GEOSYNTHETIC CLAY LINERS SUBJECTED TO DIFFERENTIAL SETTLEMENT

An important application of GCLs is as a hydraulic barrier in final covers for landfills and vertical expansion of landfills over existing facilities. Municipal solid waste landfills undergo settlement during and after their active life. This settlement is caused by the gradual decomposition and consolidation of the waste mass. Differential settlement may be characterized by the distortion Δ/L, which is defined as the settlement Δ, over the horizontal distance L. The average tensile strain (ε_t) caused by distortion can be computed from simple mechanics. If tensile strains are large enough, the barrier layer may crack and lose its hydraulic conductivity. The damaged barrier would then cause increased leachate generation, which ultimately could jeopardize surrounding groundwater quality. The cracked barrier in a closure or final cover system also could allow the uncontrolled escape of landfill gases. And if not properly repaired, the settlement cracks are likely to grow larger as infiltration erodes the sidewalls of the cracks (the “soil piping” phenomenon).

For these reasons, it is essential that the landfill cover system be capable of sustaining the anticipated differential settlement of the waste mass. Published data on tensile strains at failure for compacted clay liners indicate that the tensile strain at failure of compacted clay is typically between 0.1 and 4%. The ability of compacted clays to survive differential settlement in landfill covers has been questioned by Koerner and Daniel (1992) and Daniel and Koerner (1993), based on concerns over the brittleness of compacted clay in tension. The levels of distortion often observed in landfill covers are greater than those that would theoretically crack compacted clay. For vertical expansions this situation can be expected to be further exacerbated due to the high magnitudes of the normal stresses.

Tests were performed in steel tanks and a water-filled bladder was placed beneath the GCL to produce differential settlement. The GCL was then covered with 600 mm of gravel. The water level was brought to its final position of 300 mm above the top of the GCL. Two of the GCLs tested were needlepunched GCLs. Another GCL tested was an unreinforced geotextile-encased GCL (the original version of Claymax which is no longer manufactured). The unreinforced geotextile-encased GCL tested contained a light 0.9 oz/sq.yd. scrim backing on one side. This material has been replaced by the new version of Claymax 200R which has a heavier geotextile. A fourth GCL was a stitch-bonded GCL which also has been discontinued. The GCLs were subjected to differential settlement in either a dry state or a hydrated state. Other studies have shown that GCLs placed in contact with moist soil will quickly absorb water from the soil and hydrate within a few weeks. Therefore, in almost all instances the GCL would be hydrated when subjected to differential settlement. Thus, we will focus on data for hydrated GCLs.

The final hydraulic conductivity at the end of each increment of settlement varied with the calculated tensile strain for the needlepunched GCLs. The hydraulic conductivity of intact Bentomat GCL samples did not increase significantly, even at the largest induced tensile strain of 6%, which corresponds to Δ/L of 0.347. Overlapped panels of Bentomat GCL were subjected to maximum tensile strains of 12-15%. The hydraulic conductivity of overlapped Bentomat GCL panels did not increase significantly at tensile strains $\leq$12%! At tensile strain of 15%, an overlapped sample exhibited a hydraulic conductivity slightly greater than 1×10^{-7} cm/s, but the overlapped panels were subjected to an extreme distortion of $\Delta/L = 0.57$. Even in this case it is quite unlikely in an actual landfill that this type of trough-shaped settlement would occur, and even more unlikely that it would occur in the precise location *and* direction of an overlapped seam. Moreover, the confining stress provided by a one-foot gravel layer on top of the GCL was not representative of the confining stresses created by a 3 to 4 foot thick cover system which would tend to greatly restrict seam separation. In any case, if it is considered possible that this type of dramatic settlement is possible, the seam overlap during installation could be increased to 12 inches.

Type of GCL	**Specimen**	**Settlement Increment**	**Δ/L**	**Tensile Strain (%)**	**Final k (cm/sec)**
Bentomat (intact)	1	start	0	0	7×10^{-10}
		finish	0.325	5.0	5×10^{-9}
	2	start	0	0	1×10^{-9}
		finish	0.347	6.0	8×10^{-10}
Bentomat (overlapped)	1	start	0	0	3×10^{-9}
		finish	0.504	12.0	2×10^{-9}
	2	start	0	0	3×10^{-10}
		finish	0.574	15.0	3×10^{-7}

Another significant finding of these tests was that the bentonite mass per unit area in the Bentomat samples was the same both at the perimeter of the tank and within the central depression. This means that bentonite did not migrate downward into the bottom of the depressed area.

In conclusion, compacted clay liners cannot accommodate the differential settlement expected to occur in a typical landfill as well as GCLs. Poor settlement behavior is just one reason compacted clay liners are currently falling out of favor and GCLs are increasingly used as barrier materials for landfill cover systems.

Geosynthetic Clay Liners Subjected to Differential Settlement

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Abstract: Geosynthetic clay liners (GCLs), which consist of a thin layer of bentonite attached to one or more geosynthetic materials, are receiving increased use as low-permeability barrier layers in waste-containment systems. Tests were performed in tanks to measure the hydraulic conductivity of GCLs that were subjected to differential settlement. In most cases the GCLs maintained a hydraulic conductivity of 1×10^{-7} cm/s or less when subjected to tensile strains of 1->10%, depending on the material and test conditions. Overlapped GCL panels maintained their hydraulic integrity despite in-plane slippage of up to 25–100 mm. In general, the ability of GCLs to withstand differential settlement appears to be greater than that of compacted clay liners, but less than that of geomembranes. GCLs are a promising barrier material for situations in which differential settlement is expected, for example, in landfill final covers.

INTRODUCTION

Geosynthetic clay liners (GCLs) are commercially manufactured liner materials containing approximately 5 kg/m^2 (1 lb/ft^2) of sodium bentonite sandwiched between two geotextiles [Figs. 1(a)–1(c)] or attached with an adhesive to a geomembrane [Fig. 1(d)]. GCLs are approximately 10 mm thick and are manufactured in panels that measure about 5 m in width by 30 m in length. Panels are overlapped without mechanical welding and self-seal at the overlaps when the bentonite hydrates (Estornell and Daniel 1992). General information about GCLs is provided by Daniel (1991, 1993) and Koerner (1994).

An important application of GCLs is as a hydraulic barrier in final covers for landfills. The ability of hydraulic barriers to withstand differential settlement is an important issue with many final covers. Gilbert and Murphy (1987) demonstrated that settlement over short distances in landfill covers is more threatening to the performance of the barrier than relatively uniform settlement over longer distances. Differential settlement may be characterized by the distortion Δ/L, which is defined as the settlement Δ, over a horizontal distance L (Fig. 2). The average tensile strain (ε_t) caused by distortion can be computed by integrating over the deflected shape to determine the arc length of the deformed section (Gilbert and Murphy 1987) or from simple mechanics, as shown in Fig. 3. If tensile strains are large enough, the barrier layer (e.g., compacted clay or GCL) may crack and lose its low hydraulic conductivity.

Published data on tensile strains at failure for compacted clay are summarized in Table 1. Compacted clays are much more ductile when compacted wet, rather than dry, of optimum water content (Ajaz and Parry 1975; and Scherbeck and Jessberger 1993), and ε_t at failure increases with an increasing plasticity index and increasing clay content (Lozano and Aughenbaugh 1995). The tensile strain at failure of compacted clay is typically between 0.1 and 4% (Table 1).

Jessberger and Stone (1991) conducted centrifuge tests to study the response of compacted kaolin and a compacted sand-bentonite mixture to different settlement. A remotely controlled trapdoor generated angular distortions θ of up to 16° (Δ/L of 0.287 and tensile strain ε_t of 4%). The barriers were permeated as distortion was induced. The kaolin barrier tested

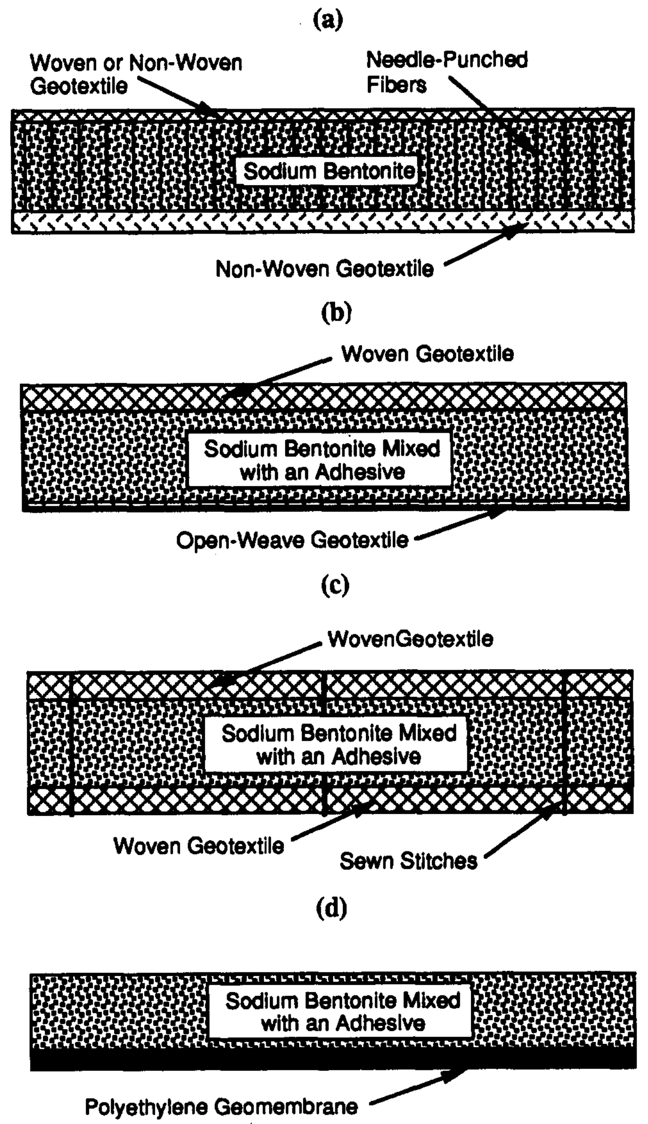

FIG. 1. Geosynthetic Clay Liners Used: (a) Geotextile-Encased, Needle-Punched GCL; (b) Geotextile-Encased, Adhesive-Bonded GCL (No Longer Manufactured); (c) Geotextile-Encased, Stitch-Bonded GCL; (d) Bentonite-Geomembrane Composite GCL

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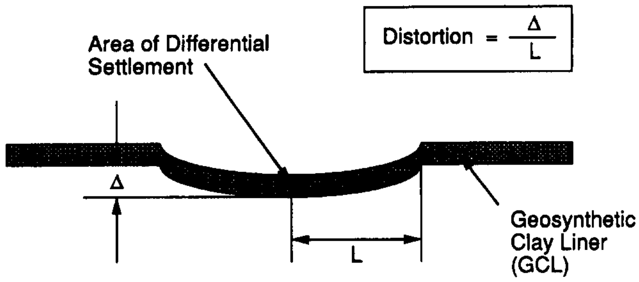

FIG. 2. Definition of Distortion, Δ/L

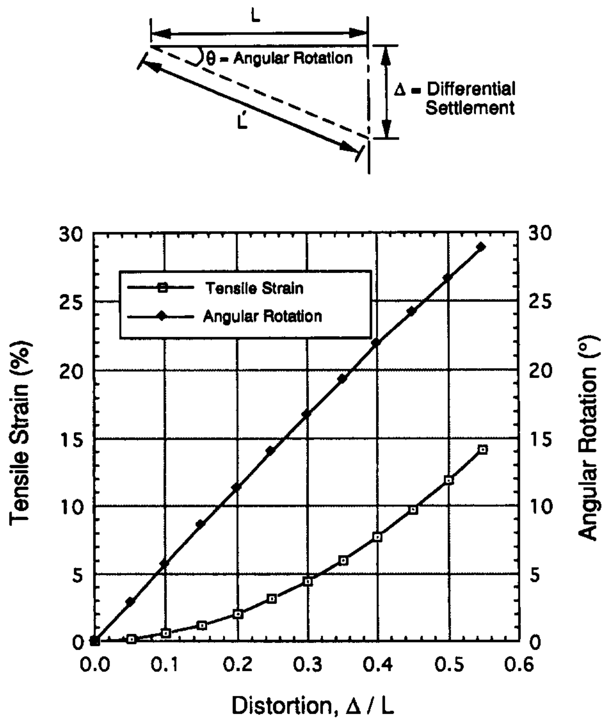

FIG. 3. Tensile Strain and Angular Rotation versus Δ/L

without any overburden stress, which simulates a landfill cover, and failed at an angular distortion of 6° ($\Delta/L \approx 0.105$, $\varepsilon_t \approx 0.45\%$). Hydraulic conductivity increased from the predistortion values of 1×10^{-7} to 2×10^{-3} cm/s at failure. For the sand-bentonite mixture without overburden, slight surface cracking occurred at θ of 7.5°, but not even the maximum θ of 16° ($e_t \approx 4\%$) produced significant cracking or breaching of the specimen. Neither the kaolin nor the sand-bentonite mixture experienced a significant increase in hydraulic conductivity when an overburden stress of 43 kPa was applied; the compressive stress prevented the development of tension cracks. The potential for clay to crack appears to be greater in landfill covers (where the overburden stress is very small) than in bottom linear systems.

The ability of compacted clays to survive differential settlement in landfill covers has been questioned by Koerner and Daniel (1992) and Daniel and Koerner (1993), based on concerns over the brittleness of compacted clay in tension. The levels of distortion often observed in landfill covers are greater than those that would theoretically crack compacted clay. Although data on differential settlement are lacking in the literature, it has been the writers' experience that settlement of 0.1–1 m, spread over horizontal distances of 1–10 m, is not uncommon in landfill final covers.

The objective of the present study is to quantify the relationship between differential settlement and hydraulic conductivity for GCLs. Only one study concerning impact of differential has been documented in the literature. Weiss et al. (1995) performed tests in which a geotextile-encased, stitch-bonded GCL (NaBento), which has parallel rows of stitches 25 mm apart, was subjected to differential settlement. In laboratory tests with a 0.7 by 0.7 m box, the GCL was deformed in a dry state. No increase in hydraulic conductivity was observed at tensile strains in excess of 5%, and there was no slippage along overlaps. In field tests, the GCL was hydrated over a 1-m wide area prior to settlement. Local maximum tensile strains of 3.0–7.3% were induced (average was about 5%) with no reported increase in hydraulic conductivity. The study by Weiss et al. (1995) was limited to one GCL, which is not presently marketed in the United States.

EXPERIMENTAL METHODS

Steel Tanks

Tests were performed in steel tanks that measured 2.4 m in length, 1.2 m in width, and 0.9 m in height (Estornell and Daniel 1992). A water-filled bladder was placed beneath the GCL to produce differential settlement.

A plan view of the tank is shown in Fig. 4, and a cross section is sketched in Fig. 5. A wood frame rested on the bottom of a tank. The space between the frame and wall of the tank was filled with bentonite to form a side seal. The wooden frame supported a steel frame, which anchored the edges of a GCL test specimen (Fig. 5) so that the induced

TABLE 1. Compilation of Published Tensile Strains at Failure for Compacted Clay

Reference (1)	Type or source of soil (2)	Water content (%) (3)	Plasticity index (%) (4)	Maximum tensile strain (%) (5)
Tschebotarioff et al. (1953)	Natural clayey soil	19.9	7	0.80
Tschebotarioffe et al. (1953)	Bentonite	101	487	3.4
Tschebotarioff et al. (1953)	Illite	31.5	34	0.84
Tschebotarioff et al. (1953)	Kaolinite	37.6	38	0.16
Leonards and Narain (1963)	Portland Dam	16.3	8	0.17
Leonards and Narain (1963)	Rector Creek Dam	19.8	16	0.16
Leonards and Narain (1963)	Woodcrest Dam	10.2	Nonplastic	0.18
Leonards and Narain (1963)	Shell Oil Dam	11.2	Nonplastic	0.07
Leonards and Narain (1963)	Willard test dam embankment	16.4	11	0.20
Ajaz and Parry (1975)	Gault clay	19–31	39	0.1–1.7
Ajaz and Parry (1975)	Balderhead city	10–18	14	0.1–1.6
Scherbeck et al. (1991)	Clay	—	32	1.3–2.8
Scherbeck and Jessberger (1993)	Kaolin	21–30	16	2.8–4.8
Scherbeck and Jessberger (1993)	Clay A	16–29	31	1.5–4.1
Scherbeck and Jessberger (1993)	Clay B	19–33	49	1.6–3.6
Scherbeck and Jessberger (1993)	Clay C	18–26	32	1.7–4.4

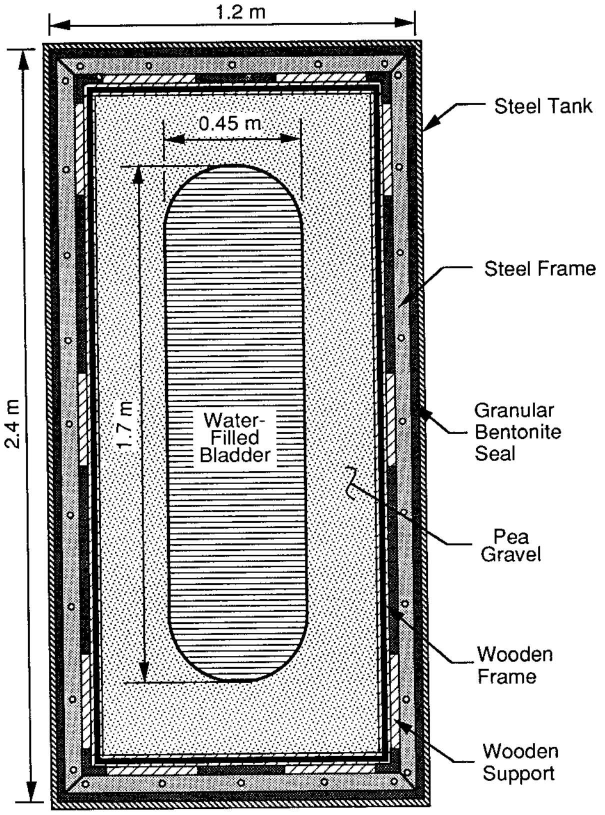

FIG. 4. Plan View of Bladder and Subdrain System in Tanks

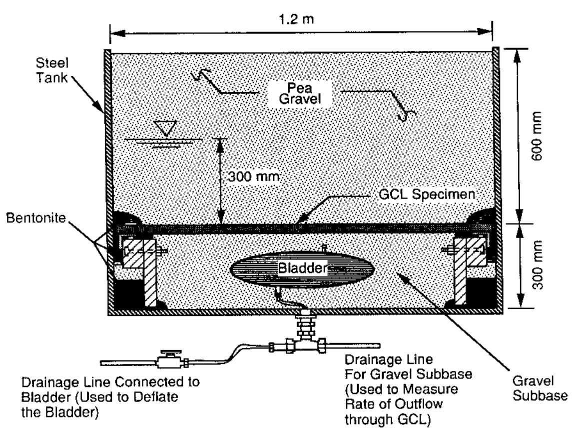

FIG. 5. Cross Section of Tanks

settlements deformed the center of the GCL instead of pulling the edges of the GCL away from the walls of the tank.

The bladder was designed to produce tensile strains across the short direction of the tank, that is, perpendicular to the long axis of the bladder. The interior of the wood frame was filled with pea gravel and the water-filled bladder. A 0.9 by 2.1 m piece of nonwoven, needle-punched geotextile [550 g/m^2 (16 oz/yd^2)] was placed over the gravel (directly beneath the GCL) to prevent the migration of bentonite into the gravel. The geotextile was slotted longitudinally so that it would not inhibit deformation of the GCL. Further details are given by LaGatta (1992).

Sample Preparation

The GCL samples were cut from roll stock and then trimmed about 6 mm less than the nominal dimensions of the steel tanks. Bolt holes on the edges of the GCL were laid out with templates. Next, 28 holes were punched through the GCLs and reinforced with grommets. The GCL was bolted to the steel frame through the grommets.

A 1-m long, 25-mm diameter polyvinyl chloride pipe (telltale) was attached to the upper surface of the GCL to monitor settlement. The GCL was then covered with 600 mm of gravel.

When it was time to hydrate the GCLs, the tanks were filled with 100 mm of water to initiate hydration. After about 3 d, the water level was brought to its final position of 300 mm above the top of the GCL. The average effective stress acting on the GCL was 7.6 kPa.

Material Tested

Five GCLs were tested. Two of the GCLs tested (Bentofix NS and Bentomat with SS grade bentonite) were geotextile-encased GCLs with a woven geotextile on one side, and a nonwoven geotextile on the other side. The nonwoven geotextiles faced downward. Another GCL tested was a geotextile-encased, adhesive-bonded GCL (the original version of Claymax, which is no longer manufactured). This GCL contained a lightweight [26 g/m^2 (0.9 oz/yd)] scrim backing on the side that faced downward, and a woven geotextile on the side facing upward. This material has been replaced by Claymax 200R in which the lightweight scrim backing has been replaced by a much heavier [110 g/m^2 or (3.25 oz/yd^2)] woven polypropylene geotextile. The fourth GCL tested consisted of a geotextile-encased, stitch-bonded GCL (Claymax 500SP). The two woven geotextiles on this material are stitched together with parallel rows of stitches spaced 100 mm (4 in.) apart and oriented parallel to the long direction of the tank. The fifth GCL was a bentonite-geomembrane composite GCL (Gundseal), which contained a 0.5 mm (20 mil) thick smooth high-density polyethylene (HDPE) component that faced upward.

Overlaps were 225 mm (9 in.) wide. The centerline of the overlap generally matched the centerline of the tanks. For the two needle-punched GCLs, dry bentonite was applied in the overlap at an application rate of 0.4 kg/m as recommended by the manufacturers.

Test Procedures

The GCLs were subjected to differential settlement in either a dry state or a hydrated state. Tests have shown that GCLs placed in contact with moist soil will quickly absorb water from the soil and hydrate (Daniel et al. 1993) within a few weeks. Therefore, in most instances the GCL would be hydrated when it is subjected to differential settlement.

The water-filled bladder was deflated, usually in four stages for GCLs that were initially hydrated in water and in one stage for GCLs that were deformed in a dry state. The settlement rate was approximately 10 mm/h.

A constant head of 300 mm of water was maintained. Outflow from the tank was collected from a line leading out from the base of the tank (Fig. 5). Hydraulic conductivity was calculated using Darcy's law. The hydraulic gradient ranged from 20 to 30. The thicknesses of the GCLs were determined from laboratory swell tests; the thicknesses of Bentofix, Bentomat, and Claymax used for computing hydraulic conductivity were 10, 9.3, and 16 mm, respectively. Hydraulic conductivity could not be properly calculated for Gundseal because it contains a nonporous geomembrane component. However, to enable comparison of test results, an ''equivalent hydraulic conductivity'' was calculated using the total area of the tank and a thickness of 8 mm.

Disassembly Procedures

The typical length of a test was four months. When a test was complete, the gravel was removed with shovels. Cross

TABLE 2. Results of Settlement Tests on GCLs

Type of geosynthetic clay liner (1)	Specimen (2)	Hydrated prior to settlement? (3)	Settlement increment (4)	Differential settlement (Δ, mm) (5)	Δ/L (6)	Tensile strain (%) (7)	Hydraulic Conductivity (cm/s): Minimum (8)	Hydraulic Conductivity (cm/s): Maximum (9)	Hydraulic Conductivity (cm/s): Final (10)
Bentofix (intact)	1	Yes	0	0	0	0	6×10^{-9}	1×10^{-8}	1×10^{-8}
			1	30	0.13	1.0	3×10^{-9}	1×10^{-8}	7×10^{-9}
			2	70	0.31	4.5	5×10^{-9}	1×10^{-8}	8×10^{-9}
			3	108	0.44	8.5	7×10^{-9}	8×10^{-9}	8×10^{-9}
	2	Yes	0	0	0	0	8×10^{-9}	2×10^{-8}	1×10^{-8}
			1	50	0.22	2.5	2×10^{-9}	5×10^{-9}	4×10^{-9}
			2	100	0.44	8.5	1×10^{-9}	3×10^{-8}	3×10^{-9}
			3	140	0.61	16	2×10^{-9}	4×10^{-9}	2×10^{-9}
Bentofix (overlapped)	1	Yes	0	0	0	0	9×10^{-9}	4×10^{-8}	2×10^{-8}
			1	30	0.13	1.0	2×10^{-8}	9×10^{-8}	2×10^{-8}
			2	60	0.26	3.5	2×10^{-9}	2×10^{-8}	1×10^{-8}
			3	100	0.44	8.5	1×10^{-8}	2×10^{-8}	1×10^{-8}
	2	Yes	0	0	0	0	2×10^{-8}	6×10^{-8}	4×10^{-8}
			1	30	0.13	1.0	3×10^{-9}	2×10^{-8}	3×10^{-9}
			2	55	0.24	3.4	1×10^{-9}	2×10^{-8}	1×10^{-8}
			3	89	0.39	7.0	8×10^{-9}	2×10^{-8}	2×10^{-8}
Bentomat (intact)	1	Yes	0	0	0	0	6×10^{-10}	$1 \times s0^{-8}$	7×10^{-10}
			1	19	0.084	0.4	7×10^{-10}	7×10^{-9}	7×10^{-9}
			2	46	0.204	2.1	3×10^{-9}	7×10^{-9}	3×10^{-9}
			3	61	0.271	3.6	2×10^{-9}	9×10^{-9}	3×10^{-9}
			4	74	0.325	5.0	1×10^{-9}	8×10^{-9}	5×10^{-9}
	2	Yes	0	0	0	0	1×10^{-10}	2×10^{-9}	1×10^{-9}
			1	17	0.076	0.3	8×10^{-10}	2×10^{-9}	2×10^{-9}
			2	40	0.178	1.6	1×10^{-9}	2×10^{-9}	1×10^{-9}
			3	84	0.347	6.0	8×10^{-10}	1×10^{-9}	8×10^{-10}
	3	No	1	75	0.333	5.4	6×10^{-10}	3×10^{-9}	3×10^{-9}
Bentomat (overlapped)	1	Yes	0	0	0	0	2×10^{-9}	4×10^{-9}	3×10^{-9}
			1	17	0.076	0.3	1×10^{-9}	3×10^{-9}	2×10^{-9}
			2	43	0.191	1.8	8×10^{-10}	5×10^{-9}	1×10^{-9}
			3	81	0.360	6.2	2×10^{-9}	3×10^{-9}	2×10^{-9}
			4	86	0.504	12.0	9×10^{-10}	6×10^{-9}	2×10^{-9}
	2	Yes	0	0	0	0	2×10^{-10}	8×10^{-10}	3×10^{-10}
			1	8	0.037	0.1	4×10^{-10}	8×10^{-10}	7×10^{-10}
			2	30	0.133	0.9	6×10^{-10}	8×10^{-10}	8×10^{-10}
			3	86	0.383	7.1	8×10^{-10}	7×10^{-7}	2×10^{-9}
			4	110	0.573	15.0	2×10^{-9}	2×10^{-5}	3×10^{-7}
	3	No	0	75	0.333	5.4	2×10^{-8}	2×10^{-6}	7×10^{-8}
Discontinued Claymax (intact)	1	Yes	0	0	0	0	4×10^{-9}	7×10^{-9}	5×10^{-9}
			1	16	0.071	0.3	4×10^{-9}	9×10^{-9}	9×10^{-9}
			2	25	0.111	0.6	2×10^{-8}	8×10^{-7}	2×10^{-8}
			3	69	0.391	9.1	3×10^{-7}	1×10^{-5}	5×10^{-7}
	2	Yes	0	0	0	0	2×10^{-9}	1×10^{-8}	1×10^{-8}
			1	10	0.131	0.8	1×10^{-8}	2×10^{-5}	2×10^{-6}
	3	No	1	75	0.333	5.4	8×10^{-8}	2×10^{-4}	3×10^{-6}
Claymax 500 SP (intact)	1	Yes	0	0	0	0	8×10^{-10}	3×10^{-9}	3×10^{-9}
			1	16	0.067	0.3	4×10^{-9}	7×10^{-9}	6×10^{-9}
			2	31	0.133	0.9	1×10^{-7}	2×10^{-6}	3×10^{-7}
			3	46	0.204	2.1	5×10^{-8}	6×10^{-7}	6×10^{-8}
			4	84	0.373	6.7	9×10^{-7}	2×10^{-5}	2×10^{-5}
	2	No	1	75	0.333	5.4	4×10^{-10}	9×10^{-9}	7×10^{-9}
Discontinued Claymax (overlapped)	1	Yes	0	0	0	0	6×10^{-9}	9×10^{-9}	9×10^{-9}
			1	12	0.053	0.1	8×10^{-9}	9×10^{-9}	9×10^{-9}
			2	22	0.200	2.0	9×10^{-9}	4×10^{-5}	1×10^{-5}
	2	Yes	0	0	0	0	4×10^{-9}	1×10^{-8}	7×10^{-9}
			1	11	0.049	0.1	2×10^{-9}	1×10^{-8}	1×10^{-8}
			2	22	0.179	1.6	8×10^{-9}	3×10^{-6}	6×10^{-7}
	3	No	1	75	0.333	5.4	2×10^{-8}	3×10^{-8}	2×10^{-8}
Claymax 500 SP (overlapped)	1	Yes	0	0	0	0	2×10^{-9}	4×10^{-9}	3×10^{-9}
			1	14	0.067	0.2	4×10^{-9}	9×10^{-9}	5×10^{-9}
			2	30	0.133	0.9	1×10^{-7}	2×10^{-6}	2×10^{-7}
			3	45	0.204	2.1	1×10^{-8}	3×10^{-7}	2×10^{-8}
			4	119	0.528	13.1	9×10^{-7}	3×10^{-6}	2×10^{-6}
	2	No	1	75	0.333	5.4	5×10^{-9}	1×10^{-8}	9×10^{-9}
Gundseal (intact)	1	Yes	4	54	0.266	3.5	No flow	No flow	No flow
Gundseal (overlapped)	1	Yes	4	124	0.813	29	No flow	No flow	No flow
	2	No	1	75	0.333	5.4	9×10^{-11}	3×10^{-9}	3×10^{-10}

sections were measured to define the final deformed shape of the GCL. Next, 150 × 150 mm coupons were cut from the GCLs for determination of water content and dry mass per unit area of the bentonite component of the GCLs.

RESULTS

The results of the 23 tests that were performed are summarized in Table 2. Most of the results are reported in detail by LaGatta (1992) and Boardman (1993). A typical plot of hydraulic conductivity versus time is shown in Fig. 6 with corresponding cross section measured at tear down shown in Fig. 7. Representative results of measurements of water content and dry mass per unit area after completion of a test are shown in Figs. 8 and 9.

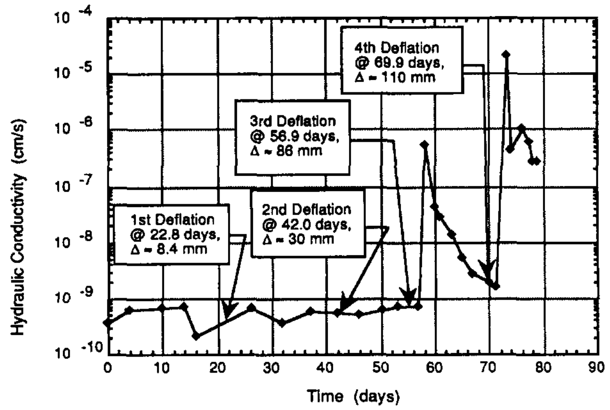

FIG. 6. Typical Plot of Hydraulic Conductivity versus Time for Overlapped Geotextile-Encased, Needle-Punched GCL (Bentomat), Specimen No. 2, Subjected to Differential Settlement after Hydration

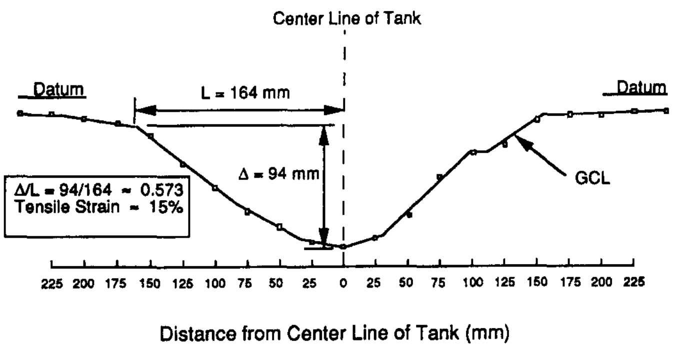

FIG. 7. Typical Shape of Deformed GCL at End of Test for Overlapped Geotextile-Encased, Needle-Punched GCL (Bentomat), Specimen No. 2, Subjected to Differential Settlement after Hydration

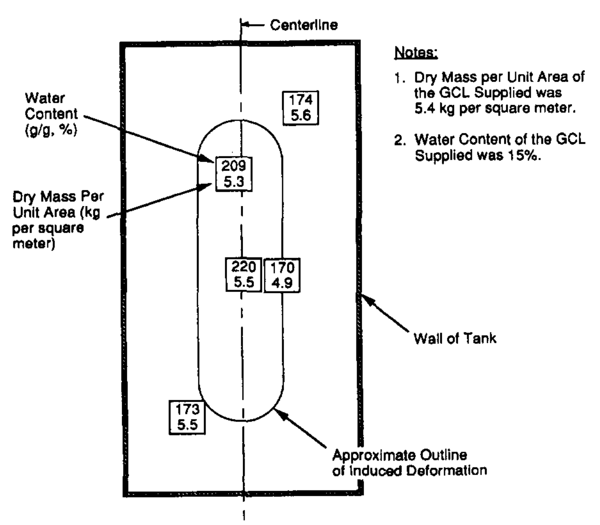

FIG. 8. Typical Results of Tests Determine Water Content and Dry Mass per Unit Area for Nonoverlapped, Geotextile-Encased, Needle-Punched GCL (Bentomat), Specimen No. 1, Subjected to Differential Settlement after Hydration

Needle-Punched GCLs (Bentofix and Bentomat)

The final hydraulic conductivity at the end of each increment of settlement varied with the calculated tensile strain for the geotextile-encased, needle-punched GCLs as shown in Fig. 10. The hydraulic conductivity of intact samples did not increase significantly, even at the largest induced tensile strain of 16%, which corresponds to Δ/L of 0.6. Both types of needle-punched GCLs performed well. The vertical deformation (Δ) of intact samples of Bentomat was limited because the GCL bridged over the settlement that occurred in the underlying gravel (note gap beneath GCL in Fig. 11). The settlement of the other needle-punched GCL (Bentofix) conformed to the deformation of the underlying gravel (i.e., no gap developed), but this particular GCL maintained a very low hydraulic conductivity even at 16% tensile strain.

Overlapped panels of the needle-punched GCLs were subjected to maximum tensile strains of 5.4–15% (corresponding Δ/L = 0.33–0.57). The hydraulic conductivity of overlapped panels did not increase significantly at tensile strains <5%

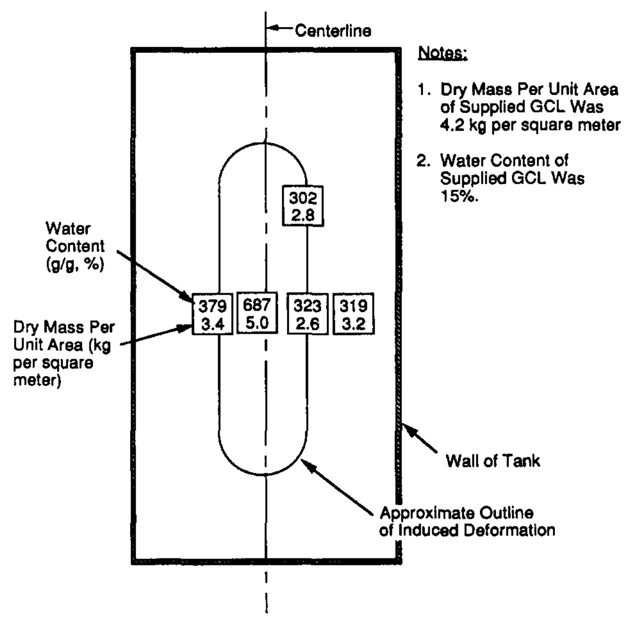

FIG. 9. Typical Results of Tests to Determine Water Content and Dry Mass per Unit Area for Discontinued Version of Claymax (Nonoverlapped Specimen No. 1, Subjected to Differential Settlement after Hydration)

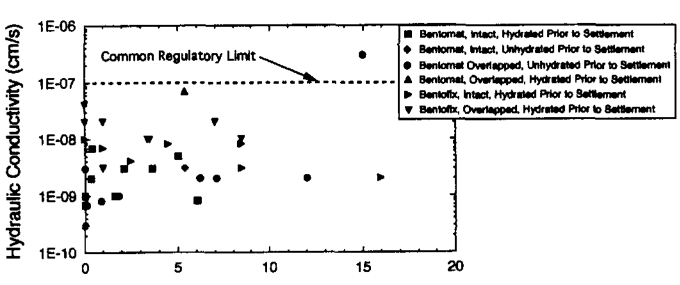

FIG. 10. Final Hydraulic Conductivity versus Tensile Strain for Geotextile-Encased, Needle-Punched GCLs (Bentofix and Bentomat)

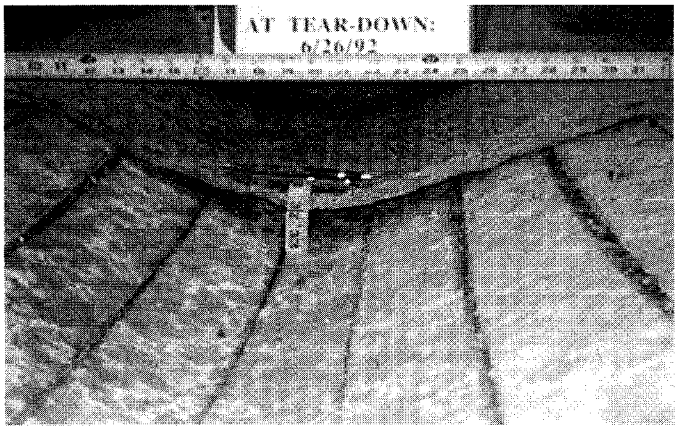

FIG. 11. Photograph Showing Intact Geotextile-Encased, Needle-Punched GCL Bridging over Subsidence (Note Gap between GCL and Underlying Geotextile)

(Fig. 10). However, at tensile strains >5%, results were variable; three samples maintained a hydraulic conductivity $\leq 1 \times 10^{-8}$ cm/s, but two samples exhibited a hydraulic conductivity approximately equal to 1×10^{-7} cm/s. One test on overlapped panels did show a final hydraulic conductivity slightly greater than 1×10^{-7} cm/s, but the overlapped panels were subjected to an extreme distortion of $\Delta/L = 0.57$ and $\varepsilon_t = 15\%$. The overlap width decreased with Bentomat (i.e., the panels slipped relative to one another), but not with Bentofix, for which there was no slippage between panels.

Four primary factors contributed to the ability of the GCLs to withstand large differential settlement while maintaining a low hydraulic conductivity.

1. The bentonite: The bentonite of the GCLs, with its ability to swell and self-heal, can deform and stretch significantly without losing its hydraulic integrity. Experiments have shown that bentonite in GCLs can self-heal punctures at least 25 mm in diameter (Shan and Daniel 1991) and self-heal after significant desiccation cracking (Boardman 1993). Experience has shown that compacted bentonite is relatively ductile in tension compared to other ''soil'' materials [Table 1 and Jessberger and Stone (1991)].
2. Needle-punched fibers: The needle-punched fibers between the upper and lower geotextile components [Fig. 1(a)] tend to hold the bentonite in place and keep it from migrating within the GCL. Observations of the dry mass per unit area (e.g., Fig. 8) at the end of each test showed that there was no discernible tendency for bentonite to migrate within the GCLs.
3. Tensile strength of geotextiles: The tensile strength and stiffness of the GCLs, which are derived from the geotextile components, give the GCLs the ability to bridge across settlement features. In cases of extreme distortion one needle-punched GCL bridged over the underlying depression created by the deflated bladder, leaving an air-filled gap beneath the GCL (Fig. 11).
4. Integrity of overlaps: The overlaps for the GCLs included 0.4 kg/m of additional bentonite. The panels slipped relative to one another, typically reducing the overlap width by about 30 mm, but the additional bentonite appeared to be uninterrupted and to maintain a seal. For field installations sufficient overlap must be provided to accommodate the anticipated slippage and reduction in overlap width that differential settlement would cause.

There was sometimes a sudden increase in hydraulic conductivity immediately after an increment of differential settlement was imposed, followed by a gradual decline in hydraulic conductivity. This is shown in Fig. 6 for the third increment of settlement (Δ = 86 mm). The cause is not known, but it is assumed that the sudden occurrence of settlement (in a period of approximately 2 h) created a pathway for flow either within the GCL or its overlap. Over the next several days the bentonite self-sealed. The final hydraulic conductivities shown in Table 2, and Fig. 10 shows the values at the end of each settlement increment.

Only two tests were performed on GCLs that were subjected to differential settlement before hydration. The intact sample exhibited a very low hydraulic conductivity (3×10^{-9} cm/s) when subjected to $\varepsilon_t = 5.4\%$, but the overlapped panels exhibited a significantly larger hydraulic conductivity of 7×10^{-8} cm/s at the same tensile strain. The supplemental bentonite placed along the centerline of the overlap was fully hydrated and appeared to be intact despite slippage of about 50 mm between the two overlapped panels. The bentonite along the upper surface of the lower GCL (a woven geotextile) was smeared (indicating shearing movement), and the bentonite along the lower surface of the upper GCL (a nonwoven geotextile) was not.

Geotextile-encased, adhesive-bonded GCL (discontinued Claymax)

The relationship between the hydraulic conductivity at the end of each increment of settlement versus the tensile strain in the GCL is shown in Fig. 12 for the discontinued version of Claymax. The material performed well up to a tensile strain of about 1%. At tensile strains >1%, results were variable with the hydraulic conductivity ranging between 1×10^{-8} and 1×10^{-5} cm/s. In general, this now discontinued GCL maintained a hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s only at $\varepsilon_t's < 1\%$.

At the end of the experiments, it was found that bentonite had migrated toward the bottom of the GCL in the pattern

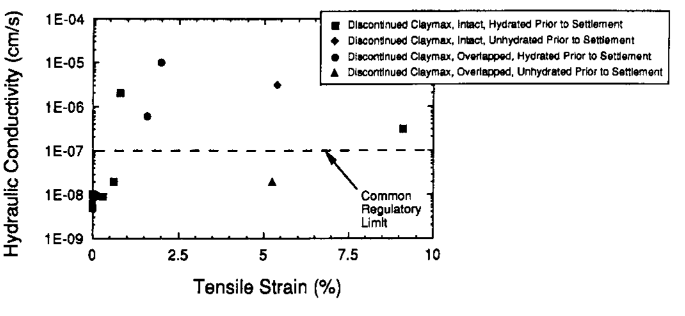

FIG. 12. Final Hydraulic Conductivity versus Tensile Strain for Tests Performed on Geotextile-Encased, Adhesive-Bonded GCL (Discontinued Version of Claymax)

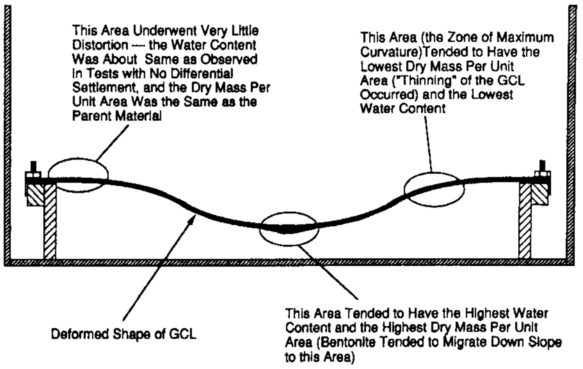

FIG. 13. Sketch Showing Areas in which Bentonite Tended to Thin and Accumulate in Geotextile-Encased, Adhesive-Bonded GCL (Discontinued Version of Claymax)

sketched in Fig. 13. Fig. 9 summarizes typical data on water content and dry mass per unit area at tear down. The dry mass per unit area along the sidewalls of the settlement "bowl" was only half the value measured in the bottom of the settlement bowl. The bentonite had thinned and migrated downslope to the bottom. At the bottom the water content was more than twice the water content elsewhere. Bentonite tended to accumulate at the bottom of the settlement bowl primarily because the upper geotextile was a woven polypropylene geotextile, and the lower geotextile was a lightweight scrim. As settlement occurred, the lightweight scrim provided almost no tensile capacity, and the scrim simply settled in the same pattern as the underlying gravel. The upper, woven geotextile, which is much stronger than the underlying scrim, tended to bridge over the settlement feature, which helped to create a gap into which the unrestrained, wet bentonite could migrate. The thickness of bentonite in the thinned area was only about 5 mm, and in the bottom of the bowl it was approximately 50 mm.

Geotextile-encased stitch-bonded GCL (Claymax 500SP)

Hydraulic conductivity at the end of each increment of settlement is plotted versus tensile strain in Fig. 14 for the geotextile-encased, stitch-bonded GCL. Hydraulic conductivity was generally $< 1 \times 10^{-7}$ cm/s for tensile strains of 5.4% or less. For ε_t's $\geq$ 6%, hydraulic conductivities were significantly greater than 1×10^{-7} cm/s. Under these conditions, this particular GCL withstood tensile strains of up to about 5–6% while typically maintaining a hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s.

Four factors were responsible for this material maintaining a low hydraulic conductivity at fairly large tensile strains

1. The bentonite: As with the other GCLs, the bentonite has a significant ability to self-seal (see earlier discussion).
2. Sewn stitches: The parallel rows of stitches aligned in the long direction of the tanks restricted the migration potential of the bentonite. Dry mass per unit area shows almost no variability. There was no tendency for accumulation of bentonite in the bottom of the GCL.
3. Tensile strength of geotextiles: The two woven geotextiles possess substantial tensile strength, which gives the GCL the ability to bridge over settlement features and eliminates the tendency for the lower geotextile to "sag" below the upper geotextile. The intact sample of the stitch-bonded material bridged over the largest settlement feature, leaving a gap similar to that shown in Fig. 11.
4. Integrity of overlaps: The overlapped panels performed about the same as the intact panels, indicating that the overlaps self-sealed despite the severe distortion created by deflation of the bladder. There was no slippage between any of the overlapped panels for this GCL. The GCL simply deformed downward and stretched without slipping at the overlaps.

The effect of the initial state of hydration (dry versus hydrated) prior to settlement was evaluated. As shown in Fig. 14, two tests at $\varepsilon_t = 5.4\%$ were performed on materials that were deformed in a dry state, and the hydraulic conductivity was $< 1 \times 10^{-7}$ cm/s. Only one test at a comparable strain ($\varepsilon_t = 6.7\%$) was performed on a GCL that was hydrated prior to settlement, and the hydraulic conductivity was significantly larger than 1×10^{-7} cm/s. The data suggest that stretching an unhydrated sample of this GCL to a tensile strain of approximately 6% produces less hydraulic damage than stretching a hydrated GCL to the same strain. Perhaps the dry bentonite in a strained GCL is better able to swell and self-seal with hydration. However, there are only three data points at comparable strain levels (and only one point for a hydrated sample), and any conclusions about the effect of hydration state for this particular GCL are tentative, at best.

Bentonite-geomembrane composite GCL (Gundseal)

Three tests were performed on the GCL that consists of a layer of bentonite attached to a geomembrane [Fig. 1(d)], with the geomembrane facing upward. In previous large-scale hydraulic conductivity tests on this material without differential settlement, no outflow was measured over a period of up to five months (Estornell and Daniel 1992). The geomembrane component of the GCL blocks most of the flow. The only potential seepage pathways are through the overlap or along the sidewall seal.

A test with an intact specimen showed no outflow after the specimen had been subjected to a differential settlement of 54 mm and a tensile strain of 3.5%. The GCL bridged over the settlement that occurred in the underlying bladder as shown in Fig. 15. For this GCL the HDPE component was responsible for the fact that there was no measurable seepage through the GCL and for the fact that the GCL bridged over the settlement feature. The manufacturer reports that the tensile strength of the 0.5-mm (20-mil) HDPE geomembrane is 7 kN/m (40 lb/in.) at yield and 12 kN/m (70 lb/in.) at break (ASTM D638). The bentonite contributed significantly to the ability of the GCL to deform without leaking—bentonite self-sealed along the edges of the tank.

Two tests were performed on overlapped panels installed with the HDPE component facing upward. In the first test, GCL was hydrated for several weeks, and then the GCL panels were subjected to increments of differential settlement. The overlap slipped laterally by about 100 mm, but no outflow

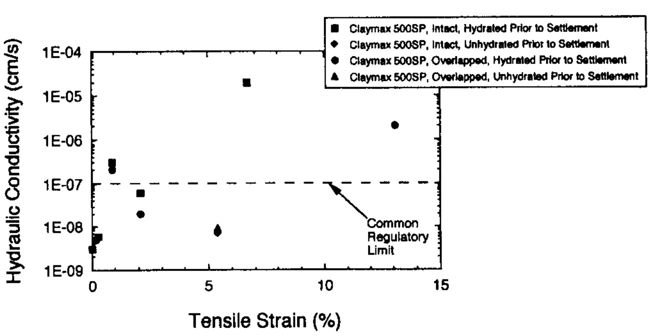

FIG. 14. Final Hydraulic Conductivity versus Tensile Strain for Tests Performed on Geotextile-Encased, Stitch-Bonded GCL (Claymax 500SP)

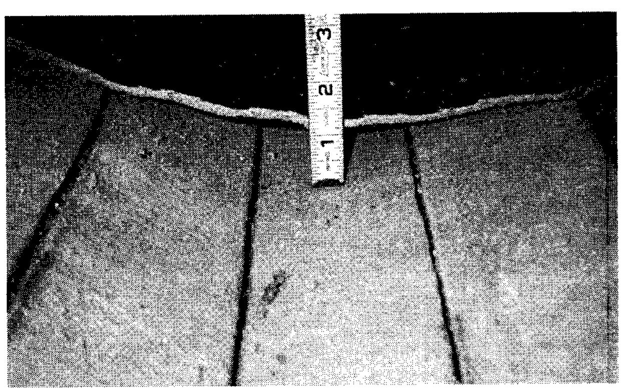

FIG. 15. Photograph Showing Intact Geomembrane-Bentonite Composite GCL (Gundseal) Bridging over Subsidence (Note Gap between GCL and Underlying Geotextile)

occurred. As with the other GCLs, the ability of bentonite to swell and self-seal enabled the GCL to withstand differential settlement and maintain hydraulic integrity. In the second test on overlapped panels, dry GCL panels were deformed in one stage to $\Delta = 75$ mm, and then the GCL was flooded with water. Some initial outflow occurred, but the outflow rate dropped by about two orders of magnitude over a period of several days. After the test was dismantled, it was found that leakage had occurred along one edge of the overlap at the end of the tank (outside the area of the underlying bladder). The leakage was related to one overlapping panel moving downward, and the other was restrained by bolts attached to the frame. Along most of the overlap, bentonite had only hydrated about 50 mm in from the edge of the overlap; the rest of the bentonite was dry, except at the location of the leak mentioned earlier. Even with the leak, the final equivalent hydraulic conductivity (computed from the outflow flux and the total area of the GCL) was in the 10^{-10} cm/s range.

In no case was there any sign of bentonite migration. The bentonite component of the GCL was hydrated only along the edges and at overlaps—elsewhere, the bentonite was dry, hard, and intact with essentially the same thickness as the manufactured product.

PRACTICAL IMPLICATIONS

The GCLs maintained a hydraulic conductivity below 1×10^{-7} cm/s when subjected to distortions (Δ/L) of 0.1–0.4, and tensile strains of 1 to >10%, depending on the material.

Laboratory test data summarized in Table 1 indicate that compacted clays fail in tension (i.e., crack) at tensile strains of 0.1–4%. The tensile strain at failure of geomembranes (also frequently used as a barrier in final covers for landfills) is typically at least 20–100% for biaxial tension (Koerner 1994), depending on the material. A reasonable conclusion is that GCLs are between compacted clay and geomembranes in terms of ability to withstand tensile strains associated with differential settlement. Based on current knowledge, the general range of tensile strains that various materials can withstand appears to be as follows:

- Compacted clay liners; 0.1–4%
- Geosynthetic clay liners: 1–10%
- Geomembranes: 20–100%

The range within each category reflects the variability from one type of material to another.

The reader is cautioned to consider the limitations of the tests described in the present paper before applying the findings. The tests were performed under carefully controlled conditions and did not involve conditions such as freeze-thaw or cyclic wetting and drying. Also, there are many additional considerations besides hydraulic conductivity and differential settlement (e.g., shear strength and slope stability) that can be crucial and that must be carefully considered by the designer. In addition, the GCL manufacturers are continually modifying and improving their materials; different results may be obtained with different materials. More independent work is needed to corroborate these findings and to verify the results in the field.

CONCLUSIONS

Intact and overlapped samples of needle-punched GCLs (Bentofix and Bentomat) maintained a final hydraulic conductivity of 1×10^{-7} cm/s or less when subjected to Δ/L as large as 0.35–0.6, which corresponds to a tensile strain of 5–16%. The tensile strength of the geotextile components in some cases enabled the intact GCL to bridge over the underlying subsidence. Needle-punched fibers limited migration of bentonite within the GCL. The overlapped area maintained its hydraulic integrity despite >25 mm slippage along the overlap. There was little difference in the results of tests performed on GCLs that were subjected to differential settlement before or after hydration.

Intact and overlapped samples of a geotextile-encased, unreinforced, adhesive-bonded GCL (a discontinued version of Claymax) maintained a hydraulic conductivity of 1×10^{-7} cm/s or less up to a distortion (Δ/L) of about 0.1, which corresponds to a tensile strain of 1%. Significant bentonite migration occurred (bentonite accumulated in the bottom of the tank), but this migration was strongly influenced both by the presence of a lightweight scrim geotextile that faced downward and by lack of confinement from needle-punched fibers or sewn stitches.

Intact and overlapped samples of a geotextile-encased, stitch-bonded GCL (Claymax 500SP) generally maintained a hydraulic conductivity of 1×10^{-7} cm/s or less up to a distortion (Δ/L) of about 0.35, which corresponds to a tensile strain of 5%. This material performed significantly better than the unstitched, discontinued version of Claymax, The tensile strength of the geotextile components enabled the intact GCL to bridge over the underlying subsidence. The sewn stitches limited the movement of bentonite within the GCL. Overlapped and nonoverlapped materials performed about the same. There was a trend for lower hydraulic conductivity when a dry GCL was subjected to differential settlement (compared to settlement of a hydrated GCL), but the data are too few to withstand a firm conclusion.

Intact and overlapped samples of a bentonite-geomembrane composite GCL (Gundseal) maintained an equivalent hydraulic conductivity of 1×10^{-7} cm/s or less for a Δ/L of up to 0.8, which translates to tensile strain of nearly 30%. The tensile strength of the geomembrane component allowed the intact GCL to bridge over areas of subsidence, and the swelling and self-healing ability of the bentonite component caused overlaps to maintain their hydraulic integrity despite approximately 100 mm of slippage along the overlap.

The literature documents tensile strains at failure of compacted clay in the range of 0.1–4% and tensile strains at failure of geomembranes subjected to biaxial strain of 20–100%. The GCLs tested maintained a hydraulic conductivity $\leq 1 \times 10^{-7}$ cm/s while subjected to a tensile strain of 1–10% or more, depending on the material and conditions of testing. In general, GCLs appear to fall between compacted clay and geomembranes in terms of ability to maintain their hydraulic integrity during distortion such as that induced by differential settlement in landfill final covers. Because the data indicate that GCLs can withstand more differential settlement than compacted clay, GCLs may be an attractive alternative to compacted clay liners in some landfill final covers, assuming that other issues such as slope stability do not preclude the use of a GCL.

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