Bentonite Mat Demonstration—Final Report (U)

by

M. G. Serrato

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BENTONITE MAT DEMONSTRATION

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by

Michael G. Serrato

December 30, 1994

Westinghouse Savannah River Company
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EXECUTIVE SUMMARY

Purpose

The Bentonite Mat Demonstration was developed to provide the Environmental Restoration Department with field performance characteristics and engineering data for an alternative closure cover system configuration. The demonstration was initiated in response to regulatory concerns regarding the use of an alternative cover system for future design configurations. These design considerations are in lieu of the US Environmental Protection Agency (EPA) Recommended Design for Closure Cover Systems and specifically a single compacted kaolin clay layer with a hydraulic conductivity of 1×10^{-7} cm/sec. This alternative configuration is a composite geosynthetic material hydraulic barrier consisting from bottom to top: 2 ft. compacted sandy clay layer (typical local Savannah River Site soil type) that is covered by a bentonite mat - geosynthetic clay liner (GCL) and is overlaid by a 40 mil High Density Polyethylene (HDPE) geomembrane - flexible membrane liner. This effort was undertaken to obtain and document the necessary field performance/engineering data for future designs and meet regulatory technical requirements for an alternative cover system configuration. The composite geosynthetic materials hydraulic barrier is the recommended alternative cover system configuration for containment of hazardous and low level radiological waste layers that have a high potential of subsidence to be used at the Savannah River Site (SRS). This alternative configuration mitigates subsidence effects in providing a flexible, lightweight cover system to maintain the integrity of the closure. The composite geosynthetic materials hydraulic barrier is recommended for the Sanitary Landfill and Low Level Radiological Waste Disposal Facility (LLRWDF) Closures.

How the Demonstration was Conducted

The Bentonite Mat Demonstration was conducted in two phases: Phase One - Control Test Pad and Phase Two - Geosynthetic Materials Test Pads. Phase One focused on the structural and hydraulic performance characteristics of a 2 ft. compacted sandy clay layer in response to induced subsidence. The sandy clay soil is the foundation of the composite geosynthetic materials hydraulic barrier and provides the performance baseline for Phase Two. Phase Two focused on the geosynthetic materials and their

structural and hydraulic performance in response to induced subsidence. All test pads used conventional construction methods and specifications. All test pads were configured identically (except for the installation of geosynthetic materials) with the following cross-section from bottom to top: a 4 ft. sand layer, 1 ft. separation layer - silty soil, 2 ft. compacted sandy clay layer and 1-2 ft. cover soil layer. Four test pads were constructed - one as the Control Test Pad and three as the Geosynthetic Materials Test Pads. Three US manufactured geosynthetic clay liner materials (GCL): Gundseal® -Gundle Lining Systems Incorporated, Claymax® 500 SP - James Clem Corporation, and Bentomat® SS - Colloid Environmental Technologies Company. In addition, each Geosynthetic Materials Test Pad was covered by a 40 mil Gundline® HD smooth High Density Polyethylene (HDPE) geomembrane from Gundle Lining Systems, Incorporated. Overlying the installed geosynthetic materials was a cover soil layer; this test pad configuration was for Phase Two.

Final Report Contents

This final report examines the testing results and observations achieved from both Phase One - Control Test Pad Testing and Phase Two - Geosynthetic Materials Test Pad Testing of the Bentonite Mat Demonstration. The final report provides an overall review of the testing results and compares the results to the previous Kaolin Clay Test Cap Testing Program conducted at the Savannah River Site (SRS).

Phase One Results

The observations and test results obtained from Phase One - Control Test Pad Testing establishes a performance baseline for the compacted sandy clay layer and its hydraulic and structural characteristics in response to induced subsidence. High and low stress testing cases were completed for unsaturated and saturated soil conditions. The sandy clay layer is a durable and resilient soil matrix that can span voids up to 6 ft. wide in an unsaturated soil condition and 5 ft. wide for a saturated soil condition. The *in situ* saturated hydraulic conductivity of a 2 ft. compacted sandy clay is 2×10^{-6} cm/sec. The combination of this soil matrix with the hydraulic properties of geosynthetic materials provides the

foundation of the composite geosynthetic materials hydraulic barrier alternative closure cover system configuration.

Phase Two Results

Phase Two - Geosynthetic Materials Test Pad Testing results demonstrated the structural and hydraulic performance characteristics of the composite geosynthetic materials hydraulic barrier under induced subsidence. High and low stress testing scenarios were examined for both saturated and unsaturated soil conditions. The composite geosynthetic materials hydraulic barrier was able to span 7 ft. void without impacting the hydraulic and structural integrity of the hydraulic barrier for both saturated and unsaturated soil conditions. This performance was not dependent on the geosynthetic materials seam alignment. The composite geosynthetic materials hydraulic barrier's hydraulic conductivity - 1×10^{-10} cm/sec - did not degrade due to induced subsidence. The composite geosynthetic materials hydraulic barrier's sealing/repair capability was demonstrated and successfully sealed a breach of the overlying geomembrane in response to induced subsidence. No differences in performance between the GCL materials tested were observed.

Comparison with Compacted Kaolin Clay

Performance characteristics comparisons were made of the composite geosynthetic materials hydraulic barrier to an established compacted kaolin clay hydraulic barrier based on the previous Mixed Waste Management Facility Clay Cap Testing Program's results. The composite geosynthetic materials hydraulic barrier increased the maximum cavity span width without a hydraulic head by 70%, and the maximum cavity span width with a hydraulic head was increased over 200%. The composite geosynthetic materials hydraulic barrier's hydraulic conductivity - 1×10^{-10} cm/sec - did not degrade responding to induced subsidence, but the compacted kaolin clay layer hydraulic conductivity did degrade.

Conclusions

The Bentonite Mat Demonstration conclusion was that the composite geosynthetic materials hydraulic barrier exceeds the performance characteristics of a compacted Kaolin Clay layer and meets or exceeds both EPA and South Carolina Department of Health and Environmental Control (SCDHEC) technical requirements for a RCRA/CERCLA Closure Cover System. The composite geosynthetic materials hydraulic barrier in a closure cover configuration provides the flexibility and durability to ensure the containment of hazardous and low level radiological waste layers for both RCRA and CERCLA Closures. This alternative cover system configuration is the recommended closure cover system hydraulic barrier configuration to be used over waste layers that have a high potential of subsidence at the SRS. The Bentonite Mat Demonstration is a pro-active approach to validate cost-effective remedial actions, continuous improvement through technology and engineering development, and to ensure our commitment to protect human health and the environment.

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INTRODUCTION

Purpose

This final report examines the testing results and observations achieved from both Phase One - Control Test Pad Testing and Phase Two - Geosynthetic Materials Test Pad Testing of the Bentonite Mat Demonstration. The final report provides an overall review of the testing results and compares the results to the previous kaolin clay test cap testing programs conducted at the Savannah River Site (SRS).

The Bentonite Mat Demonstration was conducted as a cooperative effort between Environmental Restoration Engineering, Environmental Restoration Waste Sites, Savannah River Technology Center, Bechtel Savannah River, Inc., and Raytheon Engineers and Constructors, Inc. The lead organization for this demonstration was Environmental Restoration Engineering.

The Bentonite Mat Demonstration was developed to provide field performance characteristics and engineering data for an alternative closure cover system configuration. The alternative configuration was a composite of geosynthetic materials combined with a local SRS compacted sandy clay soil to form the closure cover system hydraulic barrier. The demonstration was initiated in response to regulatory concerns regarding the use of a composite geosynthetic materials alternative cover system for future design configurations. This demonstration also established the protocol for testing/demonstrating other cover system barrier materials. This effort was undertaken to obtain and document the necessary field performance/engineering data for future design and meet regulatory technical requirements for an alternative cover system configuration. The composite geosynthetic materials hydraulic barrier is an alternative cover system configuration that adds a design option for the selection of closure cover system hydraulic barrier materials, especially over waste layers with a high potential subsidence, to be used at the SRS.

Background

The U.S. Environmental Protection Agency (EPA) - *Guide to Technical Resources for the Design of Land Disposal Facilities*¹ and EPA - *Requirements for Hazardous Waste Landfill Design, Construction, and Closure*² and EPA - *Design and Construction of RCRA/CERCLA Final Covers*³ defines the general configuration of a multi-layered closure cover system. The cover system components are (from top to bottom) the vegetative cover layer, the drainage layer, and the low hydraulic conductivity layer/barrier. The low hydraulic conductivity barrier consists of two feet of compacted clay soil overlain by a geosynthetic flexible membrane liner material(s)-geomembrane. The cover system purpose is to mitigate rainfall percolation into the waste layers and producing leachate, which contributes to groundwater contamination. Hydraulic conductivity is the measure of the infiltration rate through a material. The regulatory recommended hydraulic conductivity for the cover system hydraulic barrier is 1×10^{-7} cm/sec or less.¹

Five closure cover systems have been installed at the SRS using a compacted kaolin clay layer as the primary hydraulic barrier. These cover systems are performing as designed and do not exhibit any major effects from hydraulic deterioration or structural degradation. The placement of a compacted clay over a waste layer that has a high potential for degradation is not a suitable application.⁴ Differential settlement caused by waste layer degradation produces tensile stresses in the compacted clay layer and ultimately propagates cracking through the entire clay layer thickness. This cracking through the clay layer significantly impacts the durability and integrity of the entire cover system to minimize infiltration. To compensate for waste degradation, a flexible, lightweight cover system is needed.

Deviations from the EPA recommended general design are required to be demonstrated to show performance equivalence and meet the intent of the regulations. The Bentonite Mat Demonstration documents the composite hydraulic barrier performance characteristics and demonstrates its equivalence to the EPA recommended design.

The Bentonite Mat Demonstration presents an innovative closure cover system which capitalizes on the low hydraulic conductivity and flexibility characteristics of geosynthetic materials and combines it with the structural capacity of the onsite sandy clay soil. This "innovative" alternative design is the closure cover system configuration recommended for the Sanitary Landfill Closure and the LLRWDF Closure. The Bentonite Mat Demonstration is necessary to ensure this alternative design achieves regulatory acceptance and verifies the design parameters for future closure projects totaling over \$70 million.

DEMONSTRATION OBJECTIVES

Primary Objectives

- Determine the *in situ* hydraulic conductivity of the composite geosynthetic materials hydraulic barrier system.
- Determine the performance characteristics of the composite geosynthetic materials hydraulic barrier system undergoing induced subsidence.
- Verify the *in situ* hydraulic conductivity of a compacted sandy clay soil layer.
- Determine the performance characteristics of the compacted sandy clay soil layer undergoing induced subsidence.
- Document the installation and construction requirements of the composite geosynthetic materials hydraulic barrier system.

Secondary Objective

Secondary objective of the Control Test Pad testing is the operability of the embedded instrumentation, effectiveness of the sand evacuation methods/techniques, and the remote sensing capability to monitor the test pad performance. The embedded instrumentation used in the control test pad evaluates the possible post monitoring instrumentation/configuration that could be used in future closure cover system configurations.

Test Phases

The Bentonite Mat Demonstration was conducted in two phases: Phase One - Control Test Pad, Phase Two - Geosynthetic Materials Test Pads. Phase One - Control Test Pad testing focused on the structural and hydraulic characteristics of 2 ft. compacted sandy clay layer. The sandy clay soil is the foundation of the composite geosynthetic materials hydraulic barrier and provides the performance baseline for Phase Two. Phase Two - Geosynthetic Materials Test Pads Testing focused on the geosynthetic materials and their structural and hydraulic performance in response to induced subsidence.

This final report summarizes the pre-test computer simulation study of the compacted sandy clay layer and the composite geosynthetic materials hydraulic barrier, test pad configuration and instrumentation, Phase One test pad configuration and testing results, Phase Two test pad configurations and testing results, and compared Phases One and Two tests results with previous kaolin clay test pad program results.

To facilitate the development of the Bentonite Mat Demonstration, a structural computer model was developed. This structural model was used to determine the potential structural performance of the compacted sandy clay layer and the composite geosynthetic materials hydraulic barrier cover system.

COMPUTER SIMULATION OF STRUCTURAL CAPACITY

Introduction

The initial concept regarding the structural capacity of the compacted sandy clay layer was that this layer would have a higher structural capacity than a compacted kaolin clay layer due to the increased coarse fraction of the sandy clay soil. A pre-test study of the structural analysis of the compacted sandy clay layer was completed by the Engineering Modeling and Simulation, Applied Technology Section of the Savannah River Technology Center.⁵ The study analyzed a compacted sandy clay layer and a composite geosynthetic materials - sandy clay layer using a finite element analysis method. The ABAQUS®, Version 5 computer code was used to perform the computer numerical simulations. The computer simulation employed the Drucker-Prager / Cap Plasticity Model to analyze these cover system configurations.

Subsidence Scenarios

Two subsidence scenarios were examined: localized subsidence and general subsidence. The localized subsidence scenario was developed as the "worst case" situation, where a container in the waste layer collapses causing a void to form in the waste layer. This "worst case" situation would in turn increase the stress of the overlying cover system trying to span the void in this immediate area. Typically, this scenario occurs in waste layers having a high volume of containers, e.g., 55 gallon drums, metal boxes, etc. The general subsidence scenario was evaluated as the long term consolidation/degradation of the entire waste layer. This long term degradation would impact the entire cover system and would not be confined to a localized area. The geometry of the cavity for the localized scenario was assumed to be a circular cavity, and the assumed geometry for the general scenario was an elliptical cavity across a trench.

Study Results

The study results indicate that for a circular cavity failure (localized subsidence) the maximum cavity size was a 12 ft. diameter circular cavity, and for a trench failure (general subsidence) the maximum span width was 10 ft. These model results point out the composite geosynthetic materials hydraulic barrier resiliency to span a void created by waste degradation.

Test pad construction and field performance testing for the Bentonite Mat Demonstration was developed based on the results of the computer structural analysis study and previous test pad testing programs.

TEST PAD CONFIGURATION

Test Pad Construction

The Bentonite Mat Demonstration consists of four test pads located adjacent to the intersection of E Road and 4 Road (see Figure 1 - Bentonite Mat Demonstration Plan View). Test pad dimensions are 50 ft. X 136 ft. X 8 ft. One test pad was used as the control test pad, and the remaining three test pads were used for geosynthetic materials testing (see Figure 2 - Bentonite Mat Demonstration Test Pad Sections). The cross-sectional view of the control test pad configuration and the geosynthetic materials test pad configuration is shown in Figure 3 - Test Pad Configurations. Each test pad was constructed with a 2 ft. compacted sandy clay layer which came from a local on site borrow area, and overlaid a 4 ft. loose sand layer. A 1 ft. separation layer was used as a marker horizon during sand evacuation cycles, in-between the sand layer and the compacted sandy clay layer. These soil layers were consistent for all test pads constructed.

Sandy Clay Soil

The sandy clay soil is a local SRS soil consisting of a suitable clay content coupled with sand and gravel to form an improved underlying soil with added structural capacity in comparison to a kaolin clay. The sandy clay soil used on the test pads has a typical grain size distribution curve as shown in Figure 4.

Figure 1 - Bentonite Mat Demonstration Plan View

Figure 2 - Bentonite Mat Demonstration Test Pad Sections

Figure 3 - Test Pad Configurations

Control Test Pad Configuration

Geosynthetic Materials Test Pad Configuration

Figure 4—
Grain Size Distribution Envelope for SRS Sandy Clay Soil

The soil fines content - clay/silt content (percent finer than a # 200 sieve -- 0.08 mm) ranges between 25 - 45 % and is approximately 35 % of the total soil weight. This clay content provides the hydraulic barrier characteristic of the compacted soil layer and is on an average 40 % less than a kaolin clay, in comparison.

The coarse fraction is primarily comprised of sand and coarse sand and is approximately 50 % of the total soil weight. This coarse fraction supplies the enhanced structural capacity by formulating a stable soil matrix when a mechanical force is applied to compact the soil layer. The addition of the fines content (i.e., clay particles) plugs the voids between the coarser soil particles, thus providing the hydraulic barrier characteristics of the sandy clay soil.

The plasticity index (PI) provides a reliable index for classifying clay properties in soil.⁶ Experience has shown that if the soil has extremely low plasticity (i.e. $PI \leq 7\%$), the soil possesses insufficient clay to develop low hydraulic conductivity when the soil is compacted.⁷ The plasticity index for this sandy clay soil was determined to be an average value of 15.

Table 1 depicts how well the sandy clay soil matrix measures up to EPA standards.⁷ Note the sandy clay soil meets and/or exceeds all criteria, except for gravel content.

Table 1 -- Comparison of the Recommended
EPA Soil Matrix vs. Sandy Clay Matrix

Soil Matrix Parameter	Recommended EPA Soil Matrix ⁷	On Site Sandy Clay Soil Matrix
Percent Fines (Particle size < 0.08 mm)	~ 30 - 50	35
Percent Gravel/Sand (Particle size ≥ 4.76 mm)	~ < 50	65 (Coarse Fraction - sand & coarse sand)
Plasticity Index (%)	~ 10 - 30	15
Maximum Particle Size (mm)	~ 25 - 50	4.5

The sandy clay percent gravel or coarse fraction is above the EPA soil matrix. This should not be considered detrimental to the hydraulic barrier and structural characteristics of the sandy clay soil for the following reasons: the make-up of the coarse fraction for the sandy clay is predominantly sand and coarse sand with a maximum particle size of 4.5 mm; this portion of the soil matrix is uniformly mixed with the fines fraction -- clay particles to combine and plug the voids of the coarser soil matrix to provide the hydraulic barrier characteristics of the compacted sandy clay soil; this hydraulic barrier characteristic is an important parameter, but also parallels the increased strength and structural capacity offered by the coarse soil particles; the increased structural capacity is a major consideration when applied over an unstable waste layer, like a sanitary landfill waste layer; and the sandy clay soil matrix used as the compacted soil layer meets the recommended EPA soil make-up for a compacted soil layer for a closure cover system.

Sandy Clay Soil Compaction

The sandy clay soil layer was compacted to 90% of the maximum density as determined in accordance with ASTM D 1557 - 78, "Standard Test Method for Soil and Soil Aggregate Mixtures Using a 10 lb. Rammer and 18 in. Drop" (Modified Proctor). Figure 4 shows the test results.

Figure 5 --
Composite Modified Proctor Results Sandy Clay Soil

The average maximum density was 120.2 pound per cubic foot (pcf) at an optimum moisture content of 12.7%. The maximum density at 90% of the average maximum density was 108.2 pcf at an optimum moisture content of 12.7%.

Construction Specifications (Project Specification - Bentonite Mat Test Panel Construction, No. C-SPC-G-00068) developed for the Bentonite Mat Demonstration test pads incorporated the soil matrix make-up and the compaction requirements for the sandy clay soil layer as identified above. Each test

pad was constructed over a 4 ft. loose sand layer. A series of access pipes were embedded into the sand layer to provide a means for evacuating portions of the sand layer to create underlying cavities, thus inducing localized subsidence in the test pad. Figure 2 identified the basic test pad configuration. Infiltration/moisture data were collected for each test pad to correlate moisture movement during induced subsidence testing.

All four test pads were constructed up to the sandy clay layer. Each test pad was installed with embedded moisture and subsidence instrumentation. The Control Test Pad was the only test pad tested with regards to subsidence and *in situ* hydraulic conductivity for a compacted sandy clay layer. The three Geosynthetic Materials Test Pads were not tested during Phase One - Control Test Pad Testing because the composite geosynthetic materials were not installed on the test pads during this period. Phase One testing was also the embedded instrumentation "shake - out" phase of the demonstration. The Geosynthetic Materials Test Pads were covered with a one foot layer of sand to protect the test pads from erosion and deterioration during Phase One testing. The embedded instrumentation in these three test pads were monitored for water front movement and infiltration.

PHASE ONE -- CONTROL TEST PAD

Introduction

The Phase One - Control Test Pad Testing was designed to establish the performance characteristics of a compacted sandy clay soil. This testing phase was separated to isolate the sandy clay layer and determine the structural and *in situ* hydraulic conductivity properties of this soil layer. The data collected during the Control Test Pad testing phase form the performance baseline for subsequent evaluation of Phase Two-Geosynthetic Materials Test Pad Testing.

The objectives of Phase One - Control Test Pad Testing were:

- Verify the *in situ* hydraulic conductivity of a compacted sandy clay soil layer.
- Determine the performance characteristics of the compacted sandy clay soil layer undergoing induced subsidence.

Hydraulic Conductivity

Construction of the Control Test Pad was completed September 1993. Phase One testing began October 1993 and was concluded August 1994. Prior to commencing actual testing, four Sealed Double Ringed Infiltrimeters™ (SDRI) were installed on the Control Test Pad (see Figure 6).

Figure 6 - Control Test Pad Sealed Double Ringed Infiltrometers™ Locations

The SDRI is recognized as the most common method of measuring *in situ* hydraulic conductivity for a compacted soil layer.⁴ The wetting front method was used to calculate the hydraulic gradient as outlined in ASTM D 5093.⁸ The SDRIs provided the *in situ* hydraulic conductivity of the constructed sandy clay layer. The configuration of the SDRI is depicted in Figure 7.

Figure 7 - Typical Sealed Double Ringed Infiltrometer Configuration

The wetting front is the progressive "wetting" of the soil over time and the variation of the soil moisture content.⁷ Wetting front advancement is determined using ceramic tipped tensiometers. The principle operation for tensiometers is that they measure soil suction. As the wetting front passes the ceramic tip of the tensiometer, the soil suction of the soil matrix surrounding the tip decreases and soil matrix water re-enters the tensiometer, thus providing a decreased soil suction reading.

The typical SDRI configuration was modified with the installation of embedded soil moisture sensors which were co-located with the tensiometers. The reason for this modification was to correlate the soil moisture sensor with the accepted standard values of the tensiometer. The Water Mark Model

200 soil moisture sensor (Irrometer Company, Riverside CA, telephone number 909-689-1701) is a small ceramic cylinder containing two concentric electrodes buried in a reference matrix material and held in place by a synthetic membrane. The sensor detects changes in soil moisture by detecting changes in resistance between the two electrodes.

In operation, soil moisture is constantly absorbed or released from the buried sensor. As the soil surrounding the sensor dries out, the sensor moisture is reduced, and the electrical resistance between the electrodes is increased. This resistance (500 to 30,000 ohms) is read by the Watermark Meter™ Model 30KTCD (Irrometer Company, Riverside CA, telephone number 909-689-1701) as a relative indication of soil water tension. Water tension (suction) readings from the Watermark Meter™ are linear over its operating range, which is 0 to 200 centibar (kPa). Soil temperature is also a determining factor for soil moisture and was taken into consideration. This allows for greater accuracy, as the resistance readings vary 1 % per degree (Fahrenheit) of soil temperature. A thermocouple was embedded in the sandy clay layer of each test pad to determine soil temperature. Internally, the soil moisture sensor contains a small piece of gypsum, which provides for limited buffering against the effects of salinity. Generally, soil moisture sensor readings ranging between 0 - 20 centibar (kPa) are considered to be saturated soil conditions. The soil moisture sensor units do not respond instantaneously to changes in moisture conditions; they equilibrate over a period of an hour or two. The paired soil moisture instruments locales provided calibration data for use in interpreting the soil moisture sensor data from the other test pads.

The Geosynthetic Test Pad testing was modified to include the installation of a series of soil moisture sensors immediately above and below the level of the composite geosynthetic materials, thus correlation of the two instruments plays an important role in determining the moisture movement and infiltration of the water through the composite geosynthetic hydraulic barrier under saturated and unsaturated conditions.

Under unsaturated soil conditions within the Control Test Pad, a similar instrumentation configuration was used to measure infiltration. Tensiometers were coupled with embedded soil moisture sensors and operated concurrently. This data provided an alternative technique to measuring infiltration through the cover system and allows for the acquisition of "real-time" data hydraulic data to determine hydraulic barrier performance.

Subsidence/Deflection Monitoring

Embedded instrumentation and survey monuments were supplemented by non-invasive monitoring using geophysical techniques. The embedded subsidence instrumentation consisted of a horizontal inclinometer probe system. The non-invasive geophysical instrument/technique employed to monitor subsidence was Ground Penetrating Radar (GPR). The GPR equipment used was a Geophysical Survey System Instrument (GSSI) System 3 Radar with a 500 MHz antenna. A series of survey monuments were also installed at the surface of the compacted sandy clay layer; this is the present method used to monitor localized subsidence for closure cover systems at SRS.

The SINCO Horizontal Inclinometer Probe System (Slope Indicator Company 3668 Albion Place N., P.O. Box C-30316, Seattle, WA 98103-7991) used in this study consisted of a permanently installed horizontal casing with a pull cable arrangement and a portable instrument. The system is used for precise monitoring of settlement data. The displacement data was collected by the horizontal inclinometer probe system in the vicinity of the voids. The SINCO Digitilt Inclinometer Model 50309-E with Model 50325 Sensors was the instrument used for the inclinometer surveys. Three horizontal inclinometer tubes were embedded in compacted sandy clay layer for each of the test pads. Two of the tubes were located over the ends of the evacuation pipes and the third was located along the centerline of the test pad. Data was collected at 1 ft. intervals. The data was collected in the field by using a SINCO Digitilt Datamate, and the field data was evaluated using the SINCO Datamate Manager software. Collected data was analyzed by using incremental displacement and cumulative displacement. Incremental displacement is the difference in readings between the present and the baseline data at a given point, whereas the cumulative displacement is the difference between

the sum of the incremental displacements between the present and the baseline data. The horizontal inclinometer probe system detected incremental displacements of 0.04 inches over entire casing length - 150 ft. The instrument resolution barely exceeds 0.02 inches. The gap in data is due to the nature of the failure mode of the sandy clay layer and its inherent rigidity.

Ground Penetrating Radar

GPR was employed to monitor structural changes in the various pad layers. During test pad construction, GPR targets were installed at various depths within the test pad layers. These targets were used as reference markers for correlation with the vertical deflections of the sandy clay layer. The inclinometer casing was also used as reference point since it was embedded within the sandy clay layer. GPR Survey run - paths, both longitudinal and transverse, were established across the test pad surface.

Initially, the sandy clay failure mode was thought to be plastic, and the sandy clay would sag and fill the underlying cavity produced from the sand evacuation cycles. This type of failure mode did not occur. The sandy clay layer bridged the underlying cavities and its structural integrity was not impacted until the sandy clay layer began to "thin".

This "thinning process" was evident during the sand evacuation cycles when sandy clay "clods" were observed in the sand removed. A pipe inspection camera was used to inspect the underlying cavities and showed the sandy clay layer bottom surface to be non-uniform which was anticipated based on the "spalling" of the soil matrix. From these observations, the embedded instrumentation could not experience any flexing until the layer thinning was in the immediate area of the inclinometer casing. These results highlight the increased structural capacity of the compacted sandy clay layer and its soil arching ability.

Results from the GPR surveys along established GPR runs-paths demonstrated its effectiveness in documenting the structural integrity variations of the sandy clay layer. Figure 8 shows propagation of

the cavity vertically and the thinning of the sandy clay layer as the void is being formed. This clear area immediately adjacent to the inclinometer casing, best documents the "spalling" from the bottom of the sandy clay. Figure 8 presents the cavity progression at pipe cluster 5 of the Control Test Pad

Survey Monuments

A network of survey monuments was placed on the surface of each test cap. Concrete filled PVC pipes were placed in the vegetative layer. The monuments were founded within the vegetated layer and above the HDPE liner and were re-surveyed periodically to document surface settlement.

The method of failure of the voids created in the test pad influenced the survey monument data. The sandy clay within the test pad overlying the voids did not gradually settle but rather slowly spalled and later failed catastrophically. The survey monuments therefore did not show a gradual settlement, but they showed very small fluctuations (typically on the order of ± 0.01 ft.) followed by very large movements, on the order of inches, following the forced voids.

Phase One -- Control Test Pad testing focused on the structural and hydraulic characteristics of the local SRS compacted sandy clay soil layer of the control test pad. This compacted soil layer is the foundation for the composite geosynthetic materials hydraulic barrier.

Figure 8 - Ground Penetrating Radar Survey Record for Cavity Progression at Pipe Cluster 5

PHASE ONE -- CONTROL TEST PAD TESTING RESULTS

Compacted Sand Clay Layer Structural Capacity

Field testing of the compacted sand clay layer structural capacity was completed by removing quantities of sand to form underlying cavities thus causing deflection and subsidence and stressing the overlying layers. The size of the underlying cavities were formed incrementally to allow the overlying layers to respond and conform to the void by deflecting. Several series of sand evacuation cycles were completed until structural failure was achieved. The initial assumption was the test pad failure would occur when approximately 3 cyds to 4 cyds of sand had been removed, thus causing the compacted sandy clay to deflect beyond 1 ft. and/or catastrophically fail. The approximate span width for this cavity volume was estimated to be 4 ft. This assumption was based on the previous testing of the kaolin clay spanning an underlying cavity.⁹

Sand evacuation cycles were initially conducted on a two week cycle at a very low rate of sand removal. Initial sand removal methods were very laborious and cumbersome. Two methods used consisted of removing sand using a spoon auger to loosen and remove bulk quantities of sand, followed by using a heavy duty shop vacuum to remove residual material and breakdown the inner sand walls within the cavity formed. The quantity of sand removed each cycle was approximately 0.3 - 0.7 cyds. Five sand evacuation cycles were completed by December 1993, and the volume of sand removed approximated the cavity size to cause the anticipated deflection and/or collapse. No appreciable deflection of the compacted sandy clay was observed by either the embedded instrumentation nor the surface survey monuments. Additional sand evacuation cycles were required, and the method of sand removal was re-examined and modified.

The time period in between the sand evacuation cycles was shortened in anticipation that this would induce movement after the sand removal. Two additional sand evacuation cycles were initiated on a weekly schedule using the same removal technique, but no appreciable deflection was observed. Based on these results, the sand evacuation method was modified to use a Mobile Vacuum Loader Truck

(MVLТ). The MVLТ significantly increased the sand removal capability from 0.3 cyds per cycle to 1 cyd per cycle. Two sand evacuation cycles were completed using the MVLТ until structural failure of the compacted sandy clay layer was achieved.

Initially, sand removal operations were focused on pipe cluster 5 of the Control Test Pad (see Figure 6). This area of the test pad was under unsaturated soil conditions. Structural failure of the sandy clay was observed on February 14, 1994, after 103 days of testing. Table 2 displays the progression of the volume of sand removed from pipe cluster 5 of the Control Test Pad.

Table 2 -- Sand Evacuation Cycles
for Pipe Cluster 5 -- Control Test Pad.

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed per Cycle (cu. yds.)</u>	<u>Cumulative Total Volume of Sand Removed (cu. yds.)</u>	
1	0.35	0.35	Hand Auger/Portable Vacuum Method
2	0.69	1.04	
3	0.6	1.64	
4	0.57	2.21	
5	0.6	2.81	Initial anticipated failure point -- no deflection
6	0.57	3.38	Hand Auger/Portable Vacuum Method One Week Duration
7	0.66	4.04	
8	1.52	5.56	Modified Sand Evacuation Method -- Mobile Vacuum Loader Truck
9	2.11	7.67	Collapse of Underlying Dome

Collapse of pipe cluster 5 was a catastrophic sinkhole failure, extending to the surface of the test pad. The general shape of the cavity was an elongated ellipse. The dimensions of the elliptical cavity vary between 6.5 ft. to 7.0 ft. - wide and 11.5 ft to 12.0 ft. - long. Figure 9 depicts the location and general shape of the cavity.

Figure 9 – Cavity Collapse Under Pipe Cluster 5 Control Test Pad

The entire sand layer underneath the cavity had been removed, and a resultant dome was left. The quantity of sand removed to achieve collapse was 7.67 cyds. The failure mechanism for the sandy clay soil was a shear plane failure within the soil matrix. The compacted soil matrix initially spanned the cavity until tensile capacity of the soil matrix was exceeded and collapse occurred. The soil collapse began at the center of the layer overlying the cavity and then propagated laterally.

The next area of the test pad to fail was pipe cluster 4; located directly across from pipe cluster 5. This area was directly underneath a SDRI, thus soil conditions were saturated. Structural failure of the sandy clay was observed on February 28, 1994, after 117 days of testing. Table 3 displays the progression of the volume of sand removed from pipe cluster 4 of the Control Test Pad.

**Table 3 -- Sand Evacuation Cycles
for Pipe Cluster 4 -- Control Test Pad.**

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed</u> (cu. yds.)	<u>Cumulative Total Volume of Sand Removed</u> (cu. yds.)	
1	0.34	0.34	Hand auger/portable vacuum method
2	0.65	0.99	
3	0.59	1.58	
4	0.56	2.14	
5	0.59	2.73	Initial anticipated failure -- no deflection
6	0.52	3.25	Hand Auger/Portable Vacuum Method One Week Duration
7	0.58	3.83	
8	2.12	5.95	Modified sand evacuation method -- Mobile Vacuum Loader Truck
9	1.61	7.56	Collapse of the underlying dome

Collapse at pipe cluster 4 was a catastrophic sinkhole failure, extending to the surface of the test pad, causing the inner ring of the SDRI to collapse. The general shape of the cavity was an elongated ellipse. Figure 10 depicts the location and general shape of the cavity.

Figure 10 -- Cavity Collapse Under Pipe Cluster 4 Control Test Pad

Plan View
(Not to Scale)

The dimensions of the elliptical cavity vary between 5.5 ft. to 6.0 ft - wide and 10.5 ft to 11.0 ft. - long. The entire sand layer underneath the cavity had been removed, and a resultant dome was left. The quantity of sand removed to achieve collapse was 7.5 cyds. The failure mechanism of the soil matrix was also a shear plane failure. The compacted soil matrix initially spanned the cavity until tensile capacity of the soil matrix was exceeded and collapse occurred. The same failure propagation was observed as exhibited by the unsaturated soil condition: sinkhole - plug failure. Moisture content of the sandy clay soil in the area of the collapse was approximately 18%. Contrasting this value with the moisture content of the soil during construction (7%) shows a 57% increase in soil moisture content.

The cavities formed at pipe clusters 4 and 5 did not connect, but were separated by an estimated 5 ft. soil column. Influence from the adjacent voids was not observed. The sinkhole collapses experienced at pipe clusters 4 and 5 were initiated after a vacuum was created within the void. The

vacuum was created by sealing off four of the five sand evacuation pipes in the pipe cluster, and a negative pressure was applied to the open pipe, thus creating a vacuum in the cavity. The negative pressures ranged from 4 to 10 in. Hg and were applied at 1 in. Hg. increments. Each increment was held for a maximum of five minutes or until collapse was observed. The introduction of a negative pressure into the cavity approximates an applied load at the soil surface. An analysis of the equivalent applied surface load follows:¹⁰

- Conversion of vacuum in inches of Hg to pounds per square foot (psf),

$$70.59 \frac{\text{psf}}{\text{in. Hg}} \times 10 \text{ in. Hg} = 705.9 \text{ psf}$$

- Using a Boussinesq Stress Distribution to evaluate stress surface loads propagated up through two feet of soil spanning a 10 ft void,

$$705.9 \text{ psf} \times 10 \text{ ft} = 7,509 \text{ psf} \cdot \text{ft of void}$$

The application of a negative pressure to the compacted sandy clay soil matrix was considered a high stress test of the soil matrix. The high stress loading case approximates an applied load at the soil surface. This case is similar to the loading scenario for routine cover system maintenance, i.e., grass cutting using a utility tractor. Low stress testing of the sandy clay soil matrix was also examined, and this loading scenario is similar for long term performance of the entire closure cover system. The low stress testing scenario was conducted by forming a maximum cavity size and then allowing the weight of the overlying cover soil stress the compacted sandy clay layer until it collapsed.

A second series of cavities were formed at pipe clusters 7 and 8 of the control test pad, but no vacuum loading was applied. This second series of cavities was considered the low stress testing of the compacted soil matrix under both unsaturated and saturated soil conditions. These cavities were formed under the same soil conditions as pipe clusters 4 and 5. Table 4 depicts the creation of the cavity at pipe cluster 7. This low stress test case was under unsaturated soil conditions.

Table 4 - Sand Evacuation Cycles for Pipe Cluster 7

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed (cu. yds.)</u>	<u>Cumulative Total Volume of Sand Removed (cu. yds.)</u>	
1	0.35	0.35	Hand auger/portable vacuum method
2	0.37	0.72	
3	0.6	1.32	
4	0.58	1.9	
5	0.59	2.49	Initial anticipated failure -- no deflection
6	0.44	2.90	Hand Auger/Portable Vacuum Method One Week Duration
7	0.13	3.03	
8	1.10	4.13	Modified sand evacuation method -- Mobile Vacuum Loader Truck - 2/28/94
9	0.76	4.89	
10	1.41	6.30	
11	1.57	7.87	Date Completed 4/20/94
12	0.43	8.29	Date Completed 8/10/94

Sand evacuation cycle 12 was completed on August 10, 1994, and the underlying cavity volume was approximately 8.3 cyds. Three months (November 17, 1994) after the last sand evacuation cycle had been completed the sandy clay layer collapsed. The entire testing duration for the cavity formed under pipe cluster 7 was 348 days. The dimensions of the cavity were approximately the same as for cavity at pipe cluster 5 (7 ft - wide by 12 ft. - long).

Table 5 depicts the creation of the cavity at pipe cluster 8. This low stress test case was under saturated soil. Hydraulic conductivity data was collected during the creation of the underlying cavity.

Table 5 - Sand Evacuation Cycles for Pipe Cluster 8

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed (cu. yds.)</u>	<u>Cumulative Total Volume of Sand Removed (cu. yds.)</u>	
1	0.35	0.35	Hand auger/portable vacuum method
2	0.36	0.71	
3	0.58	1.29	
4	0.55	1.84	
5	0.59	2.43	Initial anticipated failure -- no deflection
6	0.12	2.55	
7	0.65	3.20	Modified sand evacuation method -- Mobile Vacuum Loader Truck - 1/25/94
8	0.94	4.14	Date Completed 4/18/94
9	0.37	4.51	Date Completed 4/19/94
10	1.11	5.62	Date Completed 4/20/94
11	0.44	6.06	Date Completed 5/4/94
12	0.97	7.03	Date Completed 6/3/94
13	0.49	7.52	Date Completed 7/21/94

Sand evacuation cycle 13 was completed on July 21, 1994, and the underlying cavity volume was approximately 7.5 cyds. The last hydraulic conductivity data collected for SDRI 4 was obtained August 25, 1994, and the hydraulic conductivity was 1.7×10^{-6} cm/sec. No vacuum loading was applied to this cavity and as of November 17, 1994, no appreciable deformation has been observed. This loading test under saturated soil conditions was conducted for 348 days.

The low stress testing at pipe clusters 7 and 8 of the control test pad demonstrates the long term strength under field conditions for a 2 ft. compacted sandy clay layer spanning a void. The sandy clay soil matrix has shown its ability to mitigate the effects of subsidence resulting from waste degradation.

The structural capacity of the compacted sandy clay layer was determined to span a 6 ft. void for an unsaturated soil condition and span a 5 ft. for saturated soil condition. The hydraulic conductivity of the soil matrix is an important characteristic for the performance of the composite geosynthetic materials hydraulic barrier.

In Situ Hydraulic Conductivity

The *in situ* hydraulic conductivity of the compacted sandy clay layer was determined using a SDRI.⁸ These infiltrometers are the recognized industry standard practice to ascertain the *in situ* hydraulic conductivity for a compacted clay liner.⁴ The effectiveness of the SDRI has been documented to determine low hydraulic conductivities in compacted clay liners; i.e., 1×10^{-7} cm/sec as recommended by the EPA for a compacted clay liner. The hydraulic conductivity of a compacted sandy clay soil layer was speculated to approximate a value 1×10^{-6} cm/sec based on previous laboratory testing of the sandy clay soil.⁹

Four SDRIs were installed on the Control Test Pad to determine the *in situ* hydraulic conductivity of the compacted sandy clay layer. Figure 11 depicts the locations of the SDRIs directly over sand evacuation pipe clusters. These locations were selected to optimize the hydraulic infiltration data and its correlation to deflection data in response to the formation of underlying cavities.

Figure 11 - Sealed Double Ringed Infiltrrometer
Locations on the Control Test Pad

Figure 12 shows the ability of a compacted sandy clay layer to approximate the hydraulic conductivity of 1×10^{-6} cm/sec. The initial saturation period of the sandy clay is depicted by the initial scattered data of the first 20 days. Subsequent to this period, the data is stable and consistent. SDRI No. 2, SDRI No. 3, and SDRI No. 4 were able to sustain a hydraulic conductivity range of 2.5×10^{-6} cm/sec to 1.5×10^{-6} cm/sec. The average hydraulic conductivity for two foot compacted sandy clay layer was 2.0×10^{-6} cm/sec.

The hydraulic conductivity data from SDRI No. 1 was inconsistent and sporadic as shown in Figure 12. During the initial saturation period, SDRI No. 1 hydraulic conductivity data was an order of magnitude higher than the other SDRI values. A potential reason for this inconsistency is the sandy clay in this section of the Control Test Pad may not have been compacted uniformly as the remainder of the test pad, thus allowing a higher infiltration rate.

Figure 12 - Composite Sealed Double Ringed Infiltrrometer
Results for the Control Test Pad

An examination of the hydraulic conductivity data reveals the ability of the sandy clay soil matrix to maintain its hydraulic barrier capacity while undergoing deformation due to the formation of underlying cavities. SDRI 2 (pipe cluster 4) was subjected to the high strain loading test case, and SDRI 4 (pipe cluster 8) was subjected to the low strain loading test case of the compacted sandy clay layer.

Figure 13 shows a slight increase in hydraulic conductivity 10 days prior to collapse. The hydraulic conductivity data continued to increase until collapse, but the increases in the hydraulic data can be resolved by factoring in the "spalling effect" of the sandy clay matrix. Re-analyzing the hydraulic conductivity data for SDRI 2 and estimating the variability of the sandy clay layer thickness under SDRI 2 approximates the increases observed prior to collapse. The hydraulic conductivity fluctuation was due to the variability of the hydraulic gradient in response to the soil thickness variation. The introduction of a negative pressure into the underlying cavity does increase infiltration. This increase is due to the decreased cavity air pressure impacting the soil matrix which results in increasing the hydraulic head flowing through the soil matrix.

SDRI 4 hydraulic conductivity ranged from 2.4×10^{-6} cm/sec to 1.2×10^{-6} cm/sec and relatively stable as shown in Figure 14. Immediately after sand evacuation cycles, the hydraulic conductivity data increases slightly but re-equilibrates after the soil matrix readjusts to the cavity. Sand evacuation cycle 13 was completed on July 21, 1994 and the cavity volume underneath SDRI 4 was 7.52 cyds. The last hydraulic conductivity data was collected on August 23, 1994, and the hydraulic conductivity for SDRI 4 was 1.7×10^{-6} cm/sec. The compacted sandy clay layer hydraulic conductivity response to the high stress and low strain testing cases demonstrates the durability and hydraulic performance of the soil matrix over a cavity.

Figure 13 - Sealed Double Ringed Infiltrometer
Results for SDRI No. 2

Figure 14 - Sealed Double Ringed Infiltrometer
Results for SDRI No. 4

Phase One Test Results Summary

The observations and test results obtained from Phase One - Control Test Pad testing establishes the performance baseline of the compacted sandy clay layer and its hydraulic and structural characteristics in response to the formation of underlying cavities. High and low stress testing cases were completed for unsaturated and saturated soil conditions. The sandy clay layer is a durable and resilient soil matrix that can span voids up to 6 ft. wide in an unsaturated soil condition and 5 ft. wide for a saturated soil condition. The *in situ* saturated hydraulic conductivity of a 2 ft. compacted sandy clay is 2×10^{-6} cm/sec. The range of hydraulic conductivity data for the soil matrix was 2.5×10^{-6} cm/sec to 1.5×10^{-6} cm/sec. These hydraulic values do not meet the EPA Recommended hydraulic conductivity of 1.0×10^{-7} cm/sec for a compacted clay layer.¹ The compacted sandy clay layer must be enhanced to achieve the regulatory hydraulic requirements. The combination of this soil matrix with the hydraulic properties of geosynthetic materials provides the foundation of the composite geosynthetic materials hydraulic barrier alternative closure cover system configuration.

Phase Two - Geosynthetic Materials Test Pad testing was initiated to determine the hydraulic and structural performance characteristics of the composite geosynthetic materials hydraulic barrier. The results of Phase One were incorporated into the Phase Two testing program.

PHASE TWO -- GEOSYNTHETIC MATERIALS TEST PAD TESTING

Introduction

Phase Two -- Geosynthetic Materials Test Pad Testing began at the conclusion of the installation of the geosynthetic materials on each of the geosynthetic materials test pads. The composite geosynthetic materials hydraulic barrier is a two layer system consisting of geosynthetic clay liner (bentonite mat - GCL) and overlaid by a 40 mil High Density Polyethylene (HDPE) geomembrane. The geosynthetic materials test pads were constructed with the same type of sandy clay soil used for the control test pad testing, thus same construction practices and specifications were also applied.

The objectives of Phase Two - Geosynthetic Materials Test Pad Testing were :

- Determine the *in situ* hydraulic characteristics of the composite geosynthetic hydraulic barrier system.
- Determine the performance characteristics of the composite barrier system undergoing subsidence.
- Document the installation and construction requirements of the composite barrier system.

The three geosynthetic materials test pads were constructed using the same configuration as the control test pad with the addition of the composite geosynthetic material hydraulic barrier and cover soil. The composite geosynthetic material hydraulic barrier consists of a GCL that is covered by a 40 mil HDPE geomembrane. This composite geosynthetic hydraulic barrier blankets the existing two foot compacted sandy clay layer which was identical to the control test pad configuration. Each geosynthetic materials test pad consisted of one of the US manufactured commercially available GCLs.

Bentonite Mat

The bentonite mat or GCL is defined as, *"a factory manufactured, hydraulic barrier typically consisting of bentonite clay or other very low permeability clay materials, supported by geotextile and geomembrane which are held together by needling, stitching and/or chemical adhesives"*.¹¹ GCLs are used as a hydraulic barrier to water and other liquids. This material augments or replaces compacted clay liners or geomembranes and can be used in a composite configuration to augment the traditional compacted clay liner or geomembrane materials. The selection of this material for the composite hydraulic barrier was based on the bentonite clay swelling capability when the clay is hydrated. This swelling capability is advantageous because if an overlying geomembrane's hydraulic integrity is breached by a tear and/or hole, the bentonite clay will hydrate and swell and seal the hole. This sealing capability has been documented in laboratory studies using GCLs and an overlying geomembrane configured with various holes and tears combinations.¹² The GCL is a combination of geosynthetic materials and bentonite clay to form the redundant hydraulic barrier. The GCL also provides the hydraulic sealing/repair capability of the composite geosynthetic materials hydraulic barrier. The GCL products manufactured in the US use sodium bentonite clay powder or granules which is adhered to a geomembrane or sandwiched in-between two geotextile materials. The manufactured mass per unit area of bentonite clay powder or granules ranges from 0.66 lbs/ft² to 1.22 lbs/ft² (3.2 kg/m² to 6.0 kg/m²).¹¹ The GCL material thickness ranges from 0.12 in to 0.25 in.⁷ GCL is produced in the US by three manufactures; Gundseal® -Gundle Lining Systems, Incorporated, Claymax® - James Clem Corporation, and Bentomat® - Colloid Environmental Technologies Company.

Gundseal® -Gundle Lining Systems, Incorporated (19103 Gundle Road, Houston, TX, Telephone number - 713-443-8564) is a geosynthetic clay liner consisting of a layer of sodium bentonite clay adhered to a geomembrane/flexible membrane. The geomembrane is typically a HDPE flexible membrane liner with a thickness of 20 mils (0.5 mm) or greater. The hydraulic conductivity of this GCL composite is 4×10^{-12} cm/sec for water.¹¹ The material characteristics for Gundseal® is outlined in Table 6.

Table 6 –
MATERIAL CHARACTERISTICS FOR GUNDSEAL®¹¹

<u>Material Characteristics</u>	<u>Value / Result</u>
Material thickness (mm)	6 (0.25 inches)
Bentonite Clay Loading (kg/m ²)	5 (1 lbs/ft ²)
Geomembrane Hydraulic Conductivity ASTM-E96 (cm/sec)	2.7×10^{-13}
Bentonite Clay Hydraulic Conductivity (cm/sec)	3.7×10^{-10}
Wet – Dry Cycles ASTM D 599	No effect
Freeze – Thaw Cycles ASTM D 599	No effect

Claymax® - James Clem Corporation (444 North Michigan Ave., Suite 1610, Chicago, IL, Telephone Number - 312-321-6255) is a geosynthetic clay liner consisting of a layer of sodium bentonite clay sandwiched between an upper primary woven geotextile and a lower secondary open weave geotextile. The Claymax® 500 SP is stitch-bonded to the primary and secondary geotextile materials through the bentonite clay layer to increase the shear and tensile strength of the overall GCL material. The Claymax® 500 SP is the GCL material tested in the demonstration. The hydraulic conductivity for Claymax® 500 SP is 5×10^{-9} cm/sec.¹¹ The material characteristics for Claymax® 500 SP is outlined in Table 7.

Table 7 –
MATERIAL CHARACTERISTICS FOR CLAYMAX® 500 SP¹¹

<u>Material Characteristics</u>	<u>Value / Result</u>
Material thickness (mm)	5 (0.2 inches)
Bentonite Clay Loading (kg/m ²)	4.6 (0.95 lb/ft ²)
Hydraulic Conductivity after Wet - Dry Cycles ASTM D 5084 (cm/sec)	$< 5 \times 10^{-9}$
Hydraulic Conductivity after Freeze - Thaw Cycles ASTM D 5084 (cm/sec)	$< 5 \times 10^{-9}$

Bentomat® - Colloid Environmental Technologies Company (1500 West Shure Drive, Arlington, IL 60004-1434, Telephone number 708-392-5800) is a GCL consisting of a layer of sodium bentonite clay encapsulated between an upper woven polypropylene geotextile and a lower nonwoven polypropylene geotextile. Bentomat® SS is configured by needle-punch bonding of the primary and secondary geotextile materials through the bentonite clay layer to increase the shear and tensile strength of the overall GCL material. The Bentomat® SS was the GCL material tested in the demonstration. The hydraulic conductivity for Bentomat® SS is 5×10^{-9} cm/sec.¹¹ The material characteristics for Bentomat® SS is outlined in Table 8.

Table 8 –
MATERIAL CHARACTERISTICS FOR BENTOMAT® SS¹¹

<u>Material Characteristic</u>	<u>Value / Result</u>
Material thickness (mm)	6.4 (0.25 inches)
Bentonite Clay Loading (kg/m ²)	4.9 (1.0 lbs/ft ²)
Hydraulic Conductivity ASTM D 5084 (cm/sec)	5×10^{-9}

The three geosynthetic material test pads were blanketed by one of the commercially available bentonite mats (geosynthetic clay liner /GCL) then overlain by a flexible membrane liner/geomembrane to form the composite geosynthetic hydraulic barrier.

The flexible membrane liner/geomembrane used in the testing program was a Gundline® HD 40 mil smooth HDPE flexible membrane liner material from Gundle Lining Systems, Incorporated (19103 Gundle Road, Houston, TX, Telephone Number 713-443-8564). The hydraulic conductivity for a HDPE liner material is an effective hydraulic conductivity derived from moisture vapor transmission data using ASTM E 96 testing methods is 2.7×10^{-13} cm/sec.⁹ Table 9 outlines the material properties for Gundline® HD 40 mil smooth HDPE liner material.

The HDPE geomembrane material used for the composite geosynthetic materials hydraulic barrier tested was a smooth surface material. This material surface is typical for installations where slope stability is not a concern. To mitigate slope stability concerns, a textured geomembrane surface is employed. Other geomembrane materials have been successfully used in hazardous waste closure cover systems, namely Very Low Density Polyethylene (VLDPE) and Hypalon ®. These geosynthetic materials provide the same hydraulic characteristics as the HDPE geomembrane.⁹

Table 9 -- Material Properties for
Gundline® HD 40 mil Smooth HDPE Liner Material⁹

Material Property	Value / Result
Material thickness (mils)	40 (1.0 mm) (0.04 in)
Material density (g/cc)	0.3
Tensile Properties (ASTM D 638)	
1. Tensile Strength @ Break (lbs/in width)	160
2. Tensile Strength @ Yield (lbs/in width)	95
3. Elongation @ Break (percent)	700
4. Elongation @ Yield (percent)	13
Tear Resistance Initiation ASTM D 1004 Die C (kg)	66 (30 lbs)
Puncture Resistance FTMS 101 - Method 2065 (kg)	115 (52 lbs)
Coefficient of Liner Thermal Expansion ASTM D 696 ($\times 10^{-4}$ cm/cm °C)	1.2
Modulus of Elasticity ASTM D 638 (g/cm ²)	0.017 (1.2 psi)

Geosynthetic Material Seams

The installation of the geosynthetic materials requires the joining of the geomembrane materials to form a seam. These seams are then fused together by a double seam heat weld. The joining of the GCL materials is quite different. The GCL materials are merely overlapped seams, and no fusion heat

welds are installed. This GCL seam configuration is typical for this material and is specified by the manufactures.

Each of the geosynthetic materials test pads was configured with two seam alignments for the composite geosynthetic materials hydraulic barrier (see Figure 15). The first seam alignment configuration was the GCL seam and HDPE geomembrane seam coinciding with the centerline of two test pad pipe clusters.

Figure 15 -- Geosynthetic Materials Seam Alignment

These first seam alignments were installed to approximate a worst case scenario for deflection and materials strain. This seam configuration is not typical of a composite geosynthetic materials hydraulic barrier. The second seam alignment configuration was the HDPE geomembrane seam aligned with the centerline of two test pad pipe cluster, and the GCL seam was located in between two adjacent

pipe clusters (see Figure 15). This seam alignment is typical of current installation practices. HDPE geomembrane seams are joined together by a heat weld per manufacturer's specifications. Quality control testing of the heat weld seams was completed to ensure their integrity. GCL seams were not joined in the same manner but merely overlapped. The material overlap varied between 6 in. to 12 in. (15 cm to 30 cm) per manufacturer's specifications. To help locate the seam during induced subsidence, metallic foil tape was fixed on each side of the GCL seam. GPR was used to detect the seam location and identify seam separation after induced subsidence. This approach documents strain progression of the GCL and the HDPE geomembrane as they are impacted by subsidence.

A 2 ft. cover soil was placed over the composite geosynthetic materials hydraulic barrier. The cover soil layer provides a confining pressure to the hydraulic barrier so the GCL can maintain intimate contact with the overlying geomembrane to preserve the integrity of the composite geosynthetic materials hydraulic barrier. The intimate contact of the geosynthetic materials is a key element to optimizing the sealing/repair capability of the GCL -- HDPE geomembrane composite hydraulic barrier. The soil cover also provided the media for vegetation (grasses) to propagate to minimize surface erosion.

Soil Moisture Monitoring

Soil moisture sensors were installed in the cover soil layer to monitor moisture immediately above the HDPE geomembrane. Two additional soil moisture sensors were installed in the compacted sandy clay layer during the construction of the basic test pad configuration. These sandy clay soil moisture sensors were located at the top surface of the soil layer and at the bottom six inches of the compacted soil layer. The soil moisture sensors in the overlying soil cover coupled with the soil moisture sensors installed in the compacted sand clay layer formed the leak detection system and hydraulic wetting front monitoring system of the composite geosynthetic materials hydraulic barrier during induced subsidence.

To properly evaluate the hydraulic performance of the composite geosynthetic materials hydraulic barrier during induced subsidence, a hydraulic head was introduced. A mat irrigation system was developed to saturate the cover soil immediately over the area of the underlying cavity. This irrigation system consisted of a series of "soaker hoses" - water hoses placed on the surface of the test pad and connected to a large (i.e., 55-gal) drum storage reservoirs. Water flowed from the drum under gravity feed and was slowly released through the soaker hoses into the soil. To reduce evaporation, straw mulch was placed under the hoses and over the immediate area of the cavity. The hydraulic head was maintained by periodically re-filling the storage drums. The development of a hydraulic head over the immediate area of an underlying cavity is typical of the failure mechanism in existing cover systems. Soil moisture sensor instrumentation, as outlined above, was used to detect the hydraulic head and its migration through the hydraulic barrier. Results from the soil moisture sensors were used to maintain the saturated conditions in the cover soil.

Geosynthetic Materials Installation

Installation of the composite geosynthetic material hydraulic barrier was completed using typical construction practices and methods. Quality control testing and quality assurance methods were used throughout the construction of the test pads. Industry standards were used for the installation of the geosynthetic material and verification of the geomembrane seams. All quality control testing results met industry standards and complied with the construction specifications.

Testing of the three geosynthetic material test pads was not initiated until all construction/installation of geosynthetic material and instrumentation has been completed. An initial soil moisture data set was compiled prior to and after installing the composite geosynthetic materials hydraulic barrier. This data set establishes a baseline to compare soil moisture data during induced subsidence.

PHASE TWO -- GEOSYNTHETIC MATERIALS TEST PAD TESTING RESULTS

Sand Evacuation Cycles

A key objective of Phase Two testing is the structural and hydraulic performance of the composite geosynthetic materials hydraulic barrier during settlement of the underlying waste layer. To determine these performance characteristics, a series of voids or cavities were created in the underlying sand layer for each test pad. The results from Phase One - Control Test Pad Testing were used to develop the sand evacuation methods used for Phase Two testing. All Phase Two sand evacuation cycles were completed by using a Mobile Vacuum Loader Truck (MVL). The vacuum technique used was a drum cyclone configuration. This configuration allowed the volume of sand to be collected and measured before it entered the hopper of the MVL. Typically a 4 in. diameter pipe was fitted to the vacuuming system and then inserted into the 8 in. evacuation pipe in the side slope of the test pad. Sand removal occurs as the vacuum engine is slowly brought up to operating speed.

Sand evacuation activities were completed at two pipe cluster locations for each geosynthetic materials test pad. These pipe cluster locations coincide with a seam-on-seam and a staggered seam configuration for the composite geosynthetic materials hydraulic barrier. Pipe cluster 1 corresponds to the seam-on-seam configuration, and pipe cluster 8 corresponds the staggered seam configuration.

Several sand evacuation cycles were completed for each pipe cluster - geosynthetic materials seam configuration. The formation of the underlying cavity caused the sandy clay layer to spall from the bottom of the layer and propagate the dimensions of the cavity vertically into the sandy clay layer. This "spalling effect" was anticipated based on the observations from Phase One testing. After a steady pattern of sandy clay soil was being removed, vacuum loading was applied by closing off four of the five access pipes and applying a negative pressure to one of the access pipes using the MVL. Negative pressure was applied to approximate surface loading conditions over an underlying cavity. Vacuum

loading or negative pressure ranged from 4 to 10 in. Hg applied at 1 in. Hg. increments. Each increment was maintained for a maximum of five minutes or until there was visible evidence of a surface depression. An analysis of the equivalent applied surface load follows:¹⁰

- Conversion of vacuum in inches of Hg to pounds per square foot (psf),

$$70.59 \frac{\text{psf}}{\text{in. Hg}} \times 10 \text{ in. Hg} = 705.9 \text{ psf}$$
- Using a Boussinesq Stress Distribution to evaluate stress surface loads propagated up through two feet of soil spanning a 10 ft void,

$$705.9 \text{ psf} \times 10 \text{ ft} = 7,509 \text{ psf} \cdot \text{ft of void}$$

The sand evacuation cycles of the geosynthetic materials test pads are summarized below.

Gundseal® Test Pad

Sand was evacuated from clusters 1 and 3. A total of six cycles were required to evacuate sand from cluster 1 of the Gundseal® Test Pad, while five cycles were required for cluster 3. The sand evacuation data for the Gundseal® Test Pad is provided in Tables 10, 11, and 12 for pipe clusters 1, 3, and 6, respectively.

Table 10 – Sand Evacuation Cycles for Pipe Cluster 1 - Gundseal® Test Pad
(seam-on-seam alignment)

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed per Cycle (cyds.)</u>	<u>Cumulative Total Volume of Sand Removed (cyds.)</u>	
1	1.64	1.64	Initial sand removal - 5/2/94
2	3.03	4.67	
3	1.95	6.62	
4	0.89	7.51	
5	0.56	8.07	
6	0.53	8.60	Vacuum loading applied - catastrophic collapse - 7/21/94

Table 11 – Sand Evacuation Cycles for Pipe Cluster 3 - Gundseal® Test Pad
(seams staggered)

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed per Cycle (cyds.)</u>	<u>Cumulative Total Volume of Sand Removed (cyds.)</u>	
1	2.63	2.63	Initial sand removal - 5/3/94
2	2.02	4.65	
3	2.80	7.45	
4	0.79	8.24	
5	0.18	8.62	Vacuum loading applied - 7/21/94

Table 12 – Sand Evacuation Cycles for Pipe Cluster 6 - Gundseal® Test Pad
(seam-on-seam)

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed per Cycle (cyds.)</u>	<u>Cumulative Total Volume of Sand Removed (cyds.)</u>	
1	0.73	0.73	Initial sand removal - 8/3/94
2	7.85	8.58	Vacuum loading applied - 8/4/94

The sand evacuation clusters were chosen based upon the geometry of the overlying geomembrane (flexible membrane liner - FML) and GCL. The seams of the cover materials (FML/GCL) overlying cluster 1 were aligned, whereas the seams of the cover materials overlying cluster 3 were not aligned. This arrangement allowed for the testing of the "strength" of the FML/GCL liners in a worst-case scenario and typical seam arrangement configuration. Figure 16 shows the geosynthetic materials seam arrangement and their alignment with the test pad pipe clusters. The Gundseal® Test Pad was constructed with six sand evacuation pipe clusters. This configuration was due to the width of the Gundseal® GCL material and the alignment of the seams.

Figure 16 - Gundseal® Test Pad Geosynthetic Materials Seam Arrangement

Sand evacuation at cluster 1 of the Gundseal® Test Pad began on May 2, 1994, and on cluster 3 on May 3, 1994. The volume of sand removed from cluster 1 on May 2, 1994, was 1.64 cyds. No sand was removed from cluster 3 on this date. On May 3, 1994, 3.03 cyds of sand were removed from cluster 1, and 2.63 cyds were removed from cluster 3. Sand was not removed from cluster 1 during on May 4, 1994; however, an additional 2.02 cyds was removed from cluster 3 on this date. The total volume removed from clusters 1 and 2 as of May 4, 1994, was 4.67 and 4.65 cyds, respectively. Traces of topsoil (marker horizon) began appearing in the evacuated material during this cycle. The next cycle occurred on June 2, 1994 (cycle 3 for both cluster 1 and cluster 3). During this cycle, an additional 1.95 cyds was removed from cluster 1 and 2.80 from cluster 3. Some topsoil was reported in the evacuated material from cluster 3, while both topsoil and traces of "clay" were reported as having come from cluster 1. Cluster 1 was again evacuated on June 3, 1994. On that date, an additional 0.89 cyds was removed. Once again, traces of clay were observed in the evacuated material. On July 19, 1994, sand was evacuated from both clusters. On this date 0.56 cyds was removed from cluster 1 and 0.79 cyds was removed from cluster 3. Clay was again observed to be mixed in with the sand in the evacuated material. The last evacuation cycle occurred on July 21, 1994. On this date, 0.53 cyds was removed from cluster 1 and 0.18 cyds was removed from cluster 3. Clay was once again observed to be mixed

in with the sand in the evacuated material from both clusters. The total volume of evacuated material from cluster 1 was 8.60 cyds and 8.62 cyds from cluster 3.

The first vacuum loading test was performed on clusters 1 and 3 at the Gundseal® Test Pad on July 21, 1994. On this date, the tests were performed in pipe number 1-4 and 3-2 at pressures of 2 to 10 in. Hg. Each vacuum level was applied for a period of five minutes at each cluster. The next vacuum test was performed on August 3, 1994. During this testing cycle, the vacuum load was held for a sufficient period of time that a surface expression of subsidence could be observed. The vacuum was applied at loads of 4, 6, and 8 in Hg for five minute intervals. The load was then increased to 10 in Hg. After approximately 2.5 minutes, failure occurred. The vacuum was not removed, and the overlying FML was torn. The failure of the void appeared as an approximately 3 ft. by 5 ft. by 7 ft. deep hole in the test pad. The hole extended to the surface of the test pad through the failed FML and GCL. A vacuum test was then performed on cluster 3 (pipe 3-2); however, the load was applied only until a slight amount of surface subsidence was observed.

Because the failure at cluster 1 occurred when the vacuum was not shut down quickly when the sandy clay layer failed, the decision was made to evacuate cluster 6 (opposite cluster 1) to test the long term stability of the FML/Gundseal® cover with aligned seams. Over the next two day period (August 3-4, 1994), 8.58 cyds of sand was evacuated from pipe cluster 6 of the Gundseal® Test Pad. On August 10, 1994, the vacuum loading test was performed on cluster 6. The vacuum was applied for five minutes in increments of 4, 6, and 8 in Hg. The process was repeated again until failure of the sandy clay occurred. The surface expression of the failure was a depression approximately 4 ft. - 11 in. by 4 ft. - 3 in. No catastrophic failure occurred, and the FML and GCL seam-on-seam alignment remained intact. Cluster 3 was reoccupied on this date, and the vacuum load test was performed again. Vacuum loads of 1, 2, 3, 4, and 5 in Hg were applied for 2 minute intervals until failure of the sandy clay occurred. The failure at cluster 3 appeared as a 5 ft. - 3½ in. by 5 ft. - 1 in. oval shaped depression, but no catastrophic failure was observed. The FML and GCL staggered seam configuration remained intact.

The Gundseal® composite geosynthetic materials hydraulic barrier remained intact during the induced subsidence testing. Both seam configurations were monitored for hydraulic and structural integrity. Soil moisture sensor instrument readings above the geosynthetic materials have remained saturated, and the moisture sensor readings below the geosynthetic materials have remained constant for dry conditions. GPR surveys were conducted over the seam locations and no material separations were observed. Based on the information presented, no impact to the hydraulic conductivity or the structural integrity of the Gundseal® composite geosynthetic materials hydraulic barrier was observed.

Bentomat® Test Pad

Sand was evacuated from clusters 1 and 3 of the Bentomat® Test Pad. The aligned seam arrangement of the cover components overlaid cluster 1, whereas the non-aligned arrangement overlaid cluster 3. Seven sand evacuation cycles were performed on cluster 1, while five were performed on cluster 3. The sand removal quantities are provided in Tables 13 and 14 for pipe cluster 1 and 3, respectively. The same seam alignment scenarios as the Gundseal® Test Pad were examined. Figure 17 shows the geosynthetic materials seam arrangement and their alignment with the test pad pipe clusters.

Table 13 – Sand Evacuation Cycles for Pipe Cluster 1 - Bentomat® Test Pad
(seam-on-seam alignment)

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed per Cycle (cyds.)</u>	<u>Cumulative Total Volume of Sand Removed (cyds.)</u>	
1	1.27	1.27	Initial sand removal - 4/20/94
2	2.81	4.08	
3	0.43	4.51	
4	2.57	7.08	
5	0.38	7.46	
6	0.84	8.30	
7	0.25	8.55	Vacuum loading applied - 7/21/94 and 8/3/94

Table 14- Sand Evacuation Cycles for Pipe Cluster 3 - Bentomat® Test Pad
(seams staggered alignment)

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed per Cycle (cyds.)</u>	<u>Cumulative Total Volume of Sand Removed (cyds.)</u>	
1	1.95	1.95	Initial sand removal - 4/25/94
2	3.10	5.05	
3	2.15	7.20	
4	0.32	7.52	
5	0.96	8.48	Vacuum loading applied - 7/21/94 and 8/3/94

Figure 17 -- Bentomat® Test Pad Geosynthetic Materials Seam Arrangement

Sand evacuation of cluster 1 of the Bentomat® Test Pad began on April 20, 1994. Approximately 1.27 cyds was removed from cluster 1 on this date. Sand evacuation from cluster 1 continued on April 21, 1994. During this second evacuation cycle, an additional 2.81 cyds of sand was removed. On April 25, 1994,

both cluster 1 and 3 were evacuated. Approximately 0.43 cyds was removed from cluster 1 and 1.95 cyds was removed from cluster 3. Cluster 3 alone was evacuated on April 26, 1994, and approximately 3.10 cyds was evacuated. The total volume of sand removed as of April 26, 1994, was 4.51 cyds from cluster 1 and 5.05 cyds from cluster 3. The clusters were not evacuated again until May 31, 1994. During this cycle, 2.57 cyds were removed from cluster 1 and 2.15 cyds were removed from cluster 3. A large amount of topsoil was observed after evacuating pipe 1-3, and again after evacuating cluster 3-2. Topsoil was observed after evacuating pipe 1-4 during this cycle. At the end of the shift on June 1, 1994, the cumulative volumes of sand removed from clusters 1 and 3 of the Bentomat® Test Pad were 7.46 and 7.52 cyds, respectively. Cluster 1 was evacuated next on July 19, 1994. At the beginning of the shift on this day, the length of the pipes in cluster 1 were measured to determine if any cave-in had occurred. Approximately 0.84 cyds of sand was removed on this date.

Cluster 3 was evacuated next on July 20, 1994, and approximately 0.96 cyds of sand were removed bringing the cumulative total for cluster 3 to 8.48 cyds. On July 21, 1994, cluster 1 was once again evacuated, and approximately 0.25 cyds of sand were removed. The cumulative total of sand removed as of this date was 8.55 cyds and 8.48 cyds for clusters 1 and 3, respectively.

Vacuum load testing of clusters 1 and 3 began on July 21, 1994. Pipe 1-4 was used for cluster 1, and pipe 3-4 was used for cluster 3. The vacuum load tests were once again performed on both clusters on August 3, 1994. During these vacuum load tests, pipe 1-2 was used in cluster 1, and 3-2 in cluster 3. In cluster 1, the vacuum load was applied at levels of 4, 6, and 8 in. Hg. Each level held for a period of approximately five minutes. Similar load tests were performed on cluster 3. When the vacuum was increased to 10 in. Hg, failure of the sandy clay occurred within 10 seconds. Only slight amounts of movement were observed at the surface at failure during this round of testing. A final round of vacuum testing was performed on the two Bentomat® Test Pad clusters on August 10, 1994, to enlarge the holes in the sandy clay. Pipe 1-4 was used to test cluster 1, and pipe 3-2 was used to test cluster 3. In cluster 1, the vacuum load was applied in increments of 1, 2, 3, and 4 in. Hg., and held for a period of two minutes. When the vacuum was increased to 5 in. Hg,

the surface depression began to enlarge within 30 seconds. The surface expression of the failure was an oval shaped depression approximately 5 ft. - 7 in. by 4 ft. - 10 in. In cluster 3, the loads were applied in increments of 1, 2, 3, 4, 5, 6, 7, 8, and 9 in. Hg., and held for a period of two minutes each. The surface depression began to enlarge within 30 seconds after increasing the vacuum to 10 in. Hg. In both cases, the FML and GCL remained intact and bridged the void in the sandy clay.

The Bentomat® composite geosynthetic materials hydraulic barrier has remained intact. Both seam configurations were monitored for hydraulic and structural integrity. Soil moisture sensor instrument readings above the geosynthetic materials has remained saturated, and the moisture sensor readings below the geosynthetic materials has remained constant for dry conditions. GPR surveys were conducted over the seam locations, and no record of material separation was observed. Based on the information presented, no impact to the hydraulic conductivity or the structural integrity of the Bentomat® composite geosynthetic materials hydraulic barrier was observed.

Claymax® Test Pad

Sand was evacuated from clusters 6 and 8 of the Claymax® Test Pad. The aligned FML/GCL arrangement overlaid cluster 8, whereas the non-aligned FML/GCL arrangement overlaid cluster 6. Cluster 6 was evacuated six times and cluster 8 was evacuated five times. The sand evacuation data is provided in Tables 15 and 16 for pipe clusters 6 and 8, respectively. The same seam alignment scenarios as the Bentomat® Test Pad were examined. Figure 18 shows the geosynthetic materials seam arrangement and their alignment with the test pad pipe clusters.

Table 15 – Sand Evacuation Cycles for Pipe Cluster 6 - Claymax® Test Pad
(seam-on-seam alignment)

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed per Cycle (cyds.)</u>	<u>Cumulative Total Volume of Sand Removed (cyds.)</u>	
1	2.54	2.54	Initial sand removal - 4/27/94
2	1.95	4.49	
3	2.15	6.64	
4	0.92	7.56	
5	0.64	8.20	
6	0.25	8.45	Vacuum loading applied - 7/20/94 and 8/3/94

Table 16 – Sand Evacuation Cycles for Pipe Cluster 8 - Claymax® Test Pad
(seams staggered alignment)

<u>Sand Evacuation Cycle</u>	<u>Volume of Sand Removed per Cycle (cyds.)</u>	<u>Cumulative Total Volume of Sand Removed (cyds.)</u>	
1	1.78	1.78	Initial sand removal - 4/27/94
2	2.70	4.48	
3	3.06	7.54	
4	0.76	8.30	
5	0.20	8.50	Vacuum loading applied - 7/20/94 and 8/3/94

Figure 18 - Claymax® Test Pad Geosynthetic Materials Seam Arrangement

Sand evacuation cycle 1 from cluster 6 began on April 27, 1994. Pipes 6-1, 2, 3, 4, and 5 were evacuated in order. A total of 2.54 cyds of sand was evacuated from cluster 6 during this cycle. Both cluster 6 and 8 were evacuated on April 28, 1994. Large amounts of clay were evacuated during cycle 2. An additional 1.95 cyds was evacuated from cluster 6 during this cycle. Evacuation at cluster 8 began in pipes 8-1, 2, 3, and 4 and a total of 1.78 cyds was removed from cluster 8 on this date. Cluster 8 was again evacuated on May 2, 1994. All five pipes were evacuated twice during this round of sand evacuation. Traces of clay were observed to have come from cluster 8 during this round of sand evacuation. A total of 2.10 cyds of material was removed from cluster 8. As of May 2, 1994, the cumulative volume of sand removed from clusters 6 and 8 of the Claymax ® Test Pad was 4.49 and 4.48 cyds from cluster 6 and 8 respectively. Sand evacuation at the Claymax ® Test Pad did not occur again until June 1, 1994. Some clay and topsoil were observed at various times during the evacuation of cluster 8. The total volume removed from cluster 8 on this date was 3.06 cyds. Most of the evacuated material was topsoil and an additional 2.15 cyds of material was removed on this date. Cluster 6 was evacuated again on June 2, 1994. Some clay and topsoil were observed in the evacuated material

and an additional 0.92 cyds of material were removed. The cumulative total volumes of sand removed from cluster 6 and 8 as of this date was 7.56 and 7.54 cyds, respectively. The test pads were allowed to stand with the void sizes at this volume for a period of almost two months. Both clusters were evacuated twice over the period July 20-21, 1994. Additional volumes of sand were removed from the two clusters over this two day period bringing the cumulative total to 8.45 and 8.50 cyds in clusters 6 and 8, respectively.

Vacuum load testing began at the Claymax® Test Pad on July 20, 1994. Pipe 8-4 was used to perform the test within cluster 8, and pipe 6-2 was used for cluster 6. A 4 in. Hg. vacuum was applied to both clusters for a period of five minutes. No subsidence was observed at the surface. The Claymax® Test Pad was again tested on August 3, 1994. During this testing cycle the vacuum was applied to pipe 8-2 in cluster 8. Vacuum pressures of 4, 6 and 8 in. Hg. were applied for five minute periods. When a vacuum pressure of 10 in. Hg. was applied for a period of two minutes, failure occurred in the sandy clay. This failure was expressed as a small amount of subsidence at the ground surface. A vacuum test was performed on pipe 6-2 of cluster 6 and vacuum pressures of 4, 6, and 8 in. Hg. were applied for five minutes at each pressure. Failure of the sandy clay occurred four minutes after the vacuum pressure was increased to 10 in. Hg. The final vacuum load test was performed at the Claymax® Test Pad on August 10, 1994. Vacuum pressures were applied to pipe 6-2 in increments of 1, 2, 3, 4, 5, and 6 in. Hg. and held for two minutes each to enlarge the voids in the sandy clay. The failure was expressed as a surface depression approximately 3 ft. - 3 in. by 2 ft. - 5 in. in size. The same procedure was applied to pipe 8-2. In this case, the failure of the sandy clay was expressed at the surface as a depression approximately 3 ft. - 9 in. by 3 ft. - 8 in. in size. The FML and GCL remained intact at cluster 6. However, based on the geometry of the surface depression, the GCL and FML, at cluster 8, may have torn at this time. After the second vacuum testing cycle, subsequent soil moisture sensors readings below the Claymax ® composite geosynthetic materials hydraulic barrier indicated an increase in the soil moisture content of the underlying sandy clay layer. The increased soil moisture content was confined to the top portion of the sandy clay layer, and no similar increase in the soil moisture content in the lower sensors was observed. These indications demonstrate that Claymax ® GCL was hydrated in the immediate area of the cavity and has sealed itself against the ruptured HDPE geomembrane, thus only the top portion underlying soil layer experienced an

increase in the soil moisture. Coupled with this geosynthetic materials sealing observation, the sandy clay also provided a redundant hydraulic barrier and further reduced the infiltration migration.

These results indicate the composite geosynthetic materials hydraulic barrier had been breached at the initial HDPE geomembrane, but the redundant hydraulic barrier (GCL) was activated and kept the entire hydraulic barrier intact in response to an induced subsidence event. The Claymax® composite geosynthetic materials hydraulic barrier seam-on-seam configuration was the only test location to have experienced hydration of the entire composite hydraulic barrier and the sealing capabilities of a GCL were observed. This self-healing/repair capability of the GCL is consistent with the previous laboratory studies conducted at the University of Texas, Austin.¹² The Claymax® staggered seam configuration has remained intact and no soil moisture content increases were observed.

Subsidence Instrumentation

As voids were created in the 4-ft. thick sand layer via the sand evacuation system, the overlying sandy clay soil was expected to gradually subside. The primary goals of the subsidence monitoring instrumentation were to document the location and degree of subsidence and determine the effect that subsidence had on the integrity of the sandy clay and overlying composite barrier system. The primary instrument used to monitor subsidence was the Horizontal Inclinator Probe System. Other methods were used to monitor subsidence, but the same results were observed as in Phase One testing

The Horizontal Inclinator Probe System used in this study consisted of a permanently installed horizontal casing with a pull cable arrangement and a portable instrument. The system is used for precise monitoring of settlement data. This system is the same configuration as was used for Phase One testing. Each of the geosynthetic material test pads were evaluated using this subsidence monitoring system during induced subsidence. The following sections summarize the test pad displacement during each cavity formation.

Gundseal® Test Pad

The inclinometer lines at the Gundseal® Test Pad were surveyed seven times over the period April 6, 1994, to August 15, 1994. Voids were created in clusters 1 and 3 and later in cluster 6. At the beginning of surveying on May 5, 1994, the voids in clusters 1 and 3 were 4.67 and 4.65 cyds, respectively. The maximum incremental displacement in the area of cluster 1 was -0.0027 in. and 0.0000 in. in the area of cluster 3, and the areas under the cumulative displacement curves were 0.016 and 0.013 in. in clusters 1 and 3, respectively. The Gundseal ® inclinometer lines were next surveyed on June 14, 1994. By this date, the voids in clusters 1 and 3 were increased to 7.51 and 7.43 cyds, respectively. The maximum incremental displacements and the areas under the cumulative displacement curves in the area of clusters 1 and 3 had not changed since the initial reading set taken on May 5, 1994. The next survey took place on June 29, 1994. The void sizes in cluster 1 and 3 had not been increased since the previous survey; however, the maximum incremental displacements in the areas of clusters 1 and 3 had increased to 0.1383 and 0.1332 in., respectively.

The voids in clusters 1 and 3 were failed on July 21, 1994. The round of inclinometer surveying that took place after the failure occurred on August 3, 1994. As of this date, the voids in clusters 1 and 3 had been increased to 8.59 and 8.61, respectively; however, the maximum incremental displacement had not significantly increased. Line 1 was again surveyed on August 5, 1994. Although the void size had not changed since the survey two days earlier, the maximum incremental displacement had increased to 0.1731 and 0.1824 in. in the area of clusters 1 and 3, respectively. The last inclinometer survey was performed at the Gundseal ® test pad on August 15, 1994. As of this date, the void in cluster 6 had been failed in addition to the voids in cluster 1 and 3. The final void sizes were 8.59, 8.61, and 8.58 cyds in clusters 1, 3, and 6 respectively. The final maximum incremental displacements in the area of the voids was 0.1725 in. for cluster 1, 0.1863 in. for cluster 3 and 0.0159 in. for cluster 1, 3, and 6. The area under the cumulative displacement curve had increased to 0.027 sq. in. in the area of cluster 6.

Bentomat® Test Pad

Voids were created in clusters 1 and 3 of the Bentomat® test pad. Line 1 of the Bentomat® test pad was monitored seven times from April 6, 1994, through July 13, 1994. Although all three lines were monitored during this period, voids were created only in clusters 1 and 3 which were located under line 1. Lines 2 and 3 did not show significant amounts of displacement.

The baseline inclinometer survey at the Bentomat® test pad was performed on April 6, 1994. Inclinometer monitoring of the Bentomat® test pad began on May 5, 1994. The initial void sizes were 4.51 and 5.05 cyds in clusters 1 and 3, respectively. The initial maximum incremental displacements in the areas of cluster 1 and 2 were 0.0231 and 0.0012 in., and the areas under the cumulative displacement curves were 0.018 and 0.042 sq. in., respectively. Although the void size had not increased, the deformations of the inclinometer casing over clusters 1 and 3 had increased when the casing was next surveyed on May 31, 1994. The maximum incremental displacement had increased to 0.0288 in. in the area of cluster 1 and to 0.0054 in the area of cluster 3. The areas under the cumulative displacement curves had increased to 0.036 sq. in. in cluster 1 and to 0.064 sq. in. in cluster 3. The void sizes were increased to 7.46 and 7.54 cyds in clusters 1 and 3, respectively when they were next surveyed on June 9, 1994; however, there was minimal change in both the incremental displacements and the areas under the cumulative displacement curves.

Vacuum testing at the Bentomat® test pad began on July 21, 1994. When the horizontal inclinometer casings at the Bentomat® test pad were surveyed next on August 3, 1994, the void sizes had been increased to 8.55 and 8.50 cyds in clusters 1 and 3 respectively. The maximum incremental displacement in the area of cluster 1 had increased to 0.0297 in. and in the area of cluster 3 to 0.0072 in. Although the area under the cumulative displacement curve in the area of cluster 1 did not increase, it increased to 0.075 in. in the area of cluster 3. The inclinometer casings were again surveyed on August 5, 1994. Although the void sizes had not increased, the maximum incremental displacement in the area of cluster 1 had increased to 0.2127 in., and the area under the cumulative displacement curve had increased to 0.431 sq. in. Although the maximum incremental displacement did not increase in the area of cluster 3, the area under the cumulative displacement

curve had increased to 0.140sq. in. The final round of vacuum testing at the Bentomat® test pad occurred on August 10, 1994. The last round of inclinometer surveying took place on August 15, 1994. The void sizes remained at 8.55 and 8.50 cyds in clusters 1 and 3, respectively. The final maximum incremental displacements in the areas of clusters 1 and 3 were 0.4887 and 0.0066 in., respectively. The final area under the cumulative displacement curve in the area of cluster 1 was 0.910sq. in., and 0.140 sq. in. in the area of cluster 3.

Claymax® Test Pad

Sand evacuation at the Claymax® test pad occurred in cluster 6 and 8. Line 3 of the horizontal inclinometer system overlaid these two clusters. Although all three lines were surveyed, significant displacements occurred only in line 3. The inclinometer casings at the Claymax® test pad were surveyed eight times over the period April 6, 1994, through August 17, 1994.

Baseline inclinometer surveying at the Claymax® Test Pad was performed on April 6, 1994. The initial data set was taken on May 5, 1994. At the time this data set was taken, the voids in clusters 6 and 8 were 4.50 and 4.48 cyds in size, respectively. The maximum incremental displacement in the area of cluster 6 was 0.0003 in. , and in the area of cluster 8 it was 0.0081 in. . There was no measurable area under the cumulative displacement curve. The Claymax® test pad was next surveyed on May 31, 1994. The voids in clusters 6 and 8 had not been increased; however, the maximum incremental displacements in the areas of cluster 6 and 8 increased to 0.0072 and 0.0057 in., respectively. The areas under the cumulative displacement curves increased to 0.015 and 0.011 sq. in. for clusters 6 and 8, respectively. The void sizes were increased to 7.56 cyds in cluster 6 and 7.54 cyds in cluster 8 when the inclinometer casings were next surveyed on June 13, 1994; however, no increase was observed in maximum incremental displacement or area under the cumulative displacement curves. The inclinometer casings were next surveyed on July 13, 1994. The void sizes remained at 7.56 and 7.54 cyds. The maximum incremental displacements in the areas of cluster 6 and 8 had changed to 0.0063 and 0.0090 in., respectively. The areas under the cumulative displacement curve in the area of cluster 6 had increased to 0.025sq. in., and in the area of cluster 8 to 0.014sq. in.

The voids in the Claymax® test pad were failed on July 20, 1994. At the time of failure the void in cluster 6 was 8.20 cyds, and the void in cluster 8 was 8.30 cubic yards. The inclinometer casings were again surveyed on August 3, 1994. The maximum incremental displacement in the area of cluster 6 had changed to 0.0048 in., but did not change in the area of cluster 8. The area under the cumulative displacement curve in the area of cluster 6 did not change, but increased to 0.026 sq. in. in the area of cluster 8. When the inclinometer casings were next surveyed on August 5, 1994, the void sizes had not been increased; however, the maximum incremental displacements in the areas of cluster 6 and 8 had increased significantly to 0.0330 and 0.0309 in., respectively. The area under the cumulative displacement curve in the area of cluster 6 had increased to 0.067sq. in., and in the area of cluster 8 to 0.057sq. in. The last round of inclinometer surveying at the Claymax® test pad occurred on August 17, 1994. The void sizes in clusters 6 and 8 remained at 8.20 and 8.30 cyds., respectively. The maximum incremental displacements in the areas of clusters 6 and 8 had increased to 0.0531 in. and 0.0465 in., respectively, and the areas under the cumulative displacement curves had increased to 0.084 sq. in. for both clusters.

Strain Instrumentation -- Geosynthetic Materials

A primary element of Phase Two testing was to determine the effect that subsidence had on the integrity of the sandy clay and overlying composite geosynthetic materials hydraulic barrier. Central to this was documenting the progressive strain of the GCL and the overlying HDPE geomembrane. It should be noted that the mode of failure for these two components of the composite barrier was expected to be very different, depending on the nature and locations of the seams. Where the voids were under a GCL seam, failure of the GCL would be expected to occur by the separation of the overlapping seams. Where the voids were located away from a mat seam, failure of the GCL occurred by tensile failure of the materials. In the case of the HDPE, tensile failure of the materials located over the cavity was expected.

The planned approach to documenting the separation of the GCL seams used GPR technology. Metallic tape strips were attached to the GCL along each side of the seam. The monitoring concept of the 1-in. wide metallic strips were to provide clear returns in GPR records, thus allowing the "tracking" of the seams as

they were pulled apart in response to induced subsidence. Although the tape locations could be observed with the GPR, (see Figure 19), the resolution of the records did not provide clear evidence of separation of the tape as voids developed. This is probably due to the mechanism of void failure. As mentioned above, the voids did not fail gradually. If the voids failed in this manner, the slow separation of the metallic tape may have been observed in the radar records. Rather, the voids failed catastrophically over a very short period of time. Further, the 2 ft. burial depth of the metallic tape made resolution of fine details of the GPR difficult. The signal from the tape did not appear to be strong enough at that depth to document small movements with required accuracy.

GPR Identification of Metallic Tape Strips

Phase Two Test Results Summary

Phase Two - Geosynthetic Materials Test Pad testing was concluded on September 16, 1994.

The testing results demonstrate the structural and hydraulic characteristics of the composite geosynthetic materials hydraulic barrier under actual field conditions. The composite geosynthetic materials hydraulic barrier was able to span a 7 ft. void without impacting the hydraulic conductivity and structural integrity of the hydraulic barrier. The span is estimated base volume of 8.5 cyds, on average, for each cavity formed. This performance is not dependent on the geosynthetic materials seam alignment. However, the geosynthetic materials (geomembrane/GCL) coinciding seams is not a typical installation configuration. As mentioned before, the seam-on-seam alignment configuration was tested as a "worst case" scenario. The offset seam alignment configuration for the geosynthetic materials is conventional installation standard practice. The composite geosynthetic materials hydraulic barrier's hydraulic conductivity -- 1×10^{-10} cm/sec was not degraded due the induced subsidence. The hydraulic barrier's sealing/repair capability was demonstrated and successfully sealed a breach of the overlying geomembrane.

A comparison of the composite geosynthetic materials hydraulic barrier performance results was completed with the Kaolin Clay Test Pad Testing Program results previously completed for the Mixed Waste Management Facility at SRS. The testing results from Kaolin Clay Test Pad Testing are the technical baseline requirements for constructing a RCRA Hazardous Waste Closure Cover System at SRS.

KAOLIN CLAY TEST PAD TESTING PROGRAM

Introduction

The Kaolin Clay Test Pad Testing Program¹³ was conducted from 1987 to 1989 to determine the performance characteristics of a compacted kaolin clay closure cover system for the Mixed Waste Management Facility Closure, at SRS. The objectives of the test program were to:

- determine the *in situ* hydraulic conductivity of a compacted kaolin clay layer,
- determine the response of the compacted kaolin clay layer to subsidence/deflection over a sink hole,
- determine the construction techniques to install a compacted kaolin clay layer in a closure cover system.

Hydraulic Conductivity

Results from the hydraulic conductivity testing portion of the test program showed a 2 ft. thick compacted kaolin clay layer achieved an *in situ* hydraulic conductivity of 1×10^{-7} cm/sec. This *in situ* hydraulic conductivity result was achieved after constructing several kaolin clay test pads from various kaolin clay sources and measuring the *in situ* hydraulic conductivity using several Sealed Double Ring Infiltrometers[™] on each test pad. In conjunction with the hydraulic conductivity study, the structural capacity of a compacted kaolin clay layer was also examined.

Structural Capacity

Testing results of the kaolin clay structural capacity are discussed by R.C. Warner, *Clay Cap Subsidence Demonstration Project Report for the Mixed Waste Management Facility, Savannah River Plant*,¹⁴ The conclusions of the kaolin clay structural capacity study were:

- A 22 in. thick compacted kaolin clay layer without an overlying hydraulic head can span a 46 sq. ft. cavity which was 4 ft. wide prior to collapse.
- A 22 in. thick compacted kaolin clay layer with an overlying 14 in. hydraulic head can span a 25 sq. ft. cavity which was 2.5 ft. wide prior to collapse.
- Long term subsidence was further investigated using a 22 in. thick compacted kaolin clay layer without a hydraulic head spanning a 28 sq. ft. cavity which is 2.7 ft wide.

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- Hydraulic conductivity of the compacted kaolin clay layer increased with the formation of a cavity.
 - A 14 in. hydraulic head above the compacted kaolin clay layer exacerbated the failure mechanism, thus a overlying drainage layer is needed.

Test results from the Kaolin Clay Test Pad Testing Program are the technical performance parameters for the design and construction of RCRA hazardous waste closure kaolin clay cover systems at SRS. The compacted kaolin clay cover system meets all US EPA and SCDHEC technical requirements for hazardous waste closure cover systems.

COMPARISON OF TESTING RESULTS WITH KAOLIN CLAY

The composite geosynthetic materials hydraulic barrier and compacted sandy clay layer performance results are compared to the compacted kaolin clay layer test results as outlined below in Table 17.

Table 17 -- Comparison of Performance Testing Results for Compacted Kaolin Clay, Compacted Sandy Clay, and Composite Geosynthetic Materials Hydraulic Barrier

<u>Performance Test Results</u>			
	Compacted Kaolin Clay Layer (MWMF Kaolin Clay Testing Program) ¹⁴	Compacted Sandy Clay Layer (Phase One)	Composite Geosynthetic Materials Hydraulic Barrier (Phase Two)
Maximum Cavity Span Without a Hydraulic Head Prior to Collapse	4 ft	6 ft Cavity +50% span width	7 ft (Estimated based on Cavity Volume) + 75 % span width
Maximum Cavity Span With an Overlying Hydraulic Head Prior to Collapse	2.5 ft	5 ft +100% span width	7 ft (Estimated based on Cavity Volume) + 280% span width
Impact of a Underlying Cavity on the Hydraulic Barrier Hydraulic Conductivity	Hydraulic Conductivity Did Increase	Hydraulic Conductivity <u>Did Not Degrade</u> - Remained Constant	Hydraulic Conductivity <u>Did Not Degrade</u> - Remained Constant.
Hydraulic Barrier Hydraulic Conductivity	1×10^{-7} cm/sec	2×10^{-6} cm/sec	1×10^{-10} cm/sec

The maximum cavity span identified from Phase Two testing results is an estimate of the span based on the cavity volume formed during the sand evacuation cycles and the catastrophic collapse during the initial vacuum loading at Gundseal® test pad pipe cluster 1. Quantitative measurement of all Geosynthetic test pad cavities was not possible since there was not catastrophic collapse of the composite geosynthetic materials hydraulic barrier.

The composite geosynthetic materials hydraulic barrier exceeds the hydraulic barrier performance of a kaolin clay layer and has shown superior structural in response to an underlying cavity.

The composite geosynthetic materials hydraulic barrier is an alternative closure cover system configuration with superior performance characteristics.

CONCLUSIONS

The composite geosynthetic materials hydraulic barrier consisting of a 40 mil High Density Polyethylene geomembrane overlying a geosynthetic clay liner overlying a 2 ft. compacted sandy clay layer, has exceeded the performance characteristics of a compacted kaolin clay layer, and it is a superior hydraulic barrier configuration for use as a RCRA/CERCLA Closure Cover System over hazardous/radiological waste landfills and surface impoundments. The results of Phase One - Control Test Pad Testing and Phase Two - Geosynthetic Material Test Pad Testing of the Bentonite Mat Demonstration verifies the performance structural and hydraulic capabilities of the composite geosynthetic materials hydraulic barrier cover system.

The Bentonite Mat Demonstration conclusions are listed below:

- The composite geosynthetic materials hydraulic barrier is an alternative cover system configuration with superior performance characteristics to a compacted kaolin clay layer.
- The composite geosynthetic materials hydraulic barrier is an equivalent alternative hydraulic barrier to a kaolin clay hydraulic barrier.
- Local SRS sandy clay soils have the strength and hydraulic properties to perform as a redundant hydraulic barrier using the modified general backfill specifications and normal construction methods.
- High stress testing results of the sandy clay layer demonstrates the compacted soil matrix's tensile strength to span a void and remain intact. This aspect is key in determining the factor of safety for an applied surface load. A 2 ft. compacted sandy clay layer showed a 50% increase in span width capability (unsaturated soil conditions) and a 100% increase in span width capability (saturated soil conditions) in contrast to a compacted kaolin clay layer.
- Low stress testing results of the sandy clay layer demonstrates the compacted soil matrix's long term strength capability is increased 200% over a compacted kaolin clay layer.
- The *in situ* hydraulic conductivity of a compacted sandy clay layer is on average 2.0×10^{-6} cm/sec. Compliance with the EPA Recommended Hydraulic Conductivity of 1.0×10^{-7} cm/sec for a compacted clay layer is not achieved by use of the sandy clay alone.

- The composite geosynthetic materials hydraulic barrier hydraulic conductivity is 1×10^{-10} cm/sec which exceeds the EPA recommended hydraulic conductivity of 1.0×10^{-7} cm/sec for a compacted clay layer (i.e., Kaolin Clay) by 3 orders of magnitude.
- The maximum cavity span width for the composite geosynthetic materials hydraulic barrier is increased by + 75 % for an unsaturated soil condition and + 280 % for a saturated soil condition in comparison to a compacted kaolin clay layer.
- The composite geosynthetic materials hydraulic barrier hydraulic conductivity did not degrade in response to the formation of an underlying cavity.
- The 2 ft. compacted sandy clay layer hydraulic conductivity did not degrade in response to the formation of an underlying cavity.
- Embedded moisture instrumentation can survive construction installation and provides "real time" hydraulic performance data to identify breaches and imperfections of the hydraulic barrier.

The demonstrated field performance of the composite geosynthetic materials hydraulic barrier in a closure cover configuration provides the flexibility and durability to ensure the containment of hazardous/radiological waste for both RCRA and CERCLA Closures. This alternative cover system configuration is the recommended closure cover system hydraulic barrier configuration to be used over waste layers that have a high potential of subsidence at SRS. The Bentonite Mat Demonstration is a proactive approach to validate cost-effective remedial actions, continuous improvement through technology and engineering development, and to ensure our commitment to protect human health and the environment.

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