STATE OF THE ART DESIGN:
A CLOSURE SYSTEM FOR THE LARGEST HAZARDOUS WASTE LANDFILL AT THE SAVANNAH RIVER SITE (U)

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ABSTRACT

This paper discusses the cover system proposed for a 55-acre, hazardous waste closure of the sanitary landfill at the Savannah River Site, near Aiken, South Carolina. The proposed cover system has been designed to accommodate a significant amount of post-closure settlement while maintaining a permeability of 1×10^{-7} cm/s or less throughout its 30-year, regulatory lifetime. A composite cover consisting of a geomembrane (GM) underlain by a geosynthetic clay liner (GCL) was selected because of its extremely low permeability, ability to elongate without tearing, and capacity to "self-heal" if punctured. These characteristics will enable the cover system to accommodate differential settlement without cracking or tearing, thus providing long-term protection with minimal maintenance. Also, to improve the ability of the cover system to span voids that may develop in the underlying waste, a geogrid has been included in the foundation layer. A gas vent layer has been included to allow for the safe collection and venting of landfill gases.

INTRODUCTION

The sanitary landfill at the Savannah River Site (SRS) is to be closed as an interim status, RCRA hazardous waste landfill according to a settlement agreement between South Carolina Department of Health and Environmental Control (SCDHEC) and the Department of Energy (DOE). In this agreement, DOE has consented to close approximately 55 acres of the landfill where rags and swipes contaminated with F-listed solvents are suspected of having been deposited. Also, a closure plan and post-closure plan must be submitted to SCDHEC in accordance with South Carolina Hazardous Waste Management Regulations R.61-79.265.

The sanitary landfill at SRS is a unlined, slit-trench landfill that receives about 40,000 cubic yards of waste per year (1). Operations in the original landfill began in 1974 (Fig. 1). This 32-acre tract continued to receive waste for a 12 year period from 1974 to 1985. In 1986, SCDHEC approved a 22-acre, southern expansion and a 16-acre, northern expansion to the original landfill. Operations began in the southern expansion during 1987 and continue to present. By mid-year, 1993, the southern expansion will have reached its capacity and waste disposal will begin in the northern expansion. Typical landfilled wastes are: paper, cardboard, plastics, cafeteria wastes, rubber, wood, discarded office furniture, cans, drums, pipe, culvert and miscellaneous construction rubble. Asbestos and skimmings from the waste water treatment plant have also been buried. The length and width of the slit trenches has varied throughout the operation of the landfill. Prior to 1987, when the original landfill was in use, the trenches were excavated by a dozer or front-end loader. These trenches are approximately 20 feet wide, 10 to 15 feet deep, and have variable lengths. Slit trenches in the southern expansion were excavated by a scraper, hence they are much wider. Typically, these trenches are 30 to 50 feet wide, 10 to 15 feet deep, and 300 to 500 feet long. All inactive trenches have been covered by approximately 2 feet of clayey, sandy soil that has a saturated permeability of approximately 5×10^{-5} to 1×10^{-2} cm/s. The sediments underlying the landfill are predominately clayey to silty sands with about the same permeability as the cover soils. The average depth to groundwater is about 5 to 10 feet below the bottom of the trenches in the original landfill and about 10 to 15 feet below the bottom of the trenches in the southern expansion.

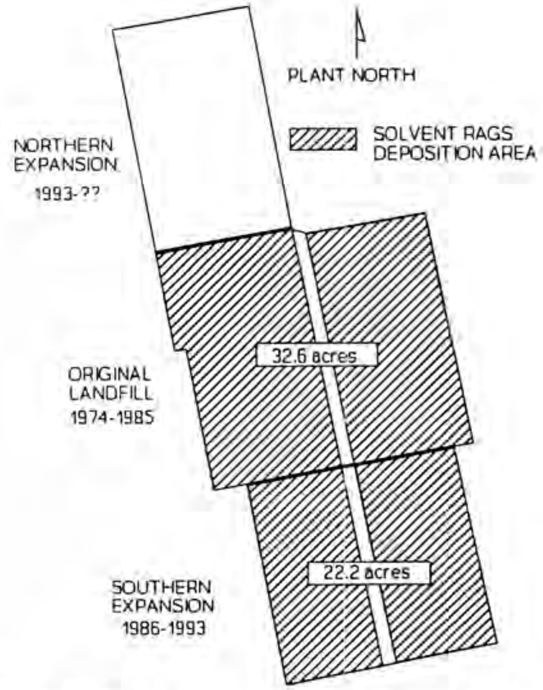

Fig. 1. Map of sanitary landfill at the Savannah River Site, Aiken, South Carolina.

Past RCRA hazardous waste closures at SRS have deployed 24 inches of compacted, kaolin clay as the impermeable barrier in the cover system. However, because solid waste landfills typically undergo a significant amount of post-closure settlement (2), we concluded that a compacted clay cover may not make a suitable impermeable barrier for the sanitary landfill. We began exploring alternative cover systems that deploy geosynthetic materials and sought SCDHEC and EPA guidance on the acceptability of these materials. Preliminary design presentations were held in the spring of 1991 with SCDHEC and EPA to discuss the potential use of geosynthetic material for the SRS sanitary landfill closure. Both agencies were open to alternative designs provided that these design meet the intent of the hazardous waste management regulations. Subpart N of these regulations, lists the performance standards for final covers (3).

1. Provide long-term minimization of migration of liquids through the closed landfill;
2. Function with minimum maintenance;
3. Promote drainage and minimize erosion or abrasion of the cover;
4. Accommodate settling and subsidence so that the cover's integrity is maintained; and
5. Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

In meeting these requirements, EPA recommends: 1) a low hydraulic conductivity geomembrane/soil layer composed of 24 inches (60 cm) of compacted or amended soil with a hydraulic conductivity of 1×10^{-7} cm/sec or less in intimate contact with a minimum 20 mil geomembrane liner, 2) a drainage layer of 12 inches (30 cm) of granular soil having a hydraulic conductivity of 1×10^{-2} cm or greater, 3) a top, vegetation/soil layer with vegetation or an armored top surface and a minimum of 24 inches (60 cm) of soil graded at a slope between 3 and 5 percent (2).

SETTLEMENT POTENTIAL AT THE SRS SANITARY LANDFILL

With time, solid waste landfills have large differential settlements due to compression and biodegradation of the buried waste (4,5,6). Based on typical values measured at other landfills, we estimate that the amount of post-closure settlement at the sanitary landfill may be as much as 10 to 15 percent of the waste thickness, or about 1 to 2 feet of total settlement (7,8). Two mechanism will produce most of this settlement: compression and biodegradation. Compression, or elastic settlement, is usually short-lived and will produce about 30 to 40 percent of the total settlement (8). Biodegradation, or secondary settlement, will be responsible for the remaining 60 to 70 percent and is long-term, lasting tens of years. During assessment activities at the landfill, we noted several six to eight-inch deep undulations across the slit trenches in the oldest section of the original landfill. These depressions suggest that some of the waste has decreased approximately 5 percent by volume in about 15 years. Because the existing cover is only 2 feet thick and is not capable of greatly compressing the waste, we attribute much of this settlement to biodegradation. Also, methane concentrations from a soil gas survey conducted at the landfill are relatively high (e.g., maximum of 50 percent by volume), suggesting that biodegradation is well underway in this area (9).

For cases where post-closure settlement may be large, EPA has suggested the placement of an interim cover, followed by the construction of a final cover upon completion of secondary settlement. EPA (2) states:

> *"Some wastes (such as loose municipal solid waste or unconsolidated sludge of varying thickness) are so compressible that constructing a cover system above the waste will almost certainly produce distortions that are far larger than 0.05 percent. The hydraulic integrity of a low conductivity layer of compacted soil is likely to be seriously damaged by the distortion caused by differential settlement. If the waste is continuing to settle, e.g., as a result of decomposition, it may be prudent to place a temporary cover on the waste and wait for settlement to take place prior to constructing the final cover system."*

This option of constructing a temporary cover, waiting for settlement to decrease, and then constructing a final cover was initially consider by the design team. However, this option was deemed undesirable because two phases of construction are required. Furthermore, a considerable period of time may be required before secondary settlement has reached tolerable levels and final cover can be constructed. This "wait until settlement has gone" approach causes additional problems with scheduling and allocating funds for a second construction phase at an unknown, future date.

EPA has also suggested that waste stabilization techniques might be used to minimize settlement prior to placement of final cover. To evaluate these options, SRS formed an academic advisory group to formulate potential waste stabilization alternatives for the sanitary landfill and other RCRA closures (10). After considering 17 options, the group narrowed the viable alternatives to dynamic compaction, grouting, and static surcharge. Dynamic compaction has been used successfully at some sites. However, wastes such as paper, plastic, and vegetation typically produce a "bouncing" effect as the weight strikes the waste. This effect indicates that the underlying waste is highly elastic and cannot be effectively compacted. These wastes are usually excavated and replaced with compacted backfill to provide a stable foundation. Because the sanitary landfill has a high percentage of paper and plastic, excavation and replacement is considered to be impractical and too costly. Also, the use of dynamic compaction at the sanitary landfill may further disrupt the buried waste, causing additional contamination to the shallow, unconfined aquifer. Other in-situ stabilization techniques (e.g., grouting and soil cementing) may be effective in reducing the amount of secondary settlement, but because of the large area involved (55 acres), these alternatives are extremely costly for the benefit gained (10).

To test the feasibility of using static surcharging to preconsolidate the waste and to refine our estimates of the potential amount of elastic settlement, a static surcharge test program was conducted at the sanitary landfill (7,11). Three test sites were chosen: one over the oldest part of the original landfill, one over the middle-aged waste in the original landfill, and one over the more recently placed waste in the southern expansion. At each site, a surcharge fill was constructed with heights that varied from 5 to 20 feet (Fig. 2). Auger-type settlement monitors were cased in PVC pipe at 3 different depths under each fill height.

The results from these tests show that most of the elastic settlement occurred during the placement of the test fills (7). The amount of settlement was a function of the fill height and varied from 0.1 to 1.1 feet at all of the test sites (Fig. 3). After completing the construction of the test fills, we have observed no appreciable settlement at any of the test sites. These results suggest that elastic settlement at the sanitary landfill will be short-lived and will occur mainly during construction activities. Thus, we believe that any post-closure, elastic settlement after construction will be minimal and does not appear to pose

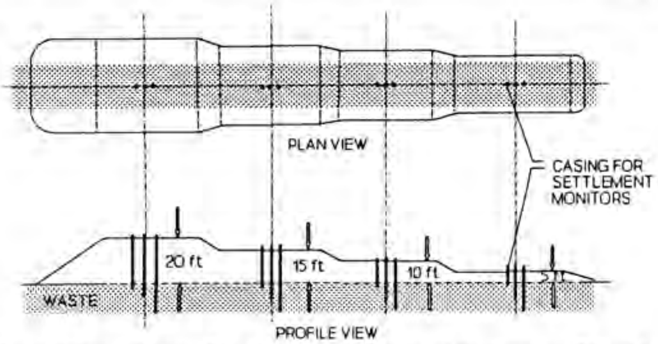

Fig. 2. Plan and profile view of a static surcharge test fill and placement of settlement monitors (after McMullin, 1992a).

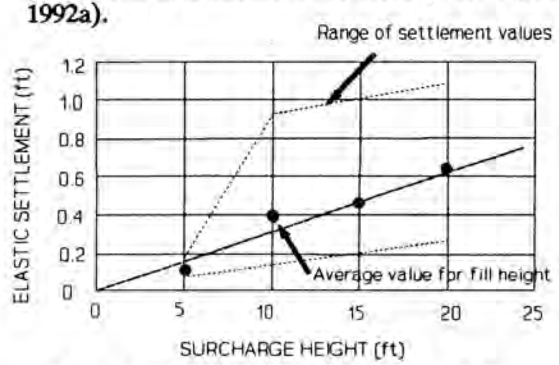

Fig. 3. Settlement versus surcharge height.

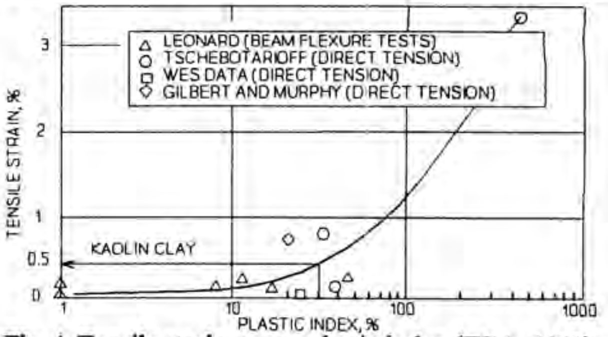

Fig. 4. Tensile strain versus plastic index (EPA, 1991).

a major threat to the integrity of the cover system. However, post-closure, biodegradation settlement may crack or tear the impermeable barrier if the cover system is not carefully engineered.

RESPONSE OF COMPACTED CLAY COVERS TO DIFFERENTIAL SETTLEMENT

Post-closure, differential settlement may be particularly damaging to compacted clay covers (2,12). Differential settlement is defined as the difference between the total settlement measured at two points. Distortion is the differential settlement divided by the horizontal distance between the two points. Large differential settlement between two nearby points yields high distortion. Distortion induces tensile stresses in the cover and may cause it to bend, crack, or excessively yield if the tensile strength of the soil is not sufficiently large enough to resist deformation.

The potential for excessive distortion at the sanitary landfill is high due to the slit trench mode of excavation that was employed. As a new trench was excavated adjacent to an existing trench, a few feet of undisturbed soil was left between the trenches. With time, the waste in trenches will undergo significant biodegradation, while the undisturbed soil in the trench walls will not settle appreciably. Performance data show that tensile strains ranging from 0.1 to 1 percent are sufficient enough to cause most compacted clay soils to crack (13). For low plastic clays, such as kaolin approximately 0.5 percent tensile strain is required to bring the clay to failure (Fig. 4). This tensile strain produces a distortion (i.e., Δ/L) of about 0.1 percent (Fig. 5), which is equivalent to a 20-foot-wide trench subsiding approximately 1 foot at its center. However, if the lower limit of 0.1 percent strain is used as a conservative estimate for design, as recommended by EPA (2), then a distortion of 0.05 becomes the maximum allowable value (Fig. 5). This is equivalent to a 20-foot-wide trench subsiding approximately 0.5 feet at its center. Any settlement exceeding 0.5 feet may sufficiently deform a compacted clay cover to cause it to crack and to loose it low permeability characteristics. As previously discussed, settlement of approximately 0.5 feet has already been observed in the older trenches at the sanitary landfill. Hence, it is likely that biodegradation has produced and will continue to produce differential settlement that is large enough to jeopardize the integrity of a compacted clay cover at the sanitary landfill.

ALTERNATIVE COVER SYSTEM FOR THE SANITARY LANDFILL CLOSURE

The generic cover design established by EPA for hazardous waste landfills does not take into account site-specific design considerations, such as the potential for large differential settlement. EPA has recognized the need to consider alternatives to its recommended generic design for cases where site conditions warrant special consideration: "*EPA encourages design innovations and will accept an alternative design provided the owner or operator demonstrates the new design's equivalency.*" (2)

State-of-the-art design for solid-waste landfills is beginning to use composite cover/liner systems consisting of a geomembrane (GM) liner, or sometimes refer to as a "flexible membrane liner" (FML), underlain by a geosynthetic clay liner (GCL) (12). The GM component typically consists of a high-density, polyethylene (HDPE) liner which is manufactured in panels and seamed during installation. The GCL component is a prefabricated, bentonite clay blanket having sodium bentonite sandwiched between a geotextile fabric or glued to the back of a HDPE liner (14). Currently, there are four GCL's available under the registered trademarks of Claymax, Bentomat, Bentofix, and a non-registered product called Gundseal (12). Most manufacturers apply 1 pound of bentonite per square foot of GCL (14).

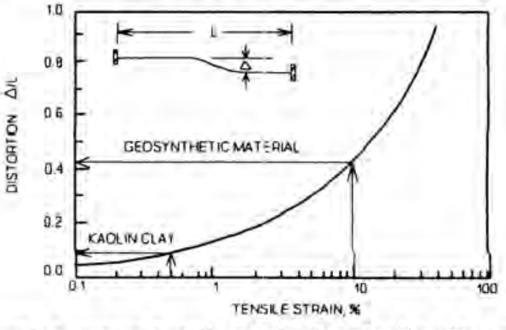

Fig. 5. Distortion versus tensile strain for Kaolin Clay and Geosynthetic.

The high tensile strength and elongation properties of GM/GCL's make them attractive alternatives to compacted clay. GM/GCL's have the ability to elongate and conform to depressions without rupturing, thus they can withstand much more differential settlement than compacted clay. Typically, GM/GCL's are capable of withstanding about 10 percent tensile strain prior to yielding (2). This means, for example, that a 20-foot-wide slit trench would have to subside approximately 4 feet at its center before the geosynthetic material would approach failure or yield excessively (Fig. 5).

In addition to the settlement that will occur across the width of subsiding trenches, sink holes may develop within the sanitary landfill as buried objects, such as drums, containers, desks, file cabinets, etc., deteriorate and collapse. Once a sink hole has formed, the structural component of the cover system must be capable of spanning the void while supporting the weight of the cover and any super-imposed loads. In spanning the void, the cover system is subjected to tensile stresses due to bending and direct elongation. As the void becomes increasingly wider, the cover system must span a greater distance; and ultimately, the tensile stresses within the cover system can reach their ultimate tensile strength and fail.

We evaluated 6 generic cover systems for their potential response to "sink hole" failure (8). The following ranking criteria were used: 1) sufficient factor of safety against cracking or excessive yield, 2) cost of construction, 3) longevity, 4) repairability, and 5) maintenance. Figure 6 shows the cover systems that were evaluated. Cover system 1 consists of a two-foot thick, compacted clay layer overlain by a one-foot thick drainage layer and a two-foot thick topsoil layer. This is a conventional design used at many landfills. If a sink hole develops underneath this cover, the compacted clay layer must be capable of spanning the void without cracking or collapsing. The design shown in cover system 2 places a geogrid beneath the clay layer to serve as reinforcement. The geogrid improves the tensile strength of the system and its ability to span larger voids without cracking or collapsing. System 3 is the composite cover recommended by EPA. It is similar to cover system 1 except that a GM liner has been placed above the compacted clay layer to improve the hydraulic performance of the impermeable barrier. Cover system 4 is identical to cover system 3 except that a geogrid has been included underneath the compacted clay layer to reinforce the compacted clay. If a void develops in this system, all three components (i.e., geogrid, compacted clay layer, and GM) must carry a proportion of the load without failing. The design of cover system 5 is similar to cover system 3 except that the compacted clay layer has been replaced by a GCL. The GCL in system 5 acts as a backup barrier or "leak stopper" to the primary GM barrier. Any water infiltrating through seam imperfections or holes in the GM will cause the bentonite in the GCL to hydrate, swell, and effectively seal the leak (14). This leak stopping ability of the GCL significantly reduces infiltration through the cover. Cover system 6 is similar to cover system 5 except that a geogrid has been placed beneath the GM/GCL liner to act as the primary structural member of this system. Also, the replacement of the 2 feet of compacted clay with a GCL makes the cap much more lightweight and significantly reduces the tensile stress that will develop in the geogrid if a void develops.

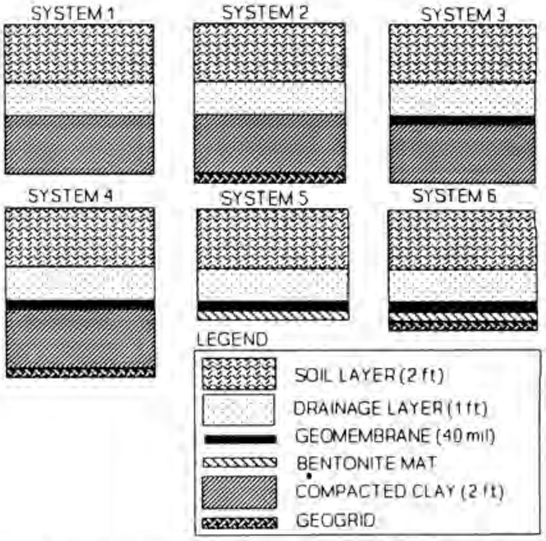

Fig. 6. Cover systems evaluated for SRS sanitary landfill.

Table I presents the rankings for the design study (8). These results are comparable to the qualitative rankings given by Koerner and Daniel of several compacted clay and GM/GCL cover systems (12). Based on these rankings, a GM/GCL cover system underlain by geogrid is recommended for the sanitary landfill.

TABLE I

Summary - Comparative Analysis of Alternative Cover Systems for the SRS Sanitary Landfill (after Bhutani and Mead, 1992)

Cover System	Maximum Allowable Sinkhole Diameter (ft)	Ease of Construction	Construction Quality Assurance	Ease of Repair	Accumulated Points	Rank
System 6	13.0	Good	Good	Good	17	1
System 5	5.6	Good	Good	Good	12	2
System 4	7.0	Difficult	Fair	Difficult	10	3
System 2	7.0	Difficult	Fair	Difficult	10	3
System 3	5.3	Difficult	Fair	Difficult	8	4
System 1	5.3	Difficult	Fair	Difficult	8	4

Maximum Allowable Sinkhole Diameter

The design calculations showed that an unreinforced compacted clay liner (CCL), as shown in cover systems 1 and 3, is capable of spanning a 5-foot-diameter sink hole before collapsing. The addition of a geogrid to the bottom of the CCL, as shown in cover system 2, allows for the spanning of a larger void (e.g., about 7-foot-diameter). However, the distortion at the center of the void may still be large enough to crack the CCL. If the CCL is replaced by a GM/GCL, as shown in cover system 5, the dead load due to the weight of the cover is significantly reduced because a GM/GCL is much lighter than a CCL. Nonetheless, even with this load reduction, the ability of system 5 to span voids is approximately equal to that of the CCL, or about 6 feet in diameter. However, the addition of a geogrid to system 5, as shown in cover system 6, potentially doubles the width of the void that may be spanned. (Design calculations suggest that sink holes as large as 13 feet in diameter may be spanned before exceeding the allowable tensile stresses in the geosynthetic materials.)

Ease of Construction

Geosynthetic materials are generally brought to the installation site in rolls and are placed using light weigh construction equipment. They are relatively easy to install and can be deployed quickly (within a few weeks). Compacted clay covers require heavy construction equipment for proper compaction and a good deal of skill to control the soil moisture/density relationships during placement (8).

Construction Quality Assurance

EPA recommends that a construction quality assurance program be implemented for the purpose of ensuring that the final cover system meets all design criteria, plans, and specifications (15). Quality assurance monitoring during the construction of the closure at the sanitary landfill is very important in ensuring the success of any cover system. During evaluation of the 6 alternative cover systems, the following findings were emphasized: 1) The performance of a compacted clay cover is highly dependent upon the quality of construction, whereas the hydraulic properties of the GM/GCL is less sensitive to construction variabilities. 2) Frequent in-place testing is required for compacted clay to verify that the material is in specification and compaction is adequate. Often test pads are required prior to construction to establish construction parameters, such as molding water content, the type construction equipment to be used, the number of compaction passes, and the lift thickness. In contrast, repeated field testing is not required for GM/GCL's. The products come pre-certified from the vendor. 3) Quality control for GCL's requires installation inspections for correct seam overlap and proper backfilling techniques to ensure that the seams remain in-place and the equipment does not tear the GCL. 4) Quality control for geogrid requires installation inspection for correct end and side seaming as well as proper anchorage. 5) Quality control for the GM involves proper seaming and field testing of seam integrity.

Ease of Repair

Repair of a compacted clay cover that has failed from excessive settlement is a rather difficult task to achieve. The clay in the failed zone must be removed and replaced with a new layer of compacted clay that meets the original material specifications. This could cause difficulty in locating the appropriate type of clay. Also, the new clay layer must be placed against or blended with the existing clay to form a bond which maintains the low permeability characteristics of the existing cover. This process typically requires extensive quality control measures to maintain the integrity of the cap. In comparison, because GM's and GCL's are manufactured materials, they are readily available from suppliers. Also, irregular shapes, cuts, and tears are easily repaired by cutting a piece of the material that is large enough to provide a generous overlap on all sides of the tear. Proper quality assurance of the repair can be easily verified for GM's by using proper seaming techniques and field testing of the seams. Thus, the time and cost to repair the cover will be substantially less for GM/GCL's than for conventional compacted clay covers (8).

OTHER CONSIDERATIONS

Longevity/Durability

Regulations require a cover to maintain its integrity and performance over a 30 year period. Compacted clay covers are particularly susceptible to cracking due to differential settlement, desiccation, and freeze-thaw. They must be protected by a suitably thick layer of cover soil to maintain their longevity (12). Geosynthetic materials are relatively new and have limited, long-term field performance. Degradation processes, such as ultraviolet, radiation, chemical, and biological degradation can affect the durability of these products (2,16). Ultraviolet degradation can be minimized by adding carbon black to the GM or by covering the GM with soil to prevent exposure to sunlight. UV degradation can be eliminated by covering the GM with as little as 15 cm of soil (16). Radiation degradation of GM's has been extensively studied. The mechanical properties of typical GM's begin to alter at a total radiation dose of between 10^6 and 10^7 rads. This does rate is several orders of magnitude larger than any rate expected at SRS, hence radiation degradation is not a potential problem at the sanitary landfill. Chemical degradation is a serious concern for liner systems because of their potential attack and breakdown of the polymers by leachate. However, for GM's installed in cover systems, the chief fluid contacting the GM will be water. This environment is essentially inert, and cover systems will be much less prone to chemical degradation than liner systems. Biological degradation of polymer resins in GM's is highly unlikely from bacteria, actinomycetes, fungi, and algae, although these may possibly attach plasticizers or additives. Polymers also do not contain food for higher forms of biological life, but animals may try to penetrate or burrow through them (16).

Permeability and Long-term Minimization of Migration of Liquids

Geomembranes are essentially impermeable and will meet the performance standard of 1×10^{-7} cm/s if they remain undamaged. Fluids will not pass through the GM unless leaks develop along the panel seams or tears and punctures develop within the panels. Thus, if properly installed properly and adequately protected from puncture by overlying soil, GM's provide a good impermeable barrier. Recent studies have shown that flaws in a GM barrier have much less of an impact on increasing infiltration if a clayey material is placed below and in direct contact with the GM (2,14). These studies recommend that a GCL be placed directly below the GM to reduce the amount of water that will infiltrate through

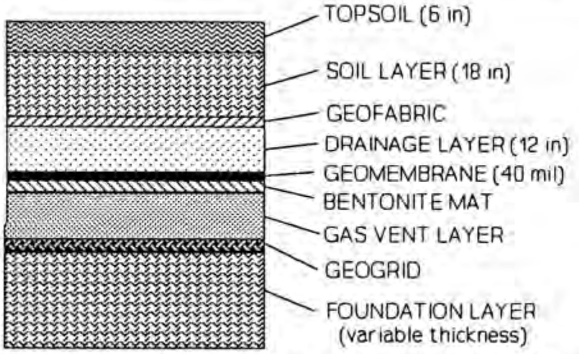

Fig. 7. Conceptual design of cover system for the sanitary landfill.

seaming flaws and penetrations (12,14). Potential leaks in the GM are sealed by the hydration, swelling, and plugging action of the bentonite contained in the GCL. To test this self-plugging action, Estronell and Daniel (14) performed hydraulic conductivity tests on individual GCL panels, on overlapped GCL panels, and on composite liners consisting of a punctured GM (3-inch diameter puncture) overlying an undamaged GCL. Hydraulic conductivity of the individual GCL panels ranged from 10^{-10} to 10^{-8} cm/s. Hydraulic conductivities of the overlapped GCL panels were about the same as those of the unoverlapped control panels. Hydraulic performance of the punctured GM panels underlain by a GCL varied for various types of GCL's tested. The best performance was achieved when the punctured GM was placed directly against the bentonite with no geotextile separating the GM and bentonite. In all tests, hydraulic conductivities of the individual GCL's, overlapped GCL's, and punctured GM/GCL composite systems remained below 1×10^{-8} cm/s.

CONCLUSIONS

Municipal landfills typically exhibit large differential settlements due to compression and biodegradation of the landfilled waste. In some cases, the total amount of settlement may be as much as 10 to 15 percent of the waste thickness. Compacted clay covers have low tensile strengths and may crack from bending stresses and elongation induced by differential settlement. Upon cracking, a compacted clay cover will not meet the hydraulic conductivity requirement of 1×10^{-7} cm/s or less. Typically, kaolin clays can withstand about 0.5 percent tensile strain before cracking. This amount of tensile strain is equivalent to a 20-foot-wide trench subsiding about 1 foot at its center-point. Because post-closure strains of this magnitude, are possible at the SRS sanitary landfill, we recommend that a compacted clay cover should not be employed. Geosynthetic materials have much higher tensile strengths and have better elongation properties than compacted clays. Most geosynthetic materials can withstand approximately 10 percent tensile strain before yielding excessively (2). This is equivalent to a 20-foot-wide trench undergoing 4 ft of settlement at its center.

Based on conceptual design calculations by Bhutani and Mead (8) and design recommendations by Koerner and Daniel (12) and Estornell and Daniel (14), a geomembrane (GM)/geosynthetic clay (GCL) composite cover system underlain by geogrid is recommended for use at the SRS sanitary landfill (Fig. 7). These studies show that flaws in a GM have much less of an impact if the GCL is placed below and in direct contact with the GM. Potential leaks in the GM will be sealed by the hydration, swelling, and plugging action of the bentonite contained in the GCL. This composite action will greatly reduce the water infiltrating through imperfections in the GM. These studies also suggest that a GM/GCL cover will be more cost effective and easier to install and maintain than a conventional compacted clay cover. A gas vent system is also recommended to allow combustible landfill gases to escape safely from underneath the GM/GCL barrier (17).

REFERENCES

1. Dames and Moore, 1984, "Report: Solid Waste Consulting Services, Sanitary Landfill, Savannah River Plant, For: E.I. du Pont de Nemours and Company, Inc.", Job No. 367-040-09, November, 1984, 15 p.
2. EPA 1991, "Design and Construction of RCRA/CERCLA Final Covers," Seminar Publication, EPA/625/4-91/025, Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, OH, May, 1991.
3. South Carolina Hazardous Waste Management Regulations, R.61-79.265.
4. EDIL, T. B., RANGUETTE, V. J., WUELINER, W. W., 1990, "Settlement of Municipal Refuse," Geotechnics of Waste Fills - Theory and Practice, ASTM STP 1070, Arvid Landva and G. David Knowles, Editors, American Society for Testing and Materials, Philadelphia, PA, pp. 225-239.
5. MORRIS, D. V. and WOODS, C. E., 1990, "Settlement and Engineering Considerations in Landfill and Final Cover Design," Geotechnics of Waste Fills - Theory and Practice, ASTM STP 1070, Arvid Landva and G. David Knowles, Editors, American Society for Testing and Materials, Philadelphia, PA, pp. 9-21.
6. RAO S. K., MOULTON, L. K., SEALS, R. K., 1977, "Settlement of Refuse Landfills," Proceedings of the Conference on Geotechnical Practice for Disposal of Solid Waste Materials, ASCE, June 13-15, 1977, pp. 574-598.
7. MCMULLIN, S. R., 1992a, "Transmittal of Interim Report: Engineering Parameter Characterization Program, Sanitary Landfill Assessment and Closure," Interoffice Memorandum No. WER-ERG-921033, Westinghouse Savannah River Company, Savannah River Site, Aiken, SC, 13 p.
8. BHUTANI, J. S. and MEAD, S., 1992, "Alternative Study of Potential Cover Systems for the Sanitary Landfill (740-G)," Report No. WSRC-TR-92-194, Westinghouse Savannah River Co., Savannah River Site, Aiken, SC, 20 p.
9. PIRKLE, R. J., and MASDEA, D. J., 1991, "Final Report Soil Gas Investigation at the Sanitary Landfill (740-G)," Savannah River Site, May, 1991, 15 p.
10. MCMULLIN, S. R., 1992b, "Evaluation of Waste Stabilization Options, Sanitary Landfill Assessement/Closure," Interoffice Memorandum No. WER-ERT-920130, Westinghouse Savannah River Company, Savannah River Site, Aiken, SC.
11. MCMULLIN, S. R., 1991, "Test Program Plan, Static Surcharge Test-Sanitary Landfill," Interoffice Memorandum No. WER-ERG-920987, Westinghouse Savannah River Company, Savannah River Site, Aiken, SC.

12. KOERNER, R. M. and DANIEL, D. E., 1992, "Better Cover-Ups," Civil Engineering, American Society of Civil Engineers, May, 1992, pp. 55-57.
13. GILBERT, P. A., and MURPHY, W. L., 1987, "Prediction/Mitigation of Subsidence Damage to Hazardous Waste Landfill Covers," EPA/600/2-87/025 (PB87-175386), Cincinnati, Ohio, U.S. EPA.
14. ESTORNELL, P., and DANIEL D. E., 1992, "Hydraulic Conductivity of Three Geosynthetic Clay Liners," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 118, No. 10, October 1992, pp. 1592-1606.
15. EPA 1989, "Final Covers on Hazardous Waste Landfills and Surface Impoundments," Technical Guidance Document, EPA/530-SW-047, Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C., July, 1989.
16. KOERNER, R. M., HALSE-HSUAN, Y., and LORD, A. E., JR., 1991, "Long-Term Durability of Geomembranes," Civil Engineering, American Society of Civil Engineers, April, 1991, pp. 56-58.
17. Methane Generation and Venting Alternatives Study, October, 1992, unpublished study by Bechtel Savannah River Incorporated, Aiken, South Carolina.

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