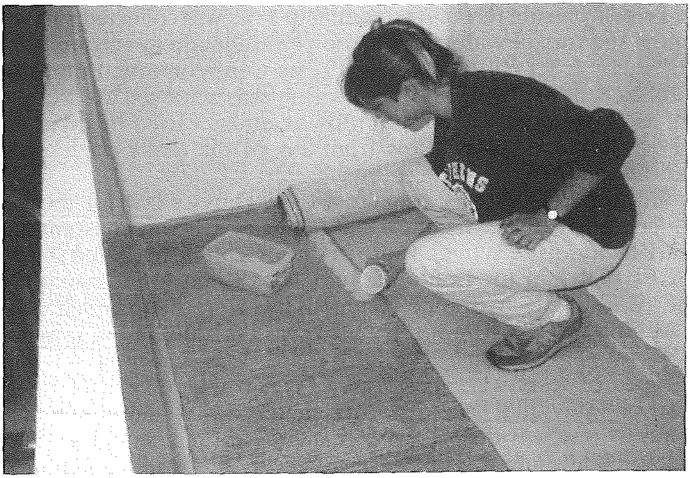

FIG. 7. Placement of Bentomat with Overlapped Seam (Note Spreading of Granular Bentonite along Overlapped Zone)

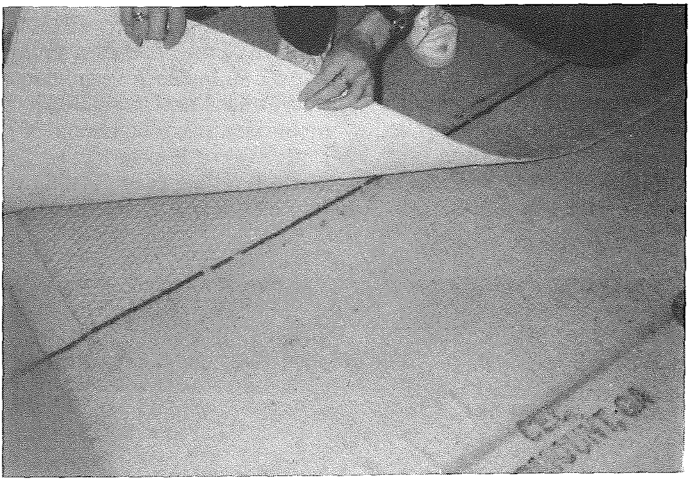

FIG. 8. Placement of Claymax with Overlapped Seam

ommended by the manufacturer [150 mm (6 in.) for Bentomat and Claymax, and 75 mm (3 in.) for Paraseal/Gundseal], and at least one test was conducted using half of the minimum recommended overlap width.

The third type of test (Fig. 6) involved a composite with the GCL overlain by a 1.5 mm (60 mil) HDPE geomembrane. Punctures that were made in the geomembrane included two 75 mm (3 in.) diameter holes, three 25 mm (1 in.) diameter holes, and three 600 mm (2 ft) long slits that were about 1 mm wide (Fig. 6).

Small-scale hydraulic conductivity tests were conducted on 100 mm (4 in.) diameter specimens. Flexible-wall permeameters were used, and pro-

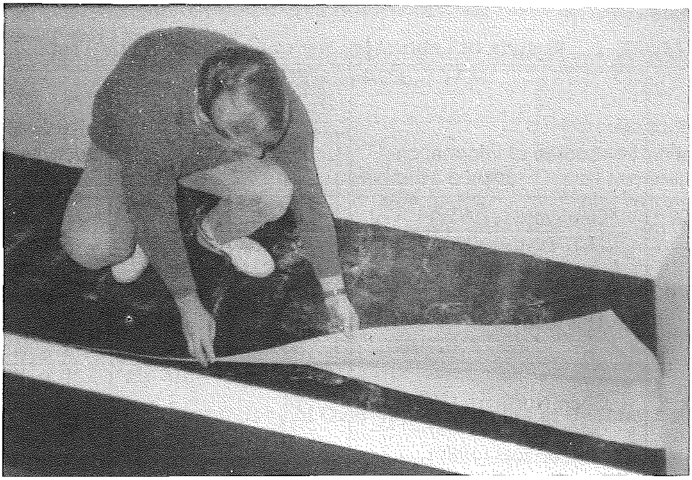

FIG. 9. Placement of Gundseal with Overlapped Seam

cedures outlined in ASTM method D5084 were generally followed. Only Bentomat was tested during this study. Tests on Claymax were performed by Shan (1990) and were not repeated. Hydraulic conductivity data for all the materials were obtained from sources cited in the next section.

Results of Laboratory Hydraulic Conductivity Tests

The results of flexible-wall hydraulic conductivity tests on the three geosynthetic clay liners are shown in Table 1 and Fig. 10. Hydraulic conductivities of all three GCLs were in the range of 3×10^{-10} to 6×10^{-9} cm/s. Hydraulic conductivity has a tendency to decrease with increasing effective stress. Individuals who compare hydraulic conductivities of different materials should be careful to compare values measured at the same maximum effective stress.

Results of Bench-Scale Tests

Bentomat and Claymax: Tests on Control and Overlapped Samples

Two control tests (no overlapped seam) were performed on 1.2 m by 2.4 m (4 ft by 8 ft) samples. Hydraulic conductivities are summarized in Table 2. The hydraulic conductivity of Claymax measured in the bench-scale tanks compared reasonably well with results of flexible-wall hydraulic conductivity tests performed on small test specimens at similar effective stress. However, with Bentomat, the hydraulic conductivity in the bench-scale tanks was about 10 times lower than values measured in flexible-wall permeameters.

Possible sources of error in the tests on Bentomat were considered. In flexible-wall permeability tests, problems were initially encountered with loss of bentonite near the edges during preparation of test specimens, which led to high flow rates near edges. The problem was minimized by hydrating an oversized test specimen, trimming the moist specimen, and smearing the edge of the test specimen with additional bentonite paste. Despite these procedures, the edge seal may still have been imperfect.

TABLE 1. Results of Laboratory Hydraulic Conductivity Tests

Material (1)	Source of information (2)	Maximum Effective Confining Stress kPa (3)	Maximum Effective Confining Stress psi (4)	Hydraulic conductivity (cm/s) (5)
Bentomat	GeoSyntec (1991a)	35	5	1×10^{-9}
	J&L Testing Co. (1990)	56	8.2	6×10^{-9}
		73	10.6	1×10^{-9}
		91	13.2	1×10^{-9}
	This study	14	2	3×10^{-9}
		34	5	3×10^{-9}
		69	10	1×10^{-9}
Claymax	Chen-Northern (1988)	24	3.5	2×10^{-9}
	Geoservices (1988)	200	29	4×10^{-10}
	Geoservices (1989)	207	30	8×10^{-10}
		207	30	3×10^{-10}
		207	30	7×10^{-10}
	Geoservices (1990)	207	30	3×10^{-10}
	GeoSyntec (1990)	6.9	1	2×10^{-9}
	GeoSyntec (1990)	10.3	1.5	4×10^{-9}
	Shan (1990)	14	2	2×10^{-9}
		34	5	1×10^{-9}
		69	10	6×10^{-10}
		138	20	3×10^{-10}
	GeoSyntec (1991b)	14	2	2×10^{-9}
	Shan and Daniel (1991)	14	2	2×10^{-9}
Gundseal	GeoSyntec (1991c)	34	5	1×10^{-9}

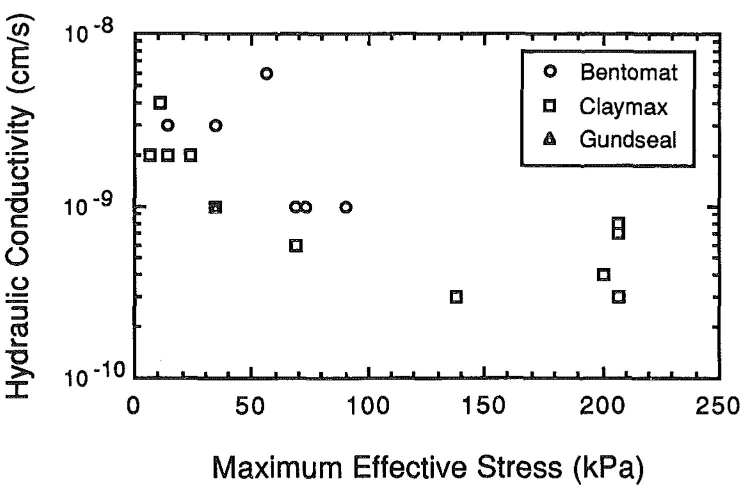

FIG. 10. Results of Flexible-Wall Hydraulic Conductivity Tests

TABLE 2. Comparison of Hydraulic Conductivities Measured on Unseamed Pieces of Bentomat and Claymax

Material (1)	RESULTS FROM BENCH-SCALE TANK TESTS: Average Effective Confining Stress, kPa (2)	psi (3)	Hydraulic conductivity (cm/s) (4)	Hydraulic conductivity measured with flexible-wall permeameters (Fig. 10) (cm/s) (5)
Bentomat	6	0.9	4×10^{-10}	4×10^{-9}
Bentomat	9	1.3	4×10^{-10}	4×10^{-9}
Claymax	6	0.9	1×10^{-8}	3×10^{-9}
Claymax	6	0.9	8×10^{-9}	3×10^{-9}

TABLE 3. Hydraulic Conductivity of Overlapped Samples of Bentomat and Claymax

Material (1)	Series (2)	Effective Stress (kPa): Top (3)	Bottom (4)	Hydraulic Conductivity (cm/s): Control (no overlap) (5)	150 mm (6 in.) overlap (6)	75 mm (3 in.) overlap (7)
Bentomat	1	8	10	4×10^{-10}	4×10^{-10}	1×10^{-9}
	2	8	10	4×10^{-10a}	—	—
Claymax	1	3	9	1×10^{-8}	3×10^{-8}	9×10^{-8}
	2	8	10	8×10^{-9}	9×10^{-9}	1×10^{-8}
	3	8	10	7×10^{-9a}	—	—

[a]Clay blanket underlain by Trevira 1135 geotextile filter.

In the tank tests on Bentomat, migration of bentonite out of the GCL and into the underlying materials may have reduced the flux of water through the GCL. When the first set of tests was dismantled, grey bentonite was visible in the geotextile/geonet/geotextile composite drainage material beneath both the Bentomat and the Claymax specimens. In the final series of tests, a thick, nonwoven geotextile was placed between the Bentomat and Claymax and the underlying Gundnet drainage composite. The geotextile was a Trevira 1135 fabric with a weight of 356 g/m² (10.5 oz/sq yd) and an apparent opening size of 0.13–0.21 mm. The thick geotextile filter stopped downward movement of bentonite from Bentomat and Claymax during the three-month testing period: bentonite could be seen on the upper surface of the geotextile filter but not in the bulk of the geotextile nor in the underlying drainage layer. However, with respect to the hydraulic conductivity anomalies, problems with bentonite migration were about the same for Bentomat and Claymax, and yet the comparison of results from tank tests and flexible-wall-permeameter tests was much different (Table 2). The writers were unable to isolate the cause for the discrepancy in hydraulic conductivity of Bentomat measured in flexible-wall permeameters and bench-scale tanks. Further investigation is recommended.

The results of tests on overlapped sheets of Bentomat and Claymax are summarized in Table 3. When the manufacturers' recommended minimum overlap width of 150 mm (6 in.) was maintained, the overall hydraulic conductivity of the overlapped panels was about the same as the hydraulic

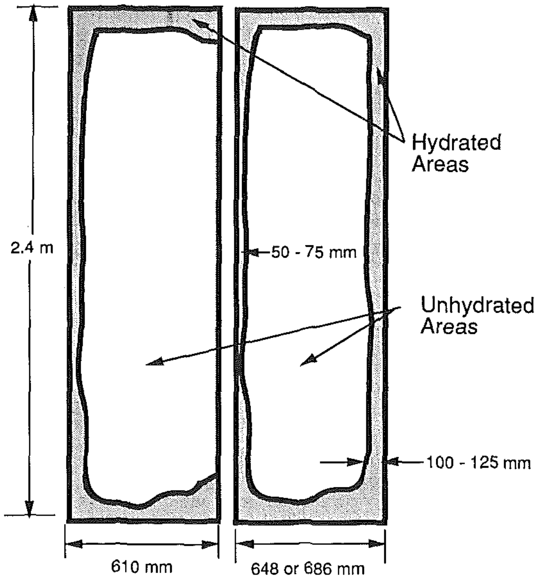

FIG. 11. Pattern of Wetting of Bentonite in Overlapped Gundseal when HDPE Faced Upward

conductivity of nonoverlapped, control panels. The GCLs self-sealed along the overlaps in these bench-scale tests.

When the overlap width for Claymax panels was reduced to half the minimum recommended value, the overall hydraulic conductivity of the overlapped panels was 1.2–9 times higher than the hydraulic conductivity of the control specimens, depending on the vertical stress applied to the specimens. For tests with effective stress greater than 7 kPa (1 psi), the performance of a narrow overlay of Claymax was better than for tests in which a lower effective stress was used. The differences between control and overlapped specimens may simply have been due to variations in the materials themselves; multiple tests for statistical purposes were infeasible due to the great time, effort, and expense associated with each of the tank tests. Intuitively, however, one would expect that the hydraulic integrity of the overlap might be more sensitive to the width of the overlap when the vertical stress is small. Overburden stress is probably needed for the Claymax seams to work because it appears that with little or no overburden, the bentonite simply expands unevenly when wetted and does not ooze through the openings of the geotextile and form a seal.

When the overlap width of Bentomat was reduced to half the minimum recommended value of 150 mm (6 in.), the hydraulic conductivity was 2.5 times greater than the value measured on the control sample with no overlap or the value measured on panels with the minimum 150-mm (6-in.) overlap (Table 3). Again, the difference may simply be the result of material variability. No tests were performed on Bentomat at the lower range of effective stress used for the first test series on Claymax.

Gundseal: Tests on Control and Overlapped Samples

Five tests were performed on Gundseal. In the first series, the HDPE geomembrane faced upward, the calculated effective stress was between 3

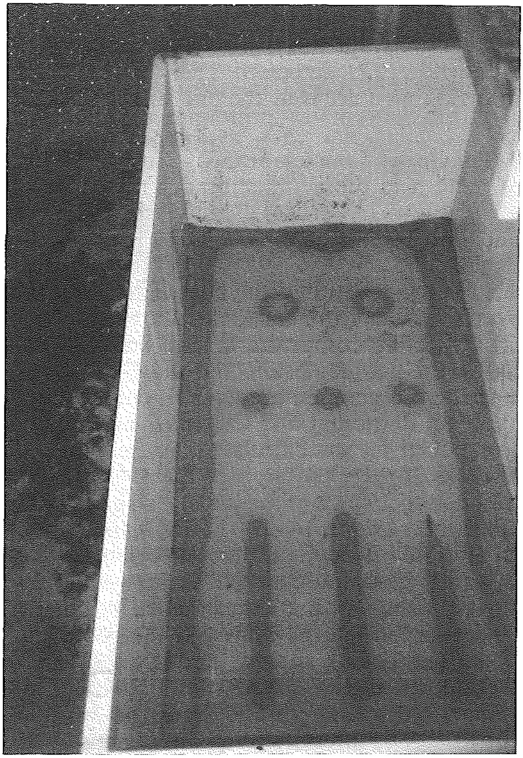

FIG. 12. Pattern of Wetting of Bentonite in Gundseal after Overlying Gravel and Punctured Geomembrane had been Removed from Tanks

TABLE 4. Results of Tests on Punctured Geomembrane/GCL Composites

Material (1)	Hydraulic Conductivity (cm/s): Control (no geomembrane) (2)	Hydraulic Conductivity (cm/s): Composite (with punctured geomembrane) (3	Conductivity ratio: column 3 divided by column 2 (4)
Bentomat	4×10^{-10}	6×10^{-10}	1.5
Claymax	7×10^{-9}	7×10^{-9}	1.0

and 9 kPa (0.4 and 1.3 psi), and the overlap widths were 75 mm (3 in.) and 38 mm (1.5 in.). A test on a control sample with no overlap was also performed. After five months of testing, no outflow was observed from any of the tanks. The tanks were dismantled, and it was found that the bentonite was wetted approximately 100–125 mm (4–5 in.) around the edges and 50–75 mm (2–3 in.) along the overlap (Fig. 11). Otherwise, the bentonite was not wetted. The tests on overlapped seams indicate that the minimum recommended overlap width contains a factor of safety under these test conditions.

In the second series, two tests were performed with the bentonite facing upward. The calculated effective stress was between 8 and 10 kPa (1.1 and 1.5 psi), and the overlap width was 0 (control test) or 75 mm (3 in.). After five months, no outflow was detected. There was still some unhydrated bentonite in the overlapped areas at the end of the tests.

Composite GCL/Punctured Geomembrane

The puncture pattern in the geomembranes that were placed on top of the GCLs is shown in Fig. 2. Vertical effective stress varied from 8–10 kPa (1.1–1.4 psi), and a pressure head of 300 mm (1 ft) of water was maintained on the materials tested.

With Gundseal, water penetrated the bentonite at the defects, but water migrated < 75 mm (3 in.) from the defects over the five-month testing period (Fig. 12). Effective composite action was obvious: the bentonite sealed off defects in the geomembrane and the GCL prevented outflow of water from the punctured geomembrane/GCL composite.

With tests involving Bentomat and Claymax, outflow did occur. An apparent hydraulic conductivity was calculated, assuming one-dimensional flow through the entire cross-sectional area of the GCL; results are shown in Table 4. Hydraulic conductivities of the punctured geomembrane/GCL composites were about the same as those of the GCLs alone. When the tests were dismantled after about three months of permeation, it was found that the bentonite was fully hydrated over the entire area of the Bentomat and Claymax sheets. It is assumed that water flowed through the punctures in the geomembranes, spread laterally through the geotextile that separated the bentonite from the geomembrane, and soaked the GCL. Once the bentonite was wetted, the high in-plane transmissivity of the geotextile that separated the punctured geomembrane from the bentonite provided an avenue for water to spread laterally from the punctures and permeate the GCLs. However, in-plane transmissivity of geotextiles tends to decrease with increasing vertical stress; the vertical stress used in these tests was low.

Conclusions

Bench-scale hydraulic conductivity tests were performed on three geosynthetic clay liners (GCLs). The purpose of the tests was to determine: (1) Whether overlapped seams self-seal when the bentonite in the GCL is hydrated; and (2) whether the bentonite forms a seal against an overlying, punctured geomembrane. Conclusions drawn from this study are as follows:

1. The GCLs that were placed in large tanks self-sealed at overlaps when the bentonite was hydrated. Except for the case where low (< 7 kPa or 1 psi) vertical effective stress was employed, the hydraulic conductivities of overlapped materials were almost identical to values measured on control samples with no overlap.
2. For tests in which the minimum vertical effective stress was greater than 7 kPa (1 psi), the overlap width could be reduced as much as 50% below the minimum values recommended by the manufacturers without significantly increasing the overall hydraulic conductivity of overlapped panels. For the carefully controlled test conditions employed in this investigation, there was a factor of safety built into the manufacturers' minimum recommended overlap widths.
3. Bentonite was found to migrate vertically out of the two GCLs that

contained bentonite between two geotextiles and into the underlying drainage layer when adequate filtration was not provided. Bentonite consistently migrated through a 200 g/m^2 (6 oz/sq yd), nonwoven, needle-punched geotextile with an apparent opening size of 0.15–0.25 mm and into an underlying geonet. However, bentonite migration was stopped during the three-month testing period by a 356 g/m^2 (10.5 oz/sq yd) nonwoven, needle-punched geotextile with an apparent opening size of 0.13–0.21 mm.

4. The effectiveness of composite action between a punctured geomembrane and the bentonite in the GCLs depended on whether a geotextile separated the punctured geomembrane from the bentonite. Good composite behavior was observed when the bentonite was in direct contact with the punctured geomembrane; liquid migrated laterally no more than about 75 mm (3 in.) from the punctures. Less effective composite action was observed when a geotextile separated the bentonite from the geomembrane.

Acknowledgments

This research was funded by the U.S. Environmental Protection Agency's (EPA) Risk Reduction Engineering Laboratory under cooperative agreement CR-815546-01-0. The EPA's project officer was Walter E. Grube Jr. The cooperation of Grube and Robert E. Landreth of the EPA are sincerely appreciated. This article has not been reviewed by the EPA. The contents do not necessarily reflect the views and policies of the EPA nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

Several graduate students who helped with the experiments are thanked: Hsin-yu Shan, Mark LaGatta, Jenghwa Lyang, and Gerald Eykholt. The cooperation of representatives of the GCL manufacturers was critical to the successful completion of this work. The writers particularly thank Thomas Stam and Robert Trauger of CETCO, Martin Simpson and William Simpson of the James Clem Corp., Mark Cadwallader and James Anderson of Gundle Lining Systems, Inc., and Brian McGroarty and Patrick McGroarty of Paramount Technical Products, Inc.

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