LONG-TERM SHEAR BEHAVIOR OF A NEEDLEPUNCHED GEOSYNTHETIC CLAY LINER

Two large-scale constant load shear testing devices were developed to evaluate the long term shearing behavior of a needlepunched geosynthetic clay liners (GCLs) and interfaces between GCLs and other geosynthetics or soils. One device was designed to evaluate GCL shear performance in a landfill cover system, and the other device evaluated a GCL's shear performance in a landfill lining system.

Test results indicate that the GCL underwent an initial distortion soon after application of the shear load, but incremental shear rates decreased considerably thereafter. The majority of shear displacement occurred in the initial portion of the test. Results are also consistent with large-scale field trials and are also consistent with short term testing that suggests a reinforced GCL is capable of sustaining greater load than were applied during the long term testing.

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LONG-TERM SHEAR STRENGTH BEHAVIOR OF A NEEDLEPUNCHED GEOSYNTHETIC CLAY LINER

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ABSTRACT: This paper describes two large-scale constant-load (creep) shear testing devices that were developed to evaluate the long-term shearing behavior of geosynthetic clay liners (GCLs) and interfaces between GCLs and other geosynthetics or soils. One device was designed to simulate loading conditions that typically occur on a GCL deployed in a landfill cover system. The other device was designed to simulate loading conditions that typically occur on a GCL deployed in a landfill lining system. A needlepunched GCL was selected for evaluation of its long-term shearing behavior under these two types of loading conditions and the test results are presented in terms of time-displacement curves and shear rate-displacement curves. The results to date show that the GCL has undergone relatively small shear displacements and that the shear displacement rates within the GCL and/or at the test interface have been continuously decreasing with time. For the conditions used in this testing program, it is believed that the GCL's behavior can be considered stable. Further testing is planned to more accurately define the time-dependent internal and interface shear behavior of the GCL.

KEYWORDS: geosynthetic clay liner, shear strength, creep, direct shear, needle-punched, reinforced, landfill cover, landfill liner, constant-load creep shear test .

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Geosynthetic clay liners (GCLs) have been generally defined as manufactured hydraulic barriers consisting of clay bonded to a layer or layers of geosynthetic material(s). The geosynthetic components are typically geotextiles and/or geomembranes, and the clay component is usually a sodium bentonite. Commercially available GCLs consist of bentonite that is either sandwiched between two geotextiles or is bonded to a single geomembrane. GCLs may further be categorized as *unreinforced* and *reinforced*. Unreinforced GCLs have no internal reinforcement and typically possess very low shear strength. Reinforced GCLs, by means of needling, stitching, or adhesives, are designed to carry and transmit shear loads within their structure and are typically used in landfill lining and closure systems built on steep slopes. The GCL used in this testing program was a reinforced GCL, known as Bentomat ST, manufactured by Colloid Environmental Technologies Company (CETCO), Arlington Heights, Illinois, and consisted of a woven geotextile on one side of the bentonite component and a nonwoven geotextile on the other side of the bentonite component, reinforced with needlepunched fibers.

GCLs are very effective hydraulic barriers due to the flat shape of bentonite platelets and their unique ability to absorb large amounts of water. These same properties, however, cause a hydrated layer of bentonite to possess very low shear strength. Prior research [1, 2, 3] has shown that the shear strength of montmorillonite, the predominant component of bentonite, ranges from 4 to 10 degrees, depending on the species of montmorillonite and the range of applied normal stresses. Other research performed on unreinforced GCLs [4] indicates internal friction angles of 6 to 8 degrees under hydrated conditions. The internal shear strengths of reinforced GCLs are typically greater then those of unreinforced GCLs. For example the results of constant-displacement rate direct shear tests performed on a hydrated needlepunched GCL indicate a peak internal friction angle of 59 degrees under low normal stress conditions (i.e., 2 to 25 kPa) and a peak friction angle of 24 degrees under high normal stress conditions (i.e., 95 to 980 kPa) [5, 6].

While the short-term peak shear strength of a needlepunched reinforced GCL is quite high, there is growing concern that a significant portion of the short-term shear strength may be lost in the long term due to creep deterioration of the geosynthetic components and/or reinforcing materials. It is important to define "creep" within the context of this study. This term has usually been applied to single-component geosynthetics such as geotextiles, geomembranes, and geogrids where creep involves the elongation/stretching of the polymeric molecules over time. In other words, a dimensional change occurs as a result of gradual molecular reorganization with time. For the GCL used in this test program, the dimensional change is known as *displacement*, which is the lateral separation of the geotextiles in response to the applied shear force. The observed displacement may be attributable to simple elongation of geotextiles and initial stretching of needlepunched fibers, true creep of the needlepunched fibers, gradual "pullout" of the fibers, or any combination of these phenomena. Loss of the short-term shear strength of the GCL must be evaluated via adequate laboratory tests.

such as large scale constant-load creep shear testing developed by the authors of this paper. Specific details of the constant-load creep shear test devices and testing procedures will be described in this paper. The constant-load shear devices were used to evaluate the long-term shear behavior of the GCL under loading conditions which typically occur in landfill cover and liner systems. The results of the tests are presented in terms of time-displacement curves and shear rate-displacement curves.

TESTING EQUIPMENT AND CALIBRATION

Equipment

Two large-scale creep shear test devices were designed and fabricated by the authors in general accordance with the equipment descriptions provided in ASTM Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method (D 5321) for constant-rate of shear testing. One device was designed to evaluate the long-term shear behavior of geosynthetics materials under low normal and shear stress conditions typically found in a landfill cover system. The other device was designed to evaluate the long-term shear behavior of geosynthetic materials under high normal and shear stress conditions typically found in a landfill liner system. The two test devices were similar in structure except for their loading systems. Each of the two test devices consisted of four major components:

- a rigid supporting table;
- an upper shear box measuring 300 mm by 300 mm in plan and 75 mm in depth and a lower shear box measuring 300 mm by 350 mm in plan and 75 mm in depth;
- a containment box to allow the test specimen to be tested under fully submerged conditions; and
- normal and shear loading systems.

For the low-pressure test device, both normal and shear loads were applied to the test specimens using dead weight. A mechanical advantage loading system was used to apply the shear force to the test specimen. The low pressure test device was designed to operate in a normal stress range of 2 to 70 kPa for a 300 mm by 300 mm test specimen. For the high-pressure test device, normal loads were applied to the test specimen through an air bladder system and shear loads through a direct loading system consisting of three 150 mm diameter air cylinders connected in parallel. The high-pressure device was designed to operate in a normal stress range of 70 to 850 kPa for a 300 mm by 300 mm test specimen. The two constant-load shear devices are schematically shown in Figs. 1 and 2.

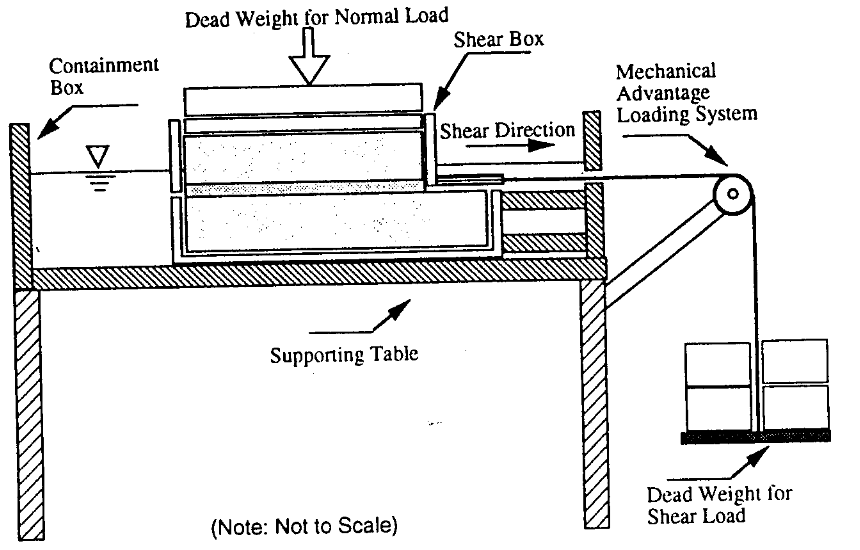


FIG. 1--Schematic of low pressure creep shear test device.

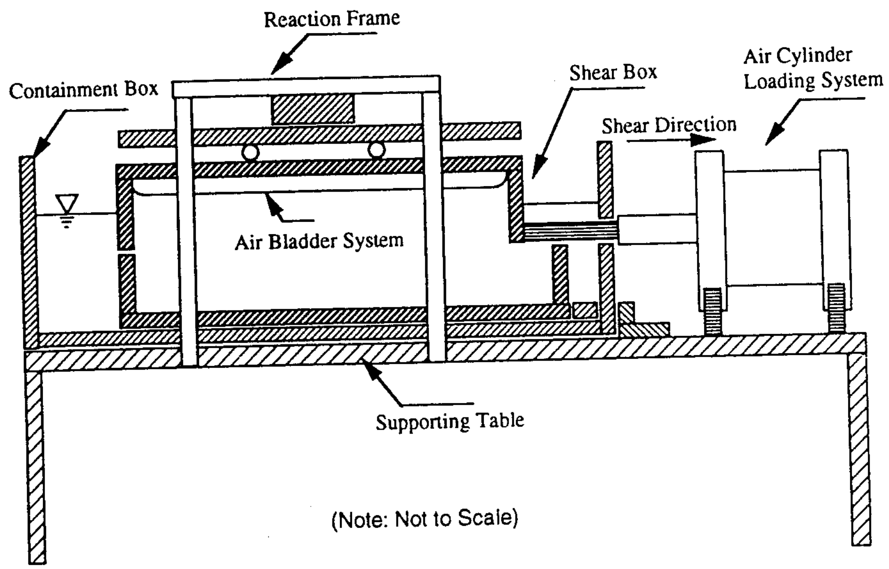


FIG. 2--Schematic of high pressure creep shear test device.

Calibration of Loading Systems

Prior to testing, calibration tests were performed on the high pressure test device to establish the relationship (i.e., calibration curve) between applied source pressures (i.e., pressure within the air cylinders and air bladder) in each loading system and actual loads delivered onto the test specimen by each loading system. Source pressures and actual normal or shear loads were measured by variable reluctance pressure transducers and electronic load cells, respectively, each recorded by a computer data acquisition system.

For the calibration of the air bladder system, an electronic load cell was placed between the air bladder system and the rigid steel reaction frame (see Fig. 2). A normal load versus pressure curve was established for source pressures ranging from 70 to 1,050 kPa. The maximum load delivered by the air bladder was approximately 80 kN at a source pressure of 1,050 kPa. It is noted that the actual normal load on top of the air bladder system is not the same as that transmitted to the test specimen. The actual applied normal load to the specimen equals the sum of the measured reaction load, weight of the air bladder system, and the test specimen itself.

For the calibration of the shear loading system (three parallel-connected air cylinders), an electronic load cell was mounted onto a steel block which was fixed to the supporting table. The load cell was then connected to the loading harness of the air cylinders through a steel rod. A shear load versus pressure curve was established for source pressures ranging from 7 to 1,050 kPa. Since the loading system was direct (no mechanical advantage), it was assumed that the applied force would remain constant and independent of displacement.

For the low pressure test device, the loads (i.e., normal and shear) were applied through dead weight, very little calibration was required. However, since a mechanical advantage loading system was used to apply the shear load, a similar calibration verification of the shear loading system was conducted except with the use of dead weight.

<u>Trial Tests</u>

To further confirm the two test devices were functioning properly, trial tests were conducted on an interface between a nonwoven geotextile and 1.5-mm thick smooth high density polyethylene (HDPE) geomembrane. The tests were conducted in accordance with the following test procedures:

- a fresh specimen of concrete sand was compacted into the lower shear box by hand tamping to a relatively dense state under dry conditions, forming a 75-mm thick bedding layer;
- fresh specimens of the geotextile and geomembrane were attached to the upper and lower shear boxes, respectively, with mechanical compression clamps;
- a rigid substrate was then placed on top of the geotextile specimen;
- normal loads were then applied to the test specimen through the air bladder system or using dead weight; and
- shear loads were then applied to the test specimen by increasing dead weight or air pressure within the air cylinders until sliding occurred at the test interface. The ultimate dead weight or maximum pressure within the air cylinders was recorded.

The results of the trial tests indicated that the friction angle of the geotextile-geomembrane interface was 13 degrees for normal stresses ranging from 7 to 35 kPa as measured in the low pressure test device, and 12 degrees for normal stresses ranging from 70 to 700 kPa as measured in the high pressure test device. These results are consistent with those measured by using a constant rate of shear displacement direct shear testing device (ASTM D 5321). Based on the results of these trial tests it was determined that the test devices were functioning properly.

TEST PROGRAMS

Test Materials

A needlepunched reinforced GCL (Bentomat ST) and a 2-mm thick blown-film textured HDPE geomembrane were used in the testing program. The reinforced GCL consisted of a bentonite layer sandwiched between a woven and nonwoven geotextile and reinforced with needlepunched fibers. The reinforced GCL had a typical bentonite mass per unit area of 5,000 g/m^2 and an initial (as-manufactured) moisture content of approximately 20 percent. The initial thickness of the reinforced GCL was approximately 6 mm.

Test Specimen Configurations

Two constant-load shear tests were conducted to evaluate the long-term shearing behavior of: (i) the reinforced GCL under loading conditions similar to those found in a landfill cover system and (ii) the reinforced GCL and an interface between the reinforced GCL and the textured HDPE geomembrane under loading conditions similar to those found in a landfill lining system. The configurations of the test specimens used in the two tests were as follows:

- *Test Number 1:* internal strength of the reinforced GCL under soaked and consolidated conditions. From top to bottom, the test specimen consisted of:
  - rigid substrate with textured steel gripping surface;
  - reinforced GCL;
  - rigid substrate with textured steel gripping surface; and
  - bedding layer of concrete sand.

- *Test Number 2:* internal strength of the reinforced GCL and interface between the woven geotextile of the reinforced GCL and the 2-mm textured HDPE geomembrane. From top to bottom, the test specimen consisted of:
  - rigid substrate with textured steel gripping surface;
  - reinforced GCL with woven geotextile against geomembrane;
  - 2-mm thick textured HDPE geomembrane; and
  - bedding layer of concrete sand.

It is noted that the textured steel gripping surfaces were developed by the authors during the course of establishing the testing procedures for measuring short-term internal shear strength of GCLs [5, 6]. The textured steel gripping surfaces are employed to minimize slippage between the geotextile component of the reinforced GCL and the rigid wooden substrate, therefore providing a relatively uniform transfer of shear load into the GCL specimen and/or onto the test interface.

Test Procedures and Conditions

For Test 1 (low pressure test), a fresh reinforced GCL specimen was trimmed from the bulk sample of the reinforced GCL and constrained between two rigid wooden substrates with the use of textured steel gripping surfaces. The ends of each geotextile were then sandwiched between a second rigid wooden substrate prior to testing as shown in Fig. 3. The entire test specimen was then placed in the shear box to provide confinement for the exposed bentonite component. The test specimen was then subjected to the following soaking and shearing target conditions:

1. Soaking. In tap water for 120 hours under a normal stress of 24 kPa. The normal stress used for soaking was applied prior to immersion.

2. Shearing. After the 120-hour soaking period, a constant shear load of 1.1 kN was applied to the reinforced GCL specimen using dead weight without any disruption of the soaking normal stress. The total shear load was applied to the test specimen over a period of 10 to 15 seconds in a controlled manner.

Two dial gages were used to measure vertical displacements of the GCL during soaking and shearing. Shear displacement of the GCL was measured by a dial gage attached to the upper shear box. Both vertical and shear displacements were monitored on a regular basis.

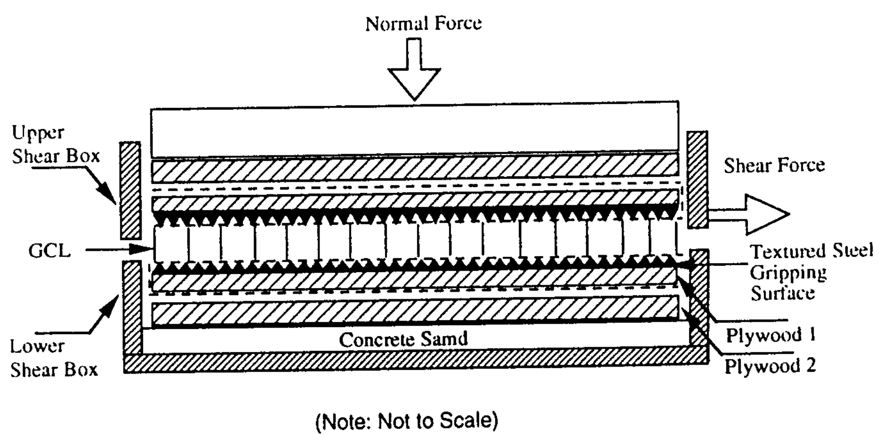


FIG. 3--Schematic of GCL test specimen configuration for Test 1.

For Test 2 (high pressure test), the concrete sand was compacted into the lower shear box by hand tamping to a relatively dense state under dry conditions, forming a 75-mm thick layer. A fresh geomembrane specimen was then placed on top of the compacted concrete sand and attached to the lower shear box with mechanical compression clamps. A fresh reinforced GCL specimen was then placed on top of the geomembrane specimen with its woven geotextile component in contact with the geomembrane. A rigid substrate with a textured steel gripping surface was placed on top of the reinforced GCL. The complete configuration of Test 2 is shown in Fig. 4. The test specimen was then subjected to the following soaking, consolidation, and shearing target conditions:

1. Soaking. In tap water for 120 hours under a normal stress of 19 kPa which was applied using dead weight. The normal stress used for soaking was applied prior to immersion.

2. Consolidation and Shearing Phase 1. Consolidated for 120 hours under a normal stress of 97 kPa and then subjected to a constant shear stress of 34 kPa for 1,000 hours.

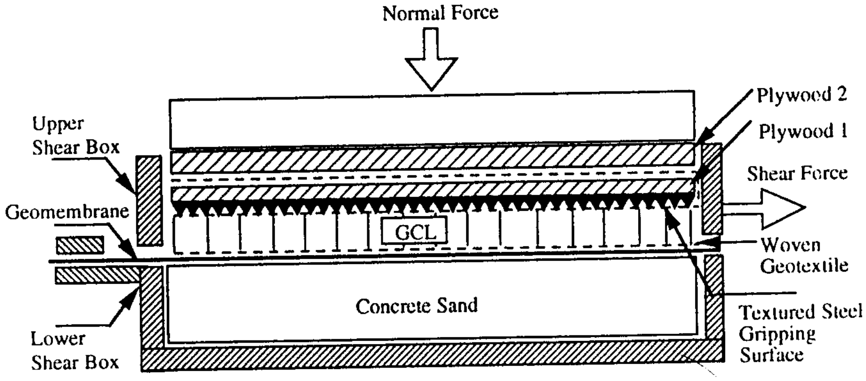
3. Consolidation and Shearing Phase 2. Consolidated for 120 hours under a normal stress of 194 kPa and then subjected to a constant shear stress of 68 kPa for 1,000 hours.

4. Consolidation and Shearing Phase 3. Consolidated for 120 hours under a normal stress of 292 kPa and then subjected to a constant shear stress of 102 kPa for 1,000 hours.

5. Consolidation and Shearing Phase 4. Consolidated for 120 hours under a normal stress of 389 kPa and then subjected to a constant shear stress of 136 kPa for 1,000 hours.

6. For each loading phase, the shear load was applied to the test specimen over a period of 10 to 15 seconds in a controlled manner.

Similar to Test 1, two dial gages were used to measure vertical displacements of the test specimen throughout the test. Shear displacements of the test specimen were measured by two dial gages attached to the upper shear box and the lower woven geotextile component, respectively. Displacements measured from the woven geotextile directly indicated the shear displacement between the reinforced GCL and the geomembrane. Differential displacements between the upper shear box and the woven geotextile indicated the shear displacement within the GCL.



(Note: Not to Scale)

FIG. 4--Schematic of GCL test specimen configuration for Test 2.

The ratio of shear load to normal load used in Tests 1 and 2 were 1:2 and 1:5 respectively. Test 1 simulated loading conditions on a GCL used in a landfill closure system constructed on a 2H:1V side slope. Test 2 simulated loading conditions on a GCL used in a landfill liner system constructed on a 5H:1V side slope. These loading conditions imposed onto each test specimen are indicated on the short-term shear strength plots for the two test specimens (Figs. 5 and 6). The constant shear stress was approximately 23 percent of the peak short-term shear strength of the reinforced GCL for Test 1 as indicated in Fig. 5. For Test 2, the constant shear stress varied from approximately 40 to 70 percent of the peak short-term shear strength of the reinforced GCL as indicted in Fig. 6. It is also noted that the short-term interface shear strength of a woven geotextile component of a reinforced GCL against a textured geomembrane is typically lower than that of the internal shear strength of the reinforced GCL.

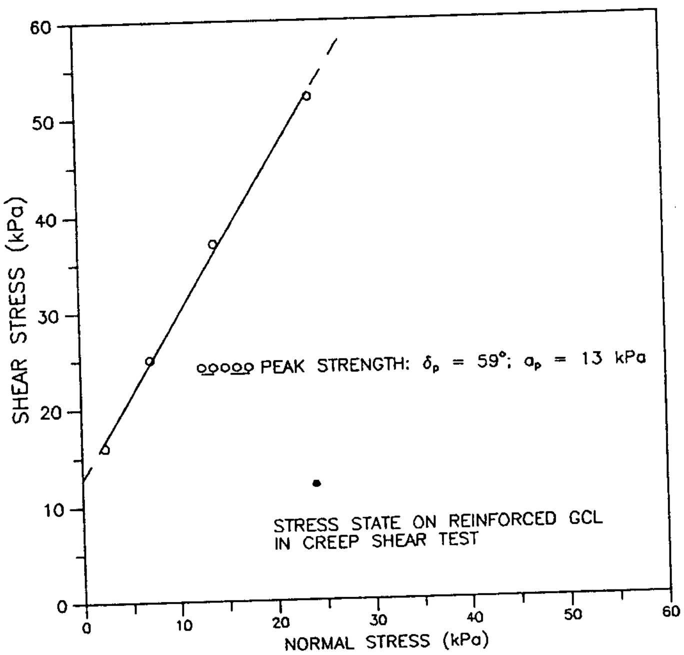


FIG. 5-- Plot of the loading condition for Test 1 on the reinforced GCL with the short-term peak shear strength envelope of the GCL at low normal stresses [5].

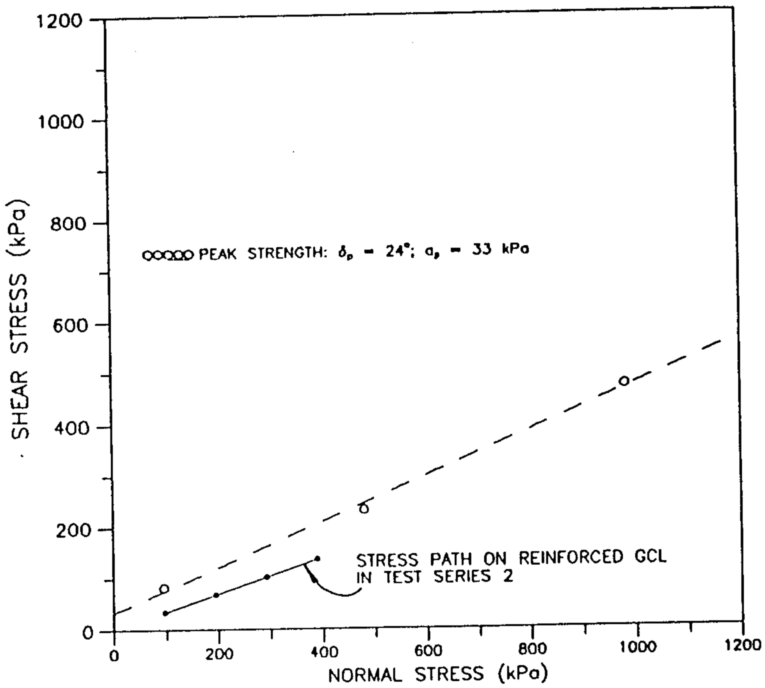


FIG. 6-- Plot of the loading path for Test 2 on the reinforced GCL-geomembrane interface with the short-term peak shear strength envelope of the GCL at high normal stresses [6].

TEST RESULTS

Test Series 1 (Low Pressure Test)

The results of the constant-load creep shear test (Test 1) conducted on the reinforced GCL are presented graphically in Figs. 7 through 10. Fig. 7 indicates that the reinforced GCL was initially compressed and then swelled under the applied soaking normal stress. Fig. 8 indicates that the reinforced GCL specimen underwent a slight shear distortion immediately after application of the shear load and that it compressed slightly during shearing. Figs. 9 and 10 indicate incremental shear displacement rates decreased from approximately 12 mm/min at the beginning of shearing to approximately 1 x 10^{-7} mm/min.

A summary of shear displacement and incremental shear rates at select times is presented in Table 1. This table presents the total shear displacements and incremental shear rates at 1, 10, 100, 500, 1,000, and 10,000 hours of elapsed time for the creep shear test. It is noted that the values of total displacement and incremental shear rate at these selected times presented in Table 1 were derived by linear interpolation between the actually measured data points at each specific time period of interest.

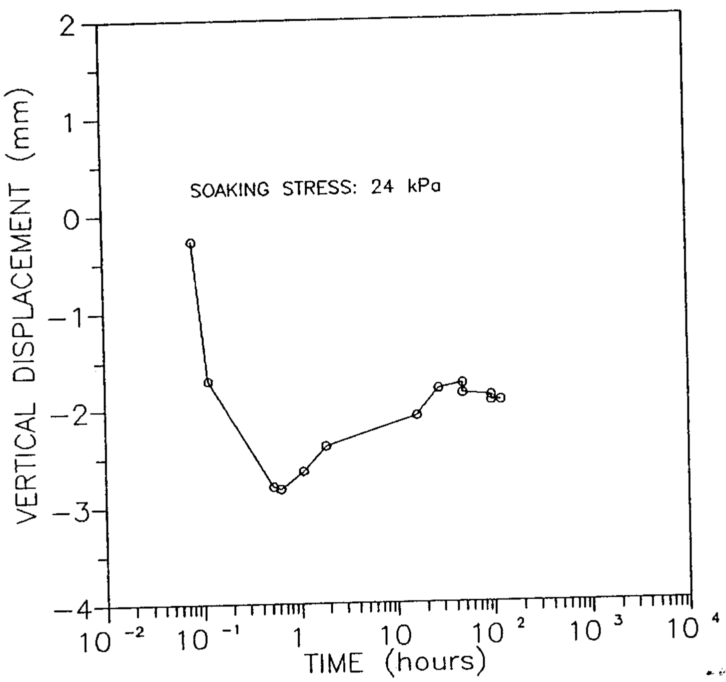


FIG. 7-- Plot of vertical displacement versus log time for Test 1.

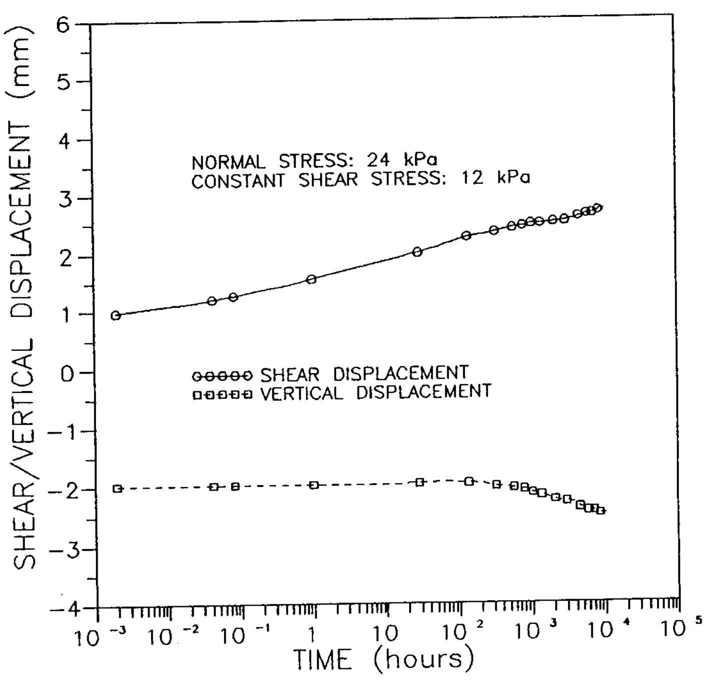


FIG. 8-- Plot of shear and vertical displacements versus log time for Test 1.

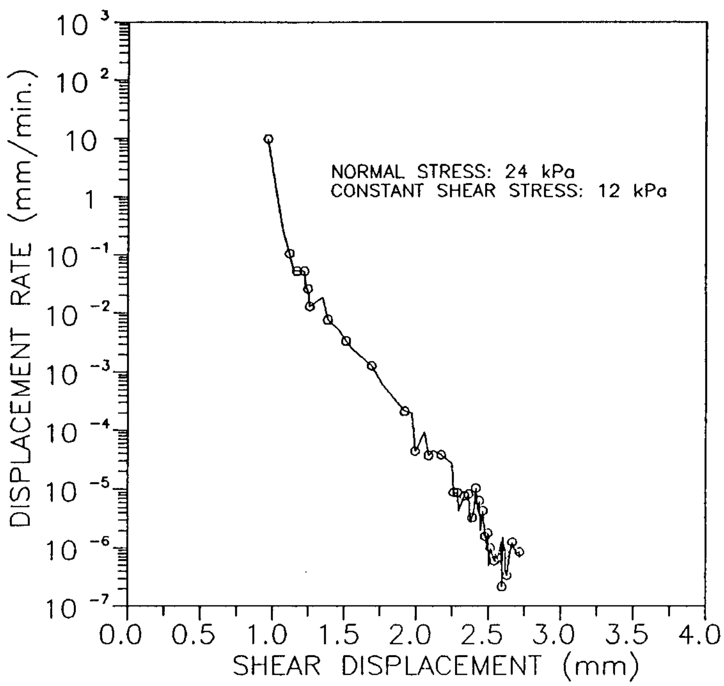


FIG. 9-- Plot of log displacement rate versus shear displacement for Test 1.

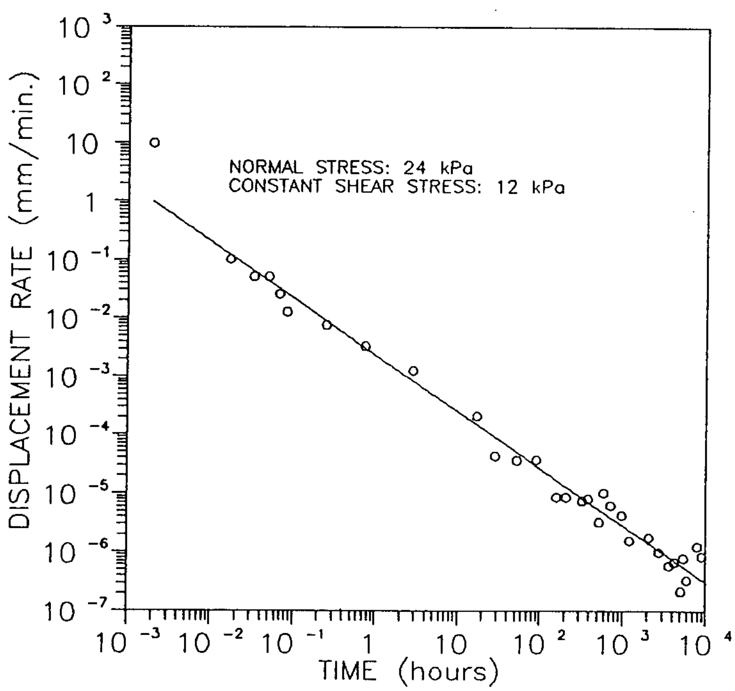


FIG. 10-- Plot of log displacement rate versus log time for Test 1.

TABLE 1--Summary of Test 1 creep shear test results.

Test Number 1 Test Specimen and Loading Conditions	Elapsed Time (hours)	Total Shear Displacement (mm)	Incremental Shear Rate (mm/min)
Needle-punched GCL Under Hydrated Conditions	1	1.5	3.38×10^{-3}
	10	1.7	9.93×10^{-4}
	100	2.1	4.22×10^{-5}
	500	2.4	4.72×10^{-6}
Normal Load: 1.1 kN	1,000	2.5	2.84×10^{-6}
Shear Load: 0.56 kN	10,000	2.7	5.49×10^{-7}

Test Series 2 (High Pressure Test)

The reinforced GCL and reinforced GCL-geomembrane interface in Test 2 were subjected to an initial soaking followed by four consolidation/shearing phases. Compression and swelling of the test specimen during the soaking phase are shown in Fig. 11. The results of a typical loading phase are graphically presented in Figs. 12 through 15 in terms of vertical/shear displacements versus logarithm of time, logarithm of shear displacement rate versus shear displacement, and logarithm of shear displacement rate versus logarithm of time.

A summary of shear displacement and incremental shear rates at select times is presented in Table 2. This table presents the total shear displacements and incremental shear rates at 1, 10, 100, 500, and 1,000 hours of elapsed time for each phase of the creep shear test. It is noted that the values of total displacement and incremental shear rate at these selected times presented in Table 2 were derived by linear interpolation between the actually measured data points at each specific time period of interest. It should be also noted that since this was a research study, some of the loading phases were maintained and monitored longer than the targeted 1000 hours (i.e., up to 1900 hours for one of the phases). The behavior of these extended loading phases was found to follow the trends established in the first 1000 hours. For comparison purposes the data for the first 1000 hours of each loading phase are presented. The overall test duration of Test 2 was approximately 7,200 hours, including all of the soaking, consolidation, and shearing phases.

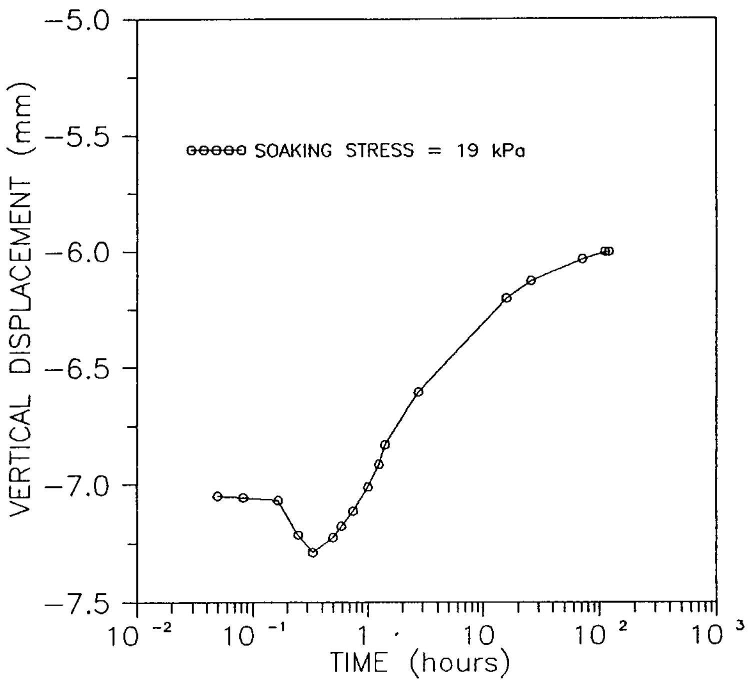


FIG. 11-- Plot of vertical displacement versus log time for the soaking phase of Test 2.

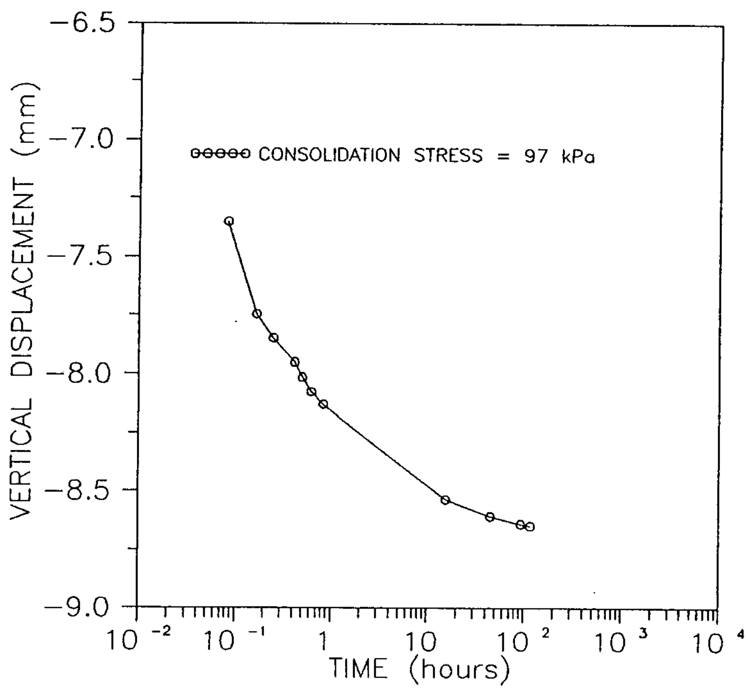


FIG. 12-- Plot of vertical displacement versus log time for one of the loading phases of Test 2.

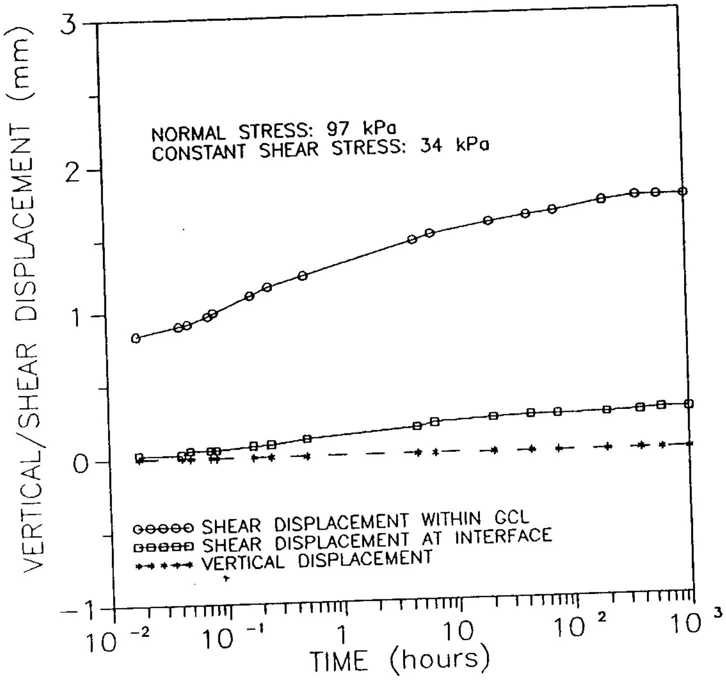


FIG. 13-- Plot of shear and vertical displacements versus log time for one of the loading phases of Test 2.

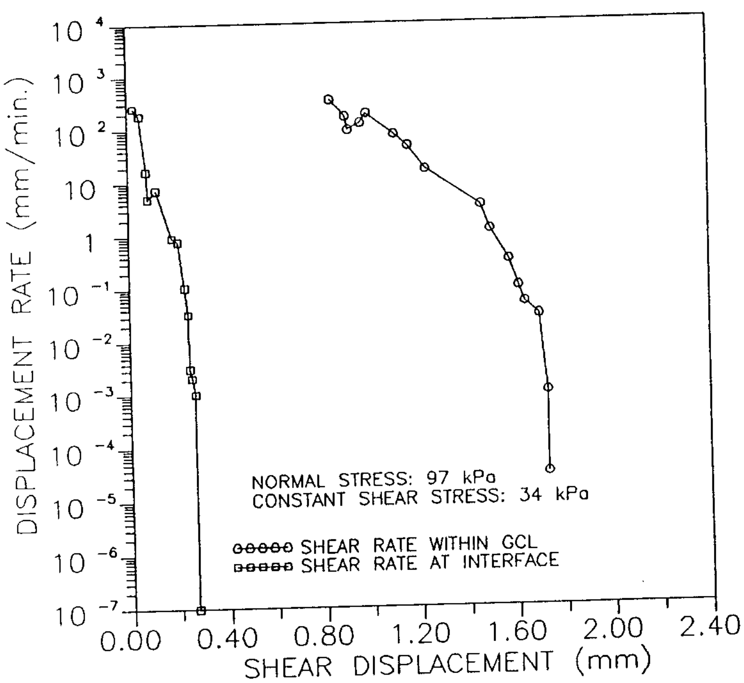


FIG. 14-- Plot of log displacement rate versus shear displacement for one of the loading phases of Test 2.

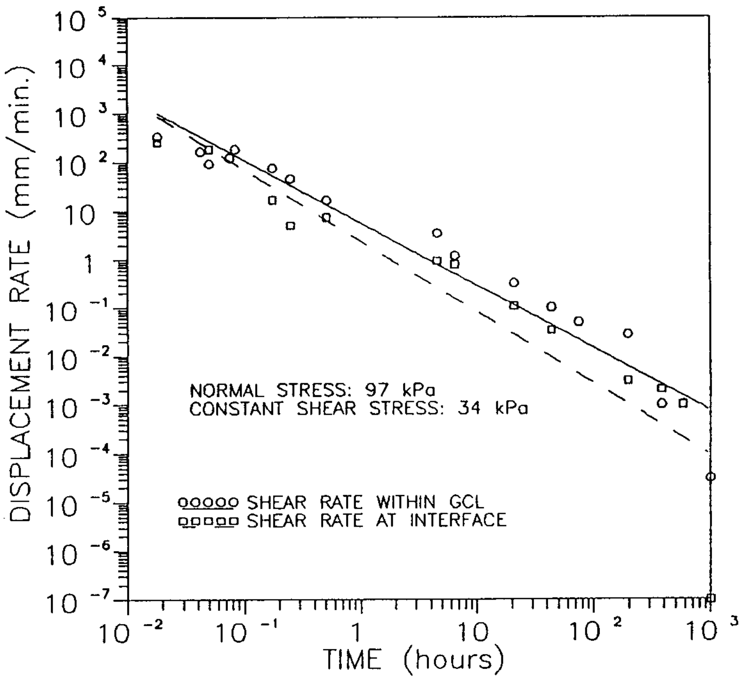


FIG. 15-- Plot of log displacement rate versus log time for one of the loading phases of Test 2.

SUMMARY AND DISCUSSIONS

Two constant-load creep shear test devices were designed and fabricated. The creep shear test devices were used to evaluate the long-term shear behavior of a reinforced GCL under loading conditions typical of those occurring in a landfill cover system and a landfill liner system. The results of these tests are presented in terms of time-displacement curves and shear rate-displacement curves. Shear displacements and shear rates for the two tests at select times are summarized in Tables 1 and 2. The test results of the two tests indicated that: (i) the reinforced GCL specimen underwent a shear distortion immediately after application of the shear load and then started to creep and (ii) incremental shear rates decreased during shearing. The results of Test 2 also indicted that the reinforced GCL specimen underwent a small "translation" along the geomembrane immediately after application of the shear load during each loading phase and then seemed to stop and creep of the reinforced GCL was observed.

Attempts have been made to address the concerns over the long-term strength behavior of the reinforced GCLs through the two constant-load creep shear tests. Data obtained from the two tests conducted at low and high normal and shear stresses indicated that the total accumulated shear displacement within the reinforced GCL or at the test interface was on the order of 0.4 mm (Test 2 interface) to 2.7 mm (Test 1 GCL) or 3.5 mm (Test 2 GCL). It can also be seen from the data for both tests that the

TABLE 2--Summary of Test 2 creep shear test results.

Test Specimen and Loading Conditions	Elapsed Time (hours)	Total Shear Displacement of GCL (mm)	Total Shear Displacement of Interface (mm)	Incremental Shear Rate of GCL (mm/min.)	Incremental Shear Rate of Interface (mm/min.)
Needle-Punched GCL/80-mil Textured HDPE Geomembrane Under Soaked Conditions Normal Load: 8.9 kN Shear Load: 3.2 kN	1 10 100 500 1,000	1.3 1.5 1.7 1.7 1.7	0.1 0.2 0.3 0.3 0.3	1.47×10^{-1} 9.78×10^{-1} 4.47×10^{-2} 4.17×10^{-3} 3.12×10^{-5}	6.6×10^{0} 6.27×10^{-1} 6.25×10^{-4} 3.15×10^{-4} 1.06×10^{-7}
Needle-Punched GCL/80-mil Textured HDPE Geomembrane Under Soaked Conditions Normal Load: 17.8 kN Shear Load: 6.2 kN	1 10 100 500 1,000	2.1 2.2 2.3 2.4 2.5	0.3 0.3 0.3 0.3 0.3	1.57×10^{-3} 8.79×10^{-4} 2.36×10^{-5} 4.78×10^{-6} 4.32×10^{-6}	0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0}
Needle-Punched GCL/80-mil Textured HDPE Geomembrane Under Soaked Conditions Normal Load: 26.7 kN Shear Load: 9.4 kN	1 10 100 500 1,000	2.6 2.6 2.7 2.8 2.8	0.3 0.3 0.3 0.3 0.3	4.14×10^{-4} 1.94×10^{-4} 2.67×10^{-5} 2.62×10^{-6} 1.74×10^{-6}	0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0}
Needle-Punched GCL/80-mil Textured HDPE Geomembrane Under Soaked Conditions Normal Load: 35.6 kN Shear Load: 12.5 kN	1 10 100 500 1,000	3.0 3.1 3.3 3.5 3.5	0.4 0.4 0.4 0.4 0.4	1.32×10^{-4} 1.71×10^{-4} 9.27×10^{-6} 1.26×10^{-7} 1.11×10^{-7}	0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0} 0.00×10^{-0}

majority of the total accumulated shear displacement happened within the first 100 hours of each test/loading phase. Hence the actual time-dependent displacement (creep) is probably on the order of 0.2 to 0.6 mm for each test/loading phase. For the reinforced GCL in both tests, incremental shear rates decreased with time from approximately 1 x 10^{-1} mm/min to approximately 1 x 10^{-7} mm/min during shearing. For the reinforced GCL-geomembrane interface, incremental shear rates decreased rapidly to zero after application of the shear load.

While no other long-term shear test data exist at this time, these results are consistent with previous project experience of the authors and the large-scale field test in progress in Cincinnati, USA, [7]. These results are also consistent with short-term testing performed on the reinforced GCL which indicates that the reinforced GCL is capable of sustaining greater loads than were applied during each of the long-term tests. More testing will be performed to further assess the long-term internal and interface shear strength behavior of the reinforced GCL under various loading conditions.

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