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**PHYSICAL AND HYDRAULIC CHARACTERISTICS
OF BENTONITE-AMENDED SOIL
FROM AREA 5, NEVADA TEST SITE**

Prepared by

William Albright

Submitted to

Nevada Operations Office
U.S. Department of Energy

August 1995

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**PHYSICAL AND HYDRAULIC CHARACTERISTICS
OF BENTONITE-AMENDED SOIL
FROM AREA 5, NEVADA TEST SITE**

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Publication No. 45137

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Nevada Operations Office
U.S. Department of Energy
Las Vegas, Nevada

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ABSTRACT

Radioactive waste requires significant isolation from the biosphere. Shallow land burial using low-permeability covers are often used to prevent the release of impounded material. This report details the characterization of a soil mixture intended for use as the low-permeability component of a radioactive waste disposal site. The addition of 6.5 percent bentonite to the sandy soils of the site reduced the value of saturated hydraulic conductivity (K_s) by more than two orders of magnitude to 7.6×10^{-8} cm/sec. Characterization of the soil mixture included measurements of grain density, grain size distribution, compaction, porosity, dry bulk density, shear strength, desiccation shrinkage, K_s , the effect of alternating cycles of drying and resaturation on K_s , the effect of water content at time of compaction on K_s , vapor conductivity, air permeability, the characteristic water retention function, and unsaturated hydraulic conductivity by both experimental and numerical estimation methods. The ability of the soil layer to limit infiltration in a simulated application was estimated in a one-dimensional model of a landfill cover.

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CHAPTER 1: INTRODUCTION

This report details the results of an investigation into one component of an innovative type of waste facility design currently being studied for application in the arid southwest. Even though scant precipitation is one of the defining characteristics of the southwest, hydrologic processes still provide the most likely mechanisms for the release of contaminants to the environment. The new designs seek to rely primarily on the natural processes of evaporation and transpiration to return precipitation to the atmosphere and prevent percolation through waste cells. In much of the arid southwest, this function is adequately performed by the top 1 to 2 meters (m) of soil along with the natural plant communities. Waste facility designs require redundant features, and a layer of low-permeability soil, 2 to 3 m below the surface provides an additional barrier to infiltration. This report summarizes an investigation of the composition as well as the hydraulic and engineering characteristics of a soil mixture proposed as a low-permeability component of a waste facility intended for application at Area 5 of the Nevada Test Site (NTS).

In addition to this introduction, Chapter 1 gives an overview of disposal alternatives, legislative history, and design of waste containment facilities. Chapter 2, Materials and Methods, develops in concept and detail each of the experimental procedures used in this investigation. The experimental results and the implications for waste containment are listed in Chapter 3, Results and Discussion. Chapter 4 describes the modeled application of a simple cover design, including a low-permeability layer of the type described in this report. Chapter 5 summarizes the relevant findings and makes a number of recommendations for further research into semi-arid region waste cover design.

HAZARDOUS AND RADIOACTIVE WASTE REGULATORY ENVIRONMENT AND POLICY

The disposal of hazardous wastes and radioactive wastes are regulated under separate but related acts of legislation. Both share the common thread of seeking to provide isolation from the environment for these dangerous substances.

Regulation of the disposal of hazardous waste has in recent years begun to address the issues of waste form and disposal technology. The Resource Conservation and Recovery Act (RCRA), passed in 1976, constitutes the landmark legislation pertaining to the disposal of hazardous materials (Caldwell, 1993). This Act directed the U.S. Environmental Protection Agency (EPA) to establish what is referred to as a "cradle to grave" policy for safe handling of hazardous materials. EPA rules and related legislation (Hazardous and Solid Waste Amendments (HSWA), 1984) have addressed all aspects of materials handling from production and intended use to transportation, treatment, storage and final disposal (EPA, 1991). The final disposal of hazardous materials in the United States must be in a facility that has met rigorous specifications with regard to design, operation and permitting. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, 1980) and the subsequent Superfund Amendments and Re-authorization Act (SARA, 1980) were established to identify and provide for the cleanup of contaminated sites. The Act provides for the recovery of cleanup costs from the firms and industries responsible for the contamination.

Within this general framework, specific acts have addressed the problems associated with the disposal and handling of radioactive substances. The Uranium Mill Tailings Radiation Control Act (UMTRCA, 1978) directed the U.S. Department of Energy (DOE) to clean up the mill tailings at the uranium mining sites under the direction of the EPA and the Nuclear Regulatory Commission (NRC).

The Low-Level Radioactive Waste Policy Act (LLRWPA, 1980, amended 1985) was passed in acknowledgment of the difficulty and cost associated with the design and permitting of sites designed to handle the disposal of low-level radioactive waste generated from medicine, research and some power generation activities. The states were encouraged to form multi-state compacts to combine their resources and responsibilities. The LLRWPA also offered a broad definition of low-level radioactive waste as any radioactive waste that is not transuranic waste, uranium mill tailings, or spent nuclear fuel.

LANDFILL CONCEPTS

Shallow land burial of hazardous and radioactive wastes requires significant isolation from the biosphere. To provide this isolation, the waste disposal cell must maximize stability, prevent intrusion by both plant and animal species, minimize vapor transport to the surface and minimize the infiltration of water into the underlying waste cells. In addition to these immediate requirements, the site must perform these same tasks over extended periods of time, reaching hundreds, and in some cases thousands, of years. This longevity feature brings added requirements concerning erosion from wind and water and the necessity of performing the intended functions after the loss of institutional control.

The shallow land burial method has four primary functions: prevent inadvertent dispersal of the material, minimize the passage of water through the waste cells and into the surrounding environment, minimize the escape of noxious gases from the waste, and prevent biointrusion into the waste (Caldwell, 1993). While the LLRWPA does not specify values for the various design parameters, the RCRA (EPA, 1982) requirements pertaining to landfill covers provide oversight of these primary objectives by stating the following:

At final closure of the landfill or upon closure of any cell, the owner or operator must cover the landfill or cell with a final cover designed and constructed to:

- (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;
- (5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

To these general recommendations the RCRA added specific requirements for a multi-layer cover as follows:

- (1) The top layer will be a vegetated or armored layer of soil at least 60 cm thick sloped at least three percent but not more than five percent.
- (2) An intermediate soil (or equivalent geosynthetic material) drainage layer of at least 30 cm thickness with a minimum hydraulic conductivity of 10^{-2} cm/sec and at least a three percent slope.
- (3) A final low-permeability layer consisting of a 60 cm layer of compacted soil with a saturated hydraulic conductivity of 10^{-7} cm/sec. For some systems a geotextile membrane may be necessary as a component in this low-permeability layer.

LANDFILL DESIGN

Landfill covers that successfully contain hazardous material must take into account the influences of wind, temperature, biological activity, and water (Hakonson et al., 1982). Root intrusion, for example, into a waste cell can transport radioactive materials such as tritium to the surface environment. Water flowing as storm runoff across a landfill cover can cause erosion of the cap and reveal the hazardous materials buried within. Infiltration of precipitation through the cap can bring water into contact with the waste, and percolation through the waste cells can release that water to the water table or the surrounding soil. Of the possible routes for a contaminant to enter the environment, those involving hydrologic processes appear to be of greatest concern. Current design criteria for landfill covers reflect the concern over these processes. Proposed solutions have involved multi-layer designs that incorporate combinations of soils, geomembranes, asphalt layers and capillary barriers. An example of this is the cover currently in the prototype testing stage at the DOE site at Hanford, Washington (Wing, 1994). A sketch of the Hanford cover is shown in Figure 1. The top two meters of this cover consist primarily of silt loam soil which provides a thick layer of fairly low permeability and high water retention. This layer is intended to hold any precipitation for its eventual return to the atmosphere via evaporation and plant transpiration. The upper one meter of this layer is mixed with 15 percent pea gravel (2-3 cm) to aid in the formation of a desert pavement surface to help resist erosion by wind. The pea gravel layer extends to one meter in depth, which is the depth reached by burrowing animals in the area. The silt loam is bounded on the bottom by sand and gravel filters, which in turn cover 1.5 m of basalt riprap. The grading of soil from the silt loam to the sand and gravel filters provides a capillary break that tends to prevent drainage of the silt layer until near saturation levels have been reached. The basalt layer prevents intrusion into the waste by deep rooting plants and provides a final barrier to burrowing animals. The low-permeability layer of this cover design is provided by a layer of asphalt which is cushioned from the basalt by a layer of drainage gravel. Another layer of gravel under the asphalt provides gas venting under the low-permeability barrier. In most cases at Hanford, the waste is already buried and the surface soils at the site are graded and prepared with a layer of sandy soil. The Hanford cover is a sophisticated design that seeks to address the multiple problems of wind and water erosion, biointrusion, vapor transport and infiltration of water.

Figure 1. A vertical cross section of the proposed landfill cover at the DOE site at Hanford, Washington (Wing, 1994).

LOW-PERMEABILITY COMPACTED SOIL LAYERS

The low-permeability layer of compacted soil is a key component in many cover designs and is the primary focus of the research reported here. Any low-permeability layer (compacted soil, geotextile, asphalt) serves two primary functions: (1) to inhibit the flow of water through the cover into the waste cells under both saturated and unsaturated conditions, and (2) to limit the passage of vapor from the waste to the surface environment (Wing, 1994). These layers, mostly geotextiles, utilize clay soil or clay amended soil in a buried layer to perform these functions. The swelling and sealing characteristics of bentonite have made it a popular soil amendment for this type of application (Mitchell, 1965; Alther, 1982).

As noted earlier in the section concerning regulation, the RCRA specifies that for hazardous waste disposal, the low-permeability layer shall have a maximum value of K_s of 10^{-7} cm/sec. Even though the LLRWPA does not specify this as a standard for a low-permeability layer in a low-level radioactive waste disposal facility, for the purposes of this report, this value for K_s will be adopted as a defining criterion. Several studies have shown that this value of K_s is easily reached in compacted soils (Elsbury et al., 1990; Daniel and Wu, 1993; Daniel and Benson, 1990; Korfiatis et al., 1987). Estimates of the percentage of clay necessary to meet this defining criterion have varied from 5 to 50 percent (Garlanger et al., 1987; Lahti et al., 1987). Daniel (1987) suggested that K_s should be very sensitive to clay content in the range from 0 to 12 percent, at which point the clay occupies all of the space between the larger grains and the soil takes on primarily the character of the clay. While the literature shows agreement on the performance of compacted soils in laboratory tests, there is disagreement on the field-scale applications of such soils. Some investigators have found little difference between laboratory results and field tests of K_s (Holtz, 1985; Johnson, 1990; Albrecht, 1989), while others have found considerable difference (Daniel, 1984; Day and Daniel, 1985; Elsbury, 1990). The latter group of investigators identifies the edge effects of sampling apparatus as well as the scale effects due to clod sizes relative to sampler sizes as being responsible for the underestimation of K_s in the laboratory. Despite these differences, small-scale field test plots using lysimeters (Fayer, 1992; Lahti et al., 1987), ponded infiltration tests (Panno, 1991; Albrecht, 1989) and dye tracer tests (Albrecht, 1989) have demonstrated that compacted soils can be effectively used to limit infiltration.

Elsbury et al. (1990) provide an excellent summary of the soil properties (gradation), design considerations (liner thickness), construction practices (lift thickness, compaction technique, clod size, moisture content of soil, dry density, bonding between lifts) and post-construction practices (desiccation) necessary to create an effective cover. Soil gradation is a major factor in determining the suitability of a soil for the construction of a compacted barrier. Enough fine particles must be present to allow the compacted soil to meet the specification for K_s . The thickness of a compacted layer determines the length of seepage paths through the layer and the likelihood that defects in the layer will be connected, allowing for preferential pathways for infiltration. Lift thickness determines the uniformity of compaction of a layer. It has been demonstrated that in a lift of 23 cm, the value of K_s can vary by a factor of nearly 9 from the top of the lift to the bottom (Thomas and Brown, 1992). The compaction technique can have a large influence on the final K_s of a compacted layer. A rolling

and kneading method of compaction generally results in a lower value of K_s than impact methods (Daniel and Benson, 1990). Along with dry bulk density, clod size and molding water content are of major importance in determining the performance of a compacted layer. It has been well demonstrated that the moisture content at the time of compaction can greatly influence the final K_s of a soil (Daniel and Benson, 1990; Daniel and Wu, 1993). One explanation holds that the moisture content determines whether the final clay particle structure is flocculated or dispersed (Lambe, 1958). At present, a more commonly accepted explanation is that wetter soils allow remolding of soil clods, eliminating macropores between clods and thus reducing the flow of water (Olsen, 1962; Houston and Randeni, 1992).

The lack of bonding between the lifts of a compacted layer is thought to be one of the reasons that compacted low-permeability layers fail in the field (Elsbury, 1990). The planes between lifts can provide conduits for water and allow infiltration water to connect between defects in the individual lifts. Desiccation both during and after construction can result in the formation of cracks in a clay layer (Daniel and Wu, 1993). The soils that are commonly used to construct low-permeability layers often contain large percentages of swelling clays that may experience large changes in volume with varying water contents.

The low-permeability layer also plays an important role in limiting the passage of noxious vapors through a landfill cover (Wing, 1994). The passage of vapor through soil depends on the presence of interconnected air-filled voids. The ability of vapor to pass through soil is decreased as the air in these spaces is replaced by water. Fine-grained soils retain water to a greater degree at negative potentials than do more coarse-grained soils (Hillel, 1980). It then follows that a clay soil that retains a high moisture content at negative potentials will serve to restrict the movement of vapor phase materials.

Potential Concerns with Compacted Soil Barriers

The potential for failure in compacted soil barriers in waste disposal covers has been reviewed by Suter et al. (1993). Design parameters, inadequate construction practices, and intrusion by both plant and animal species are listed as concerns.

Design considerations include the thickness of the soil layers that cover the low-permeability layer. Nyhan (1989) showed that increasing this top soil layer from 0.2 to 0.7 m provided a much larger storage reservoir to absorb and hold precipitation for removal by transpiration processes. Thickness of the surface layer is also a factor in erosion control.

Quality assurance problems include inadequate compaction, the use of soil materials not meeting design specifications, inadequate binding of soil lifts in the low-permeability layer, and the formation of desiccation cracks that result from improper maintenance of the water content during construction (Miller and Misra, 1989). Desiccation cracks can become enhanced through successive shrink-swell cycles (Brady, 1974).

Long-term problems facing the integrity of compacted soil barriers include the intrusion of plant roots. Several studies have documented the release of contaminated materials from shallow

land burial sites through the action of plants (Suter et al., 1993). Roots may penetrate a barrier and transport waste materials to the surface. Decomposed roots may leave channels in the low-permeability layer, uprooted large plants can leave holes in a protective cover, and transpiration from deep roots can substantially change the water balance of a buried soil layer. It has been noted, however, that high clay content and high bulk density can provide a substantial barrier to root penetration (Veihmeyer and Hendrickson, 1948; Wiersum, 1957).

Burrowing animals have also threatened the integrity of hazardous waste covers. Intrusions into waste cells have been documented at a uranium mill tailings site in Colorado and a waste trench at the Hanford Reservation in Washington (Suter et al., 1993). In addition to transporting waste to the surface, the burrows can provide large channels for the intrusion of water deep into the cover. There is some evidence that the presence of animal burrows may actually help remove water from the soil (Landeem and Kemp, 1991).

Clearly some of these issues are beyond the scope of this treatise. The use of out-of-specification materials during construction and improper bonding between soil lifts are concerns for a construction engineer. The problems associated with burrowing animals can best be addressed by proper thickness of the surface topsoil layer and the presence of a biointrusion layer (see the Hanford design in Figure 1). The depth of topsoil needed to contain the roots of plants likely to eventually inhabit the site is a topic for an arid region plant physiologist.

The results of tests described in this report can be used to address a few of these concerns. The potential for desiccation cracking, the shrink-swell characteristics of the soil and the ability of the soil layer to limit plant root growth are considered and discussed in the results and discussion sections.

CHAPTER 2: MATERIALS AND METHODS

The purpose of this study is to determine the composition of an amended native soil mixture suitable for application as a low-permeability layer and then to characterize that soil with regard to its hydraulic and other relevant physical properties as a long-lasting low-permeability layer in an integrated cover. This chapter will describe the experimental approach to the problem, develop the theory of each of the methods, and detail each experimental procedure. A flow diagram indicating the steps followed in this research is shown in Figure 2.

As mentioned in the introduction, a maximum value of saturated hydraulic conductivity (K_s) (1×10^{-7} cm/sec) has been established as the primary screening criterion for the low-permeability soil mixture studied for this report. As noted, there are alternative designs that employ a variety of features to limit infiltration through a cover. These designs include such things as capillary breaks and asphalt layers. For the purposes of this study, the low-permeability layer is designed to be a compacted soil or amended soil layer with a maximum value of K_s of 1×10^{-7} cm/sec.

Prior to the commencement of experimental work, the issue of sample cell design was addressed. Since the experimental protocol called for individual samples to be subjected to a sequence of procedures, an apparatus was needed that would allow multiple operations without the repacking of samples. This is addressed first in a section on sample cell design and validity. The topic of cell design is followed by a description of sample preparation.

Compaction to known dry densities was a basic requirement for all samples and the modified Proctor test (ASTM, 1992) was used for the compaction tests. Particle density, particle size distribution, and the shrink-swell characteristics were determined to provide additional basic engineering parameters. Particle size distribution was determined by sieving. The pycnometer method (Klute, 1986) was used to determine grain density. The shrink-swell character of the soil was determined by measuring the height of samples in dry and saturated states.

The value of K_s is the primary criterion for the low-permeability component of a cover system and it was the characteristic that was tested to choose the one soil mixture that would be carried through all other experiments. The falling head permeameter technique for determining K_s is most appropriate for low-conductivity soils and was chosen for this study (Fetter, 1988). Given the very long-term requirements for functional performance of radioactive waste landfill covers there is concern about performance following significant changes in climate. Long-term changes in moisture content may result in changes in soil structure that in turn may influence hydraulic properties. This issue was addressed by subjecting soil samples to a series of three cycles consisting of saturation and drying followed by a final test of K_s .

Knowledge of the water retention characteristics of soil is important for understanding the movement of water under both saturated and unsaturated conditions. Since no single technique for measuring water retention provides the entire range of values, three techniques were used for this determination. The hanging water column method was used for the soil at or near saturation (Jury et al., 1991). Ceramic pressure plate extraction was used to describe the mid-range values (Klute, 1986). A chilled mirror hygrometer was employed for the drier soil samples (Gee et al., 1992).

Figure 2. Flow diagram indicating the progression of experimental work.

Although the requirement for K_s is the primary criterion for the low-conductivity layer, it is likely that at the NTS location, the movement of water under unsaturated conditions will be of greater concern. The estimation of unsaturated conductivity was made by two techniques, one experimental and the other by use of a numerical estimation technique. The first is a direct laboratory measurement of hydraulic diffusivity by an evaporation method (Rose, 1968). Measured diffusivities combined with appropriate values from the water retention curve are converted to values of hydraulic conductivity. The second method is a predictive technique that uses the RETC (REtention Curve) code (van Genuchten et al., 1991) along with retention data to predict K_s as a function of water content.

In addition to the movement of liquid water, there is the issue of the movement of vapor phase materials through the layer. A measurement of air permeability was made by determining the flow of air through a soil sample at a given moisture content at a known pressure drop.

The issue of spatial variability is difficult to address in the context of a laboratory study of an engineered soil mixture that will cover acres. Since the samples used in the laboratory procedures were cores just a few centimeters in diameter, it was decided that a measurement of field-saturated conductivity with the use of a disk permeameter (Perroux and White, 1988) would suffice to partially address this question.

Clarification of Terminology

Prior to description of the various methods, a brief note is in order concerning the terminology for water contents. In this report, water content is most often referred to as volumetric water content. This is to be taken as the volume of water per unit volume of soil.

SAMPLE CELL DESIGN AND VALIDITY

The need to investigate the response of individual soil samples to a variety of tests requires a single apparatus that can accommodate the requirements of the various tests. No currently available design meets this criterion, so sample cells were designed and fabricated. A primary requirement of the cell is the strength to withstand vigorous compaction of soil to experimental densities. Additional design requirements are: (1) minimize edge effects such as preferential flow along the cell walls by using a flexible rubber lining, (2) provide for pressurization of the space between the lining and the rigid cell wall to adequately seal the spaces between this lining and the soil core, (3) end plates that can be tightly sealed, and (4) even distribution of both water and air across the surfaces of the soil core. Soil particles must be restrained from migrating at the ends of the cells by some sort of retaining screen system. These requirements need to be met in a durable apparatus that allows visual inspection of the soil cores.

The apparatus was constructed from acrylic material and consisted primarily of short sections of thick-walled tubing lined with sections of motorcycle tire innertubing and bounded on the ends by thick disks of acrylic plate. A schematic representation is shown in Figure 3. The cell side walls were made of 5.3-cm sections of 10.2-cm-diameter acrylic tubing with a wall thickness of 1.2 cm. The rubber lining was passed through the center, folded over each end and fastened with two hose

Figure 3. Schematic of permeameter cell.

clamps. The side wall was drilled and tapped to allow for pressurizing the space between the rubber and the acrylic. The end plates were 13.5-cm disks of 1.75-cm-thick acrylic plate. The top plate was drilled and tapped to allow flow through the cell. A series of radial grooves and circular grooves was machined into the inner surface of the top plate to allow even distribution of water and air over the entire surface of the soil core. Two types of bottom plates were fashioned. One was identical to the top plate and was to be used in applications where the flow exiting the cell required a measurement. The other style had 50 evenly spaced, 0.25-cm holes through the plate to allow even flow of water out of the cell. Two types of screening were employed to retain soil particles and allow the distribution of water across the soil surface. Nylon fabric of 240 threads per inch (corresponds to a bubbling pressure of 2.75 KPa) was placed directly upon the soil surface and was backed up with wire screen. Upon assembly, the end plates were through-bolted with machine screws. During compaction of the soil samples into the cells, a 10-cm-long sleeve of the acrylic tubing was placed on top of the cell body to hold the loose soil for compaction by a rammer.

Prior to the experimental work, there was concern about changes in soil bulk densities within the sample cells following the various procedures. Saturated conductivity measurements are commonly done in a triaxial apparatus which allows movement of the soil in three dimensions. In contrast, the necessity of subjecting the samples in this study to several procedures in sequence made necessary the use of a fixed wall cell. A method was devised to check the density of the samples at different locations before and after the saturation process to identify any particle migration problems. The method involved excavating one half of a prepared sample, measuring the excavated volume, and determining the relative dry densities of the excavated and remaining portions.

Laboratory Procedure for Establishing Validity of Sample Cell Apparatus

Four samples were compacted and two were saturated according to standard procedures described below. The top plates of all the samples were removed and about one half of the saturated soil was removed carefully to minimize disturbance of the remaining soil in the cell. The resulting cavity was lined with thin plastic wrap and the top plate was replaced. An initial weight was recorded at this point. Water was introduced through the top port until the excavated cavity was filled and a final weight was recorded. The weight of added water was converted to give a measured volume of excavated soil. Both the excavated soil and the remaining soil in the cell were then oven dried to determine the mass of each. With the volume and mass of both samples now known, the bulk densities of the top and bottom halves were computed.

POROSITY AND COMPACTION

One of the basic defining characteristics of an engineered soil system is dry bulk density. Soil used in engineering applications is compacted to achieve several desirable characteristics, among them an increase in shear strength and decreases in compressibility and hydraulic conductivity. Soils vary in the ease with which they can be brought to a given dry density. Current laboratory procedures seek to define a maximum dry density and the optimum water content at which that density is reached using a constant compactive effort (Norris, 1983). As the optimum water content is approached, the dry density of the compacted soil increases and then decreases with additional added water in excess

of the optimum water content. Optimum moisture content and maximum dry density provide a baseline upon which other laboratory tests can be performed and construction practices judged. Proctor (1933) detailed a procedure in which a given effort is expended upon a given volume of soil at a range of moisture contents. That procedure has been modified to fit modern engineering methods and is used here as the modified Proctor test (ASTM Test Method D 1557-91, ASTM 1992). Appropriate calculations follow:

$$\rho_m = (M_t - M_{md})/V \quad (1)$$

$$\rho_d = \rho_m / (1 + w/100) \quad (2)$$

where M_t is the mass of moist sample and compaction mold, M_{md} is the mass of the compaction mold, V is the volume of the compaction mold, ρ_m is the moist density of the compacted specimen, ρ_d is the dry density of the compacted specimen and w is the gravimetric water content. It is common construction practice to specify that, at a minimum, a soil will be compacted to a given percentage of maximum Proctor density. Commonly, this figure is 90 percent and that figure was chosen as the density of all soil samples used in this study (Daniel and Benson, 1990). The water content at compaction, or molding water content, can be a factor in determining the final value of K_s (Daniel and Benson, 1990). The samples for this study were compacted at a moisture content two percent in excess of that needed to achieve maximum density (two percent wet of optimum). Compaction tests were performed on the four initial soils mixtures and then on the mixture chosen for the remaining tests.

Given that desired dry density of a soil is known through compaction tests, and the density of the granular material has been determined by the pycnometer method (see the section on grain density), it is a simple matter to calculate the resulting porosity of the soil:

$$\text{porosity}(\%) = \frac{\rho_g - \rho_d}{\rho_g} \times 100 \quad (3)$$

where ρ_g is grain density and ρ_d is dry bulk density of the soil, and porosity is expressed as a percent of the total soil volume.

The construction of a low-permeability layer as a means of limiting infiltration is not a simple matter of spreading and compacting a layer of soil. The water content at compaction and the method of compaction can greatly influence the final characteristics of the compacted layer (Daniel and Benson, 1990). A rolling or kneading method of compaction, such as the use of a sheep'sfoot roller with fully penetrating pads, will result in lower final saturated hydraulic conductivities than will a compaction method that utilizes impact as the means of delivering the compactive effort. Of greater consequence may be the water content at the time of compaction, also called the molding water content. Studies have shown that the saturated conductivity of a clay layer may vary by two orders of magnitude depending on the molding water content (Mitchell et al., 1965; Daniel and Benson, 1990). Lambe (1958) hypothesized that molding water content largely determined the dispersed or

flocculated nature of the resulting clay structure. Olsen (1962) attributed this effect to the ability of wetter soil clods to be remolded and thus reduce the macropores between clods. The resulting conductivity of some soils decreases rapidly with increasing molding water content until the maximum dry density is reached and maintains near minimum values with the addition of a few percent additional moisture.

Laboratory Procedure for Compaction Tests

Procedure A as defined by the ASTM is to be used if 20 percent or less by weight of the soil is retained on a No. 4 (4.75 mm) screen. The procedure consists of compacting the soil into a 4.0-inch diameter, 4.584-inch-high mold in five lifts or layers. Each lift was subjected to 25 blows of a 10 lb rammer which was lifted 18 inches for each blow. The total number of blows (125) amounts to a predetermined compactive effort (56,000 ft-lb/ft³). The resulting samples were trimmed even with the top of the mold and weighed. The samples were then extruded from the mold and split lengthwise to allow sampling of the center of the core. A representative sample was taken for the determination of gravimetric water content. Those samples were placed in a tared weighing dish, weighed, dried in an oven at 105°C for 24 hours, cooled in a desiccator and weighed a final time. The entire process was repeated with the same soil until it became apparent from decreasing total weights that the dry density of the soil was decreasing with additional water. The results of these tests were plotted as a curve of dry density as a function of water content.

PARTICLE SIZE DISTRIBUTION

The particle size distribution of a soil system directly affects all hydraulic parameters. Determination of the distribution is commonly performed by sieving the sample through a series of nested sieves of progressively smaller mesh size. The procedure used in this study is outlined by Norris (1983).

Laboratory Procedure for Particle Size Distribution

Oven dried soil was weighed and placed on a #200 sieve and washed to remove the fraction smaller than 200 mesh (referred to as the -#200 fraction). The wash water and the fine soil fraction were captured in a pan placed under the sieve and were oven dried to determine the mass of the -#200 fraction. The retained soil was oven dried, agitated to break up any cementation and placed on a nest of tared sieves consisting of #4, #8, #16, #30, #50, #100, and #200 sieves. A solid pan bottom and a lid were added and the apparatus was agitated for ten minutes. Final weights of sieves and retained soil were recorded. The weight of the retained fraction was computed by subtracting the weight of the sieve from the final total weight. The sum of collected fractions was compared to the original sample weight.

PARTICLE DENSITY

Determination of the soil grain density was made with the pycnometer method (Klute, 1986). This simple method utilizes a glass flask, and by the use of several weighings, calculates particle density according to the following formula:

$$\rho_p = \rho_w(W_s - W_a)/[(W_s - W_a) - (W_{sw} - W_w)] \quad (4)$$

where ρ_p is the particle density, ρ_w is the density of water, W_s is the weight of the pycnometer plus the soil sample corrected to oven-dry water content, W_a is the weight of the pycnometer filled with air, W_{sw} is the weight of the pycnometer filled with soil and water, and W_w is the weight of the pycnometer filled with water at the temperature observed.

Laboratory Procedure for Determination of Particle Density

The weight of a clean, dry 100-ml flask was recorded. The weight of the flask filled with distilled, boiled, and cooled water was recorded. About 50 grams of air dried soil was added to the clean, dry, weighed 100-ml flask. The combined weight of the flask and soil was recorded. The moisture content of a duplicate sample of soil was determined by oven drying. The flask was half filled with distilled water and the contents were gently boiled with constant agitation for five minutes. The flask and its contents were cooled to room temperature and the flask was filled to the 100-ml mark with distilled water that had been boiled to remove any air. The outside of the flask was dried and cleaned prior to being weighed a final time. The current temperature was recorded for an accurate determination of the density of water.

SAMPLE PREPARATION

The water for all procedures in this study was distilled, de-aired by boiling and stored in sealed bottles. The ionic strength was increased with the addition of 0.005 M CaSO_4 to prevent dispersion of clay in the samples. Experimental water was saturated with thymol to inhibit the growth of organisms in the soil (Klute, 1986). Soil used in the study was collected from the Area 5 region of the Nevada Test Site. Three five-gallon containers were filled with soil that had been excavated from a shallow trench. Upon arrival in the Desert Research Institute laboratory, the soil was passed through a #4 screen to remove the larger particles that might damage the test apparatus. The fraction removed by this process constituted less than two percent by weight of the total. The remaining soil was thoroughly mixed to provide a homogeneous bulk sample. Bentonite used as a soil amendment in the study was blue, unoxidized sodium bentonite from Wyoming.

Prior to creating the various mixes, the moisture contents of both the soil and the bentonite were determined by oven drying samples of each. The mixes were created as mass fractions of soil and bentonite. The bulk materials were not oven dried prior to mixing. Prior to compaction into the sample cells, the moisture content of the soil was brought to a level equal to two percent in excess of the optimum level determined by the compaction tests. The appropriate mass of soil needed to meet the desired dry density for each sample was weighed and transferred to the sample cell. The decision was made to place the soil in the cell in one layer, or lift, to avoid the questions involved in multi-layer compaction. An extension sleeve was placed over the cell to contain all of the soil which was then impacted by a five pound rammer designed to simulate the technique used in the compaction tests. The weight of this rammer was one half that used in the compaction tests. The intent here was to maintain the impact method of compaction as discussed in the results and

discussion section. The ratio of the area of the rammer face to the sample surface was made the same as that of the compaction test apparatus. A small amount of silicon grease was applied to the top and bottom surfaces of the cell side walls to provide a tight seal. Screens to hold the soil in place were placed top and bottom, the end plates were fixed in place and the entire apparatus was through-bolted, resulting in a solid, leak-tight assembly. Prepared samples were then flushed with carbon dioxide to remove any trapped air prior to saturation. Saturation was achieved by submerging the entire prepared sample in water and applying a vacuum to the fitting in the top plate. Samples were submerged for several days (10 to 20) to allow complete saturation during which time 10 to 15 pore volumes of water were drawn through each sample. Since the weight of the apparatus and soil samples as well as the soil particle density were known, saturation could be verified by weighing the entire apparatus. The range of saturation was calculated to be between 95 and 98 percent for all samples.

SHRINK-SWELL CHARACTERISTICS

The shrink-swell characteristics of a compacted low-permeability layer influence the long-term performance and raise quality assurance concerns during construction. The procedure for determining this parameter was simply a matter of measuring the height of the sample cores with the end plates removed when fully saturated and again following pressure plate extraction and oven drying.

Laboratory Procedure for Determining Shrink-swell Characteristics

Following a saturating or drying procedure, the top and bottom plates were removed from a sample cell along with the fabric and metal screens. A straight edge was placed across the top of the cell body and the depth to the soil surface was determined with a millimeter-scale rule.

SATURATED HYDRAULIC CONDUCTIVITY

As mentioned above, the primary criteria for judging the performance of a clay layer in a landfill application is the K_s . The proportionality coefficient relating hydraulic head to volumetric flow is termed the saturated hydraulic conductivity (K_s) and combines in one term the relevant physical characteristics of both the porous media and the moving fluid (Fetter, 1988). The hydraulic conductivity is used to relate a given gradient in hydraulic head to the actual flow one may expect through a cross-sectional area (A):

$$Q = - K_s A \frac{dH}{dL} \quad (5)$$

where Q is volumetric flow rate and dH/dL represents the gradient in hydraulic head.

Two methods were employed in this study to derive values of K_s . The falling head permeameter is a laboratory method most suitable for soils of low permeability (Fetter, 1988). A disk permeameter was used as an alternative method, and to provide some measure of the effect of sample size on the value of K_s (Perroux and White, 1988).

As mentioned in the introduction to this section, K_s tests were also performed on four samples that had undergone a series of wetting and drying cycles to simulate long-term climate change. This climate change was simulated by subjecting four samples to three cycles of drying and subsequent re-wetting. Values of K_s were determined before and after this procedure by the falling head technique.

Laboratory Procedure for K_s by Falling Head Permeameter

The use of a small-diameter falling head tube can allow easily measured changes in hydraulic head to occur while involving small quantities of volumetric flow. The initial (H_0) and final (H_1) hydraulic head values are noted over a measured time interval (t). The hydraulic conductivity is determined by the formula:

$$K_s = \frac{aL}{At} \ln\left(\frac{H_0}{H_1}\right) \quad (6)$$

where a is the cross-sectional area of the standpipe, L is the length of the sample, A is the cross-sectional area of the sample (Fetter, 1988).

Samples were prepared following the guidelines outlined in the section on sample preparation. Following saturation, the samples were fitted with a polyethylene tube attached to a 1-mm inside-diameter glass tube which served as the standpipe. The elapsed times to record a suitable reading were, in several cases, quite lengthy, so the tops of the glass tubes were sealed with tape to prevent evaporative loss of water. A pin hole in the tape allowed maintenance of atmospheric pressure within the tube.

To simulate long-term climate change as mentioned above, four samples were subjected to three cycles of drying followed by resaturation. The resaturation process was as described for sample preparation. The first two of the drying cycles were performed by oven drying at 65-70° C. The final drying was performed by equilibrating the samples in a pressure plate extractor (see soil water retention characteristics) to a pressure of 1.8 MPa. Following the final resaturation, K_s measurements were performed as described above.

Laboratory Procedure for K_s by Disk Permeameter

The disk permeameter is a device that allows the measurement of soil conductivity function in the field without the trouble and problems associated with taking soil samples or cores to a laboratory (Perroux and White, 1988). The device delivers water to the soil at slight negative pressures. The quantity of water that is drawn by the soil in the very early stages of an experiment is dependent primarily on the capillary forces present in the soil and thus provides an estimate of the sorptivity of the soil at its initial water content. The later, steady state, flow of water represents a combination of these capillary forces plus the effects of gravity upon the water that has entered the soil. When the water drawn by sorptive forces is subtracted from this steady-state value, a reasonable value for field-saturated hydraulic conductivity is obtained:

$$K(h) = I - \frac{4(b)S(\theta_i, \theta_f)^2}{\pi r \Delta \theta} \quad (7)$$

where $K(h)$ is the field-saturated conductivity at the applied head, I is steady state infiltration, $S(\theta_i, \theta_f)$ is sorptivity, r is the radius of the permeameter base, $\Delta \theta$ is the difference in volumetric water content before and after the test, and b is a constant equal to 0.55 derived from

$$b = D_{avg} \frac{(\theta_{wet} - \theta_{dry})^2}{S(\theta_i, \theta_f)^2} \quad (8)$$

where D_{avg} represents average diffusivity.

The base of the disk permeameter is 21 cm in diameter and this large sample surface area was intended to describe to some degree the effect of sample size on the measurements of the hydraulic properties of the soil.

During operation of a disk permeameter the soil exerts tension on the water in the instrument. The only path for air to replace the volume of water lost to the soil is through an inlet tube which has its lower edge below the water level in the bubble tower. The depth of this edge below the water surface determines the tension required of the soil to draw water from the permeameter. Infiltration rates are recorded by time resolved readings of the height of water in the permeameter. The permeameter used for this study is equipped with a pressure transducer which measures the height of water in the tower and transmits the information to a datalogger.

The soil used for this experiment was prepared at a moisture content of four percent wet of optimum. The soil was placed in a pan 45 cm long by 30 cm wide and was compacted to 90 percent of Proctor density and to a depth of 10 cm with a five pound rammer. Prior to placement of the permeameter a soil sample of known volume was taken by pressing a 4.75-cm-diameter, 1.8-cm-long metal ring flush with the soil surface. The soil surface where the permeameter was to be placed was then covered with a thin (1 to 2 mm) layer of fine sand to provide good hydraulic contact with the disk permeameter. The permeameter was firmly placed on the prepared surface and pressure transducer readings were recorded every 10 seconds for 3.25 hours. Immediately upon removal of the permeameter following the test, the sand layer was removed and another soil sample was taken to determine final water content. Volumetric water contents of the soil samples were determined by oven drying.

SOIL WATER RETENTION CHARACTERISTICS

The ability of a soil to retain water at negative pressures is a basic component of the hydraulic properties of the soil. Soil that is above the water table retains moisture according to its grain size distribution, mineralogy and chemistry. The process of determining a water retention curve involves measurements of the potential energy of the water in the soil at various moisture contents. The resulting curve plots potential energy per unit weight of water versus volumetric water content of the soil.

The laboratory procedures used to determine the soil water retention curve involved the use of a pressure plate extractor, a chilled mirror hygrometer and a hanging water column. None of the three techniques adequately describes the entire range of potentials encountered, although there is considerable overlap among them.

Laboratory Procedure for Chilled Mirror Hygrometer

The chilled mirror hygrometer technique (Gee et al., 1992) measures the humidity of a small confined air space immediately above the soil sample. A small mirror in the air space serves to reflect a beam of light to a light sensor. The mirror is gradually cooled until the dew point of the air is reached. Moisture condensing on the mirror scatters the light beam signalling the dew point. This measure of dew point indicates the activity of the water in the air space. Assuming that the water in the soil and air space are in equilibrium, the potential of the soil water, in terms of energy per unit volume (MPa), can be calculated by the following procedure:

$$\psi_T = (\ln A_w)RT/M \quad (9)$$

where ψ_T is the calculated sum of matric and osmotic water potentials, R is the universal gas constant for water vapor, T is the temperature in degrees Kelvin, M is the molecular weight of water, and A_w is the measured activity of water.

For the chilled mirror hygrometer method, 200 to 300 gram soil samples at a variety of water contents were allowed to equilibrate in airtight jars for several days. Subsamples consisting of a few grams of soil were placed in plastic cups one cm in diameter and one half cm in height. The soil was lightly tamped with a rubber stopper to insure that the cup was no more than half full. Compaction to field conditions is not necessary for this procedure. Chilled mirror hygrometers are useful in the moisture range where the soil moisture is held in films and not in capillaries that would be affected by compaction. A tight fitting lid was placed on the sample cup to prevent drying. These operations were conducted in a glove box environment in which a high level of humidity was maintained to prevent drying of the samples. The lid was removed just prior to the sample being placed in the sliding tray of the instrument. Following equilibration of temperature and humidity, the water activity in the air space above the sample was recorded. The remainder of the sample was used for volumetric moisture determination by the oven drying procedure.

Laboratory Procedure for Pressure Plate Extraction

In pressure plate extractor technique (Klute, 1986) soil samples are placed in a pressure vessel. Air pressure within the vessel is increased to specified levels and the soil water is evacuated from the samples until the soil water pressure is in equilibrium with the air pressure. Samples are contained in a metal ring and are placed on a saturated ceramic plate. The ceramic plate has a pore size sufficiently small to resist desaturation by the applied pressure. The underside of the plate is enclosed by a rubber bladder which in turn is vented through the wall of the pressure vessel containing the entire apparatus. This configuration provides a conduit for water leaving the soil as equilibration between air and soil water pressure is approached. At the initial low pressures, the

larger soil pores are evacuated first, followed by successively smaller pores as higher pressures are reached. The relationship between vessel pressure and pore radius is defined by the following (Jury et al., 1991)

$$P_v - P_w = \frac{2\sigma \cos \phi}{r} \quad (10)$$

where P_v is vessel pressure, P_w is soil water pressure, σ is the surface tension of water, r is the pore radius and ϕ is the contact angle between the soil water and the soil pore surface. As successively higher pressures are applied, water leaves the soil pores in accordance with equation (10), and flows out through a tube in the vessel wall where it is captured and weighed. Potential is recorded as applied pressure, and volumetric water contents are recorded by weighing the vented water and by periodic weighing of the samples.

Soil samples used in this study were of very low hydraulic conductivity which necessitated the fabrication of sample rings that were of large diameter and small height. This was to allow equilibration with the applied pressure in a reasonable amount of time. The rings were 7.28 cm in diameter and 1.00 cm in height. Soil samples were weighed to achieve the desired dry bulk density and were tamped into the rings. Saturation was achieved by submerging the samples in a vacuum vessel for several hours. A thin layer of soil that had been sieved through an 80 mesh screen was used to ensure good hydraulic contact between the samples and the ceramic plate. Vented water was collected in an enclosed plastic bottle to prevent evaporative losses and was weighed periodically on a Mettler BB2400 balance. Moisture content measurements were made at -0.3, -1.0 and -1.8 MPa.

Laboratory Procedure for Hanging Water Column

The hanging column technique (Jury et al., 1991) provides very good resolution of the retention characteristics at near saturation conditions. Tension is placed upon the soil water by literally hanging from it a column of water that is in hydraulic contact with the soil water. The column consists of a U-shaped tube that permits accurate determination of the volume of water drawn from the soil sample in response to varying degrees of tension. Potential is recorded as the elevation difference between the surface of the soil and the water level in the tube.

Soil samples were tamped into a 3-cm-high, 5.39-cm-diameter brass ring to the appropriate dry bulk density. Saturation was achieved by submerging the samples in water in a vacuum vessel for several days and was checked by weighing. The samples were sealed by o-rings to plastic plates top and bottom. The bottom plate was fitted with a porous ceramic plate that served to retain the soil while allowing hydraulic contact with the hanging column. The external port of the bottom plate was fitted to a tube that in turn was attached to the tip of a 50-ml buret. The entire apparatus was filled with water up to the mid point of the buret. As the buret was lowered, tension was applied to the soil water and the extracted water served to register a new level in the buret. Each step spanned several days to allow equilibration. Readings were taken at tensions of about 10, 20, 50, 100, and 200 cm of tension. At each step the volumetric water contents were calculated by subtracting the extracted water from saturation water content.

UNSATURATED HYDRAULIC CONDUCTIVITY

One may expect that in unsaturated soil the movement of water is in response to a gradient in some soil water physical characteristic and indeed this is the case. However, here the gradient is most easily described in terms of volumetric water content over distance, and the proportionality coefficient describing the porous media and the moving fluid is termed the hydraulic diffusivity (D). Richards (1931) combined Darcy's equation with the concept of continuity to develop the governing equation for unsaturated flow:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(D(\theta) \frac{\partial \theta}{\partial z} \right) - \frac{\partial K(\theta)}{\partial z} \quad (11)$$

where θ is volumetric water content, t is time, z is depth, and $K(\theta)$ is hydraulic conductivity. Introduction of the Boltzmann variable, $\lambda = zt^{-1/2}$, allows integration of Richard's equation to the form (Hillel, 1980):

$$D(\theta) = -\frac{1}{2} \frac{d\lambda(\theta)}{d\theta} \int_{\theta_i}^{\theta} \lambda(\theta) d\theta \quad (12)$$

This report describes the investigation of unsaturated hydraulic conductivity by two methods. One involves a direct experimental measurement of hydraulic diffusivity as described by Rose (1968), and the subsequent conversion to hydraulic conductivity. The second utilizes the commonly used numerical estimation technique, RETC, which employs the equations of Mualem (1976) and van Genuchten (1980) to determine unsaturated hydraulic conductivity as a function of water content. The movement of water vapor is also modeled.

Rose (1968) described a laboratory technique to determine hydraulic diffusivity involving the evaporation of water from one end of a homogeneous column of soil. At any given time the moisture profile of the column can be plotted as volumetric moisture content versus the Boltzmann variable. Diffusivity can be computed by integrating from the initial water content (θ_i) to the water content of interest (θ) and multiplying by one half the slope of the curve at that point (see equation 12). Unsaturated hydraulic conductivity is then computed from the definitive relationship of diffusivity to hydraulic conductivity:

$$K(\theta) = D(\theta) \frac{\partial \theta}{\partial h} \quad (13)$$

The final term of this equation ($\partial \theta / \partial h$) is the slope of the water retention curve at the appropriate volumetric water content.

Meyer and Warrick (1990) developed an equation to fit the curve described by the water content versus Boltzmann variable. The equation allows easy determination of the integrals and derivatives associated with each point. Their equation is of the form:

$$\theta = \theta_i + \frac{(\theta_o - \theta_i)[1 - (\lambda/\lambda_i)]}{1 - A(\lambda/\lambda_i)} \quad (14)$$

where θ_o is the water content at the drying end of the column and θ_i and λ_i are the water content and Boltzmann variable, respectively, at the wet end of the column. Solving for λ in equation (14), substituting into equation (12) and integrating results in:

$$D(\theta) = \frac{1}{2} \left[\frac{A_3 - A_1 A_2}{(A_3 - A_2 \theta)^2} \right] \int_{\theta}^{\theta_i} \frac{\theta - A_1}{A_3 - A_2 \theta} d\theta \quad (15)$$

where $A_1 = \theta_o$, $A_2 = -A/\lambda_i$, and $A_3 = -(\theta_o - \theta_i)/\lambda_i - A\theta_i/\lambda_i$. Hydraulic conductivities are calculated by equation (13).

Laboratory Procedure for Unsaturated Hydraulic Conductivity

An excess of soil was brought to approximately 20 percent volumetric water content and allowed to equilibrate for several weeks. The soil was then placed into a column consisting of 6-inch-diameter PVC pipe (see Figure 4). The lower 25 cm of the column was fashioned of a single piece of pipe and was to provide the 'semi-infinite' character of the column. The remaining 20 cm of column consisted of 1-cm rings separated by neoprene gaskets to provide air-tight sealing of the column. Time domain reflectometry (TDR) probes were placed through the column at 1, 2, 3, 4 and 10 cm depths. The soil was compacted in lifts with the aid of a five pound rammer. In the lower section of pipe, the lifts were of 5 cm depth. In the upper 20 cm, the lifts were of 3 cm depth, except where the presence of a TDR probe necessitated the preparation of one ring at a time. The top of the column consisted of 5 cm of unfilled pipe which provided access for various fittings and the headspace for air circulation. The drying force was provided by circulating air through a closed loop containing a 25-cm-long, 5-cm-diameter cannister of desiccant (indicating anhydrous calcium sulfate). A diaphragm pump circulated air at the rate of 500 ml per minute through the headspace, the desiccant, and the polyethylene tubing connecting the various components. The desiccant cannister was easily removed and was periodically weighed on a Mettler Model B2400 balance to provide a measure of total water flux through the surface of the soil. TDR readings were made at similar time intervals to aid in monitoring the location of the drying front. When the TDR readings indicated equilibrium water content in the surface layer of soil, the column was sectioned at the rings. The soil in each ring was placed in a glass jar, sealed tightly, and allowed to equilibrate for several days. Subsamples were taken for total water potential readings by the chilled mirror hygrometer method. The remaining portions of the samples were weighed, dried in an oven at 105°C for 24 hours and re-weighed to determine water contents.

Modeling Technique for Unsaturated Hydraulic Conductivity

Most methods for direct measurement of unsaturated hydraulic conductivity are laborious and time consuming and most have relatively large errors associated with the results (Rose, 1968). It is

Figure 4. Schematic drawing of the apparatus designed to determine hydraulic diffusivity by the evaporation technique of Rose (1968).

no surprise that modeling techniques to predict unsaturated flow are popular for this purpose. The model used in this report is the RETC code (van Genuchten et al., 1991). RETC fits a curve to experimentally derived water retention data and uses the soil characteristic parameters so derived in an unsaturated hydraulic conductivity model. The equation used to describe the water retention curve is that of van Genuchten (1980) and is the form:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha h)^n]^m} \quad (16)$$

where α , n and m are empirical constants fit to the shape of the retention curve and θ_r and θ_s are the residual and saturated water contents. RETC fits an equation of this form to experimental data using a least squares regression method. These parameters are then incorporated into Mualem's (1976) hydraulic conductivity model:

$$K(h) = \frac{K_s[1 - (\alpha h)^{mn}[1 + (\alpha h)^n]^{-m}]^2}{[1 + (\alpha h)^n]^{m\ell}} \quad (17)$$

where ℓ is described as a pore connectivity parameter which Mualem thought to be about 0.5 for many soils. To derive equation (17) requires the relationship between m and n to be fixed at $m=1-1/n$.

In most soil environments of interest, the movement of liquid is by far the primary mechanism of mass transport. Large air-filled porosities in near surface soils can make vapor flow an important component of total water movement. In dry soils, the air-filled porosity can be such that vapor movement becomes the dominant factor.

To model the flow of vapor the method of Philip and de Vries (1957) is used here along with Troeh et al.'s (1982) refinement of the tortuosity term. The vapor conductivity (K_v) is taken here to be:

$$K_v = (D_v Q_{vs} M g / Q_w R T) R H \quad (18)$$

where Q_{vs} is the saturated vapor density, M is the molecular weight of water, g is the acceleration due to gravity, Q_w is the density of water, R is the gas constant for water vapor, T is the temperature in °K, RH is the relative humidity and D_v is the diffusivity of water vapor in the porous media. The value of D_v is derived from the free air diffusivity and is modified by the tortuosity of the soil matrix in addition to being a function of the air-filled porosity ($\theta_s - \theta$).

$$D_v = \alpha(\theta_s - \theta) D_a \quad (19)$$

where α is the tortuosity of the soil matrix and D_a is the free air diffusivity. Troeh et al.'s description of tortuosity involves an empirically derived equation fit to several historical data sets:

$$\alpha(\theta_g) = [(\theta_g - u)/(1 - u)]^v \quad (20)$$

where θ_g is air-filled porosity.

The empirical constants u and v (0.03 and 1.5, respectively) used here are derived from Troeh et al.'s analysis of data from Ayres' (1972) work with 'disturbed soils.'

AIR PERMEABILITY

The ability of a soil cover to transmit gaseous substances directly affects the ability of the site to isolate volatile materials. The movement of air or volatile materials through a porous material can be in response to diffusion processes as well as pressure gradients resulting from changes in pressure. Air permeability is calculated from the relationship (Klute, 1986):

$$k_{\text{air}}(\theta) = \frac{\eta_{\text{air}} VL}{t A \rho_l g h} \quad (21)$$

where $k_{\text{air}}(\theta)$ is the air permeability of the soil at a given water content, η_{air} is the viscosity of air at laboratory temperature, V is the volume of air passing through the soil core in a specified time (t), L is the length of the sample, A is the cross-sectional area of the soil core, ρ_l is the density of the manometer liquid, g is the acceleration due to gravity, and h is the manometer displacement.

Care must be taken when using this term $k_{\text{air}}(\theta)$. One concern in quantifying a gas permeability is the moisture content of the soil. If the soil is completely saturated there is no air-filled porosity to conduct the passage of air through the soil. It is apparent that not only must there be some level of desaturation of the soil but that this level must be quantified and maintained constant during the experiment. For this study, it was decided that air permeability would be measured for amended soil cores that had been allowed to equilibrate in a pressure plate extractor at a pressure of -1.8 MPa. This pressure corresponds to a volumetric water content of 14 percent (see Figure 11 in results). Subtracting volumetric water content from total porosity gives an air-filled volumetric porosity of about 20 percent (see results of soil compaction and porosity). Since the value of $k_{\text{air}}(\theta)$ so derived does not represent the passage of air through a dry porous medium, the reported value of $k_{\text{air}}(\theta)$ should not be taken for a value of intrinsic permeability. A comparison of air permeability at a given volumetric water content (in this case, 14 percent) to a value of unsaturated hydraulic conductivity at the same volumetric water content might give some indication of the nature of the interaction between water and the soil matrix (Sully, 1995, personal communication).

The technique for the determination of the air permeability of a porous material is similar to that for liquid conductivity. A difference in pressure is applied across a known distance, the resulting flow is noted and the proportionality coefficient is determined.

Laboratory Procedure for Air Permeability

Following the initial -1.8 MPa extraction, the amended soil cores were again fitted with plastic end plates. The compressed air used for the procedure was bubbled through water to add humidity. A high-resolution regulator was used to provide accurate control of the pressure across the soil core.

To give precise measurement of pressure, a water manometer was placed across the soil core and the air pressure was regulated to about 1 cm of water. Air flow was measured by directing the flow through a soap film flowmeter. Time resolved readings of air flow were recorded.

SHEAR STRENGTH OF MATERIALS

The strength of a soil can be tested by applying strain at a constant rate while monitoring the resulting buildup of stress (Norris, 1983). If confining pressures are added to partially saturated soil specimens or specimens that are allowed to consolidate, there is an increase in the stress needed to cause failure. The response of the soil to confining pressure is important because subsurface soil is subjected to confining pressures that increase with depth. To define this relationship between confining pressure and stress at failure, at least two tests must be performed at different confining pressures. For this study, three tests were performed at different confining pressures.

The triaxial test apparatus was designed to apply a confining pressure and subject soil samples to a constant rate of strain and record the resulting stresses up to and beyond failure. Cylindrical samples enclosed in a membrane are placed in a cylindrical cell filled with water. Pressure applied to the water provides the confining pressure while the samples are vertically strained to failure by means of a computer controlled hydraulic loading system. In triaxial testing, both the process of confining, and of straining, the sample may produce pore water pressure changes within the sample. It is important to specify whether the excess pressure is allowed to drain during either or both stages of the experiment. Since the samples used for the triaxial tests in this study were of unsaturated soil, the assumption is made that there were no positive excess pore water pressures during either stage of the testing. The tests were performed as 'unconsolidated,' undrained experiments. By 'unconsolidated' it is meant that the pore water drainage valve was closed, thus preventing drainage of any water from the sample. Due to the partially saturated nature of the samples, some further compaction of the samples probably did occur as a result of compression of the air in the voids.

A commonly used method of representing the stress and failure relationships involves the use of a Mohr circle diagram. Plotting the confining and applied stresses as a Mohr circle allows representation of the normal and shear stresses acting on any plane in a soil mass under a given applied stress. When the applied stress results in failure, the results from two or more tests allow the description of the failure envelope relating confining and applied stress to the shear stress needed for failure.

Laboratory Procedure for Shear Strength of Material

In preparation for the strength tests, a quantity of amended soil was brought to a moisture content of two percent wet of optimum as determined by the modified Proctor method. The soil was then placed into a 3.56-cm-diameter, 10.16-cm-long mold and compacted in four lifts to the specified dry density of 1.70 grams/cm³ (90 percent of the maximum dry density). This figure represents 90 percent of the maximum dry density as determined by the modified Proctor test detailed in the section on compaction. The mold was split lengthwise to allow easy removal of the compacted sample. Following removal from the mold, the sample was enclosed in a thin latex

membrane between the cell base and a metal cap. The sample was then placed in the triaxial cell which was filled with water. Two samples were tested with confining pressures of 25 and 50 kPa and one was tested without confining pressure. The apparatus applied strain at a constant rate of two percent per minute to the sample via a metal rod screwed into the metal sample cap. The corresponding stress was monitored by a load cell. All samples were strained to failure.

CHAPTER 3: EXPERIMENTAL RESULTS AND DISCUSSION

This section presents the results of experiments performed to quantify the hydraulic and other relevant properties of a soil mixture intended for use as a low-permeability layer in the shallow land burial of hazardous and radioactive waste. Current designs for hazardous waste landfill covers often include a low-permeability layer placed below one to three meters of other soil and rock layers. The purpose of this layer is to provide a final impediment to the passage of precipitation through the cover and into the waste cells. It is this layer that is the focus of this report.

The material used in this investigation and referred to as "soil," is unconsolidated alluvium from the Area 5 portion of the NTS. Soils from this area typically have a high K_s , therefore, bentonite has been proposed as an amendment to reduce the K_s to meet the stated criterion of 1×10^{-7} cm/sec. K_s tests were performed on various mixtures of native soil and bentonite. The addition of 6.5 percent bentonite by weight resulted in a mixture with a K_s value of 7.6×10^{-8} cm/sec.

To further characterize the hydraulic and physical character of this soil mixture, a series of tests was performed to characterize the compaction, grain size distribution, porosity, shrink-swell, grain density, air permeability, water retention characteristics, unsaturated hydraulic conductivity and strength of the optimum soil mixture. A disk permeameter was used to provide an alternative method for field-saturated conductivity and provide some indication of the importance of sample size on this parameter.

A summary of experimental results from the various tests performed in this study is described below.

VALIDITY OF SAMPLE CELL APPARATUS

The stability of the sample with regard to particle migration during the saturation process and resulting changes in dry density was investigated by the method described in the section on sample cell validity. This procedure was designed due to concerns that, during the process of saturation, fine particles might migrate through the soil cores altering the dry density of the samples.

It can be seen from Table 1 that the dry densities of the excavated and unexcavated portions were similar in both the saturated and unsaturated samples. In particular, the ratio of dry densities shows no significant difference within the sample set. It can be concluded that the process of saturation did not cause significant migration of particles within the samples.

It can also be seen from Table 1 that the excavated portions of all samples had dry densities approximately 5 to 6 percent greater than the unexcavated portion. The excavated portion was, in all cases, the top of the sample and had received the blows from the rammer during sample compaction. With an impact technique that directs all of the compactive energy to one end of the sample, it will be expected that the end that receives the blows will be of higher dry density. It can be concluded that compaction of a 5-cm sample in one lift results in a measurable difference in bulk density within the sample.

TABLE 1. RESULTS OF TESTS TO DETERMINE THE EXTENT OF PARTICLE MIGRATION DURING SAMPLE SATURATION AND DIFFERENCES IN DRY DENSITY WITHIN INDIVIDUAL SAMPLES. Cells 2 and 13 were compacted and saturated prior to density measurements. Cells 14 and 11 were tested as compacted without saturation.

Cell ID#	2	13	14	11
Total cell volume (cm ³)	261.3	261.7	260.7	261.6
Water to fill excavated volume (cm ³)	137.8	162.1	117.5	13.9
Dry weight excavated soil (g)	240.8	282.2	204.9	215.7
Dry density of excavated portion (g/cm ³)	1.75	1.74	1.74	1.76
Dry weight remaining soil (g)	203.4	162.7	238.2	229.0
Dry density remaining soil (g/cm ³)	1.65	1.63	1.66	1.65
Dry density ratio (excavated/remaining)	1.061	1.067	1.048	1.067

PHYSICAL PARAMETERS

Particle Density

The particle density of the amended Area 5 soil was determined by the pycnometer method (Klute, 1986) to be 2.58 grams/cm³. Data from the various weighings are shown in Table 2.

TABLE 2. RESULTS OF THE DETERMINATION OF GRAIN DENSITY OF THE AMENDED AREA 5 SOIL BY THE PYCNOMETER METHOD.

Weight of pycnometer (W _a)	49.56 g
Weight of pycnometer and soil (W _s)	105.72 g
Weight of pycnometer, soil and water (W _{sw})	183.20 g
Weight of pycnometer and water (W _w)	148.84 g
The density of pure water (ρ _w) at experimental temperature (21°C) is 0.998g/cm ³ .	

$$\rho_{\text{grains}} = \frac{\rho_w(W_s - W_a)}{(W_s - W_a) - (W_{sw} - W_w)} \quad (22)$$

$$\rho_{\text{grains}} = \frac{(0.998\text{g/cm}^3)(105.72\text{g} - 49.56\text{g})}{(105.72\text{g} - 49.56\text{g}) - (183.20\text{g} - 148.84\text{g})} = 2.58\text{g/cm}^3 \quad (23)$$

Sieve Analysis

Results of a sieve analysis on unamended Area 5 soil are shown in Figure 5. The unamended Area 5 soil was determined to be a loamy sand as described by the USDA textural triangle (Klute, 1986) and an SP-SM by the Unified Soil Classification System (USCS) (Norris, 1983). This dual

Figure 5. Particle size distribution, unamended Area 5 soil. 'Percent passing' refers to the percentage of the total soil sample that passes through a sieve of a given size.

classification by the USCS is indicative that the percentage of fines, or the percentage passing a #200 sieve, is between five and 12 percent. Thus, the soil is not clearly a poorly graded sand (SP) nor is it clearly a silty sand (SM), but is intermediate in character and thus carries a dual classification.

Soil Porosity and Compaction

The dry density of the samples was determined by the modified Proctor test (ASTM, 1993). Table 3 shows the results of the compaction tests on the four initial mixtures and the final mixture chosen for the study.

TABLE 3. RESULTS OF THE COMPACTION TESTS PERFORMED ON FIVE MIXTURES OF AREA 5 SOIL AND BENTONITE. These figures are maximum densities. The samples tested for hydraulic properties were prepared at 90 percent of these figures.

Soil Mixture (% bentonite by weight)	Dry Density (g/cm ³)	Water Content (%)
0%	1.92	11.0
5%	1.90	11.5
10%	1.88	12.1
15%	1.90	11.3
6.5% (selected mixture)	1.89	11.5

Figure 6 displays the results from Proctor density tests of the various mixtures in detail. The increase in bulk density that results from increased amounts of water is apparent for all samples.

Samples tested for hydraulic properties in this study were compacted to 90 percent of the maximum dry bulk (Proctor) density. Moisture contents of the samples at compaction, or molding water contents, were two percent in excess of that required for maximum density. The 90 percent figure is a common construction specification and provides a convenient reference benchmark for the evaluation of the samples (Daniel and Benson, 1990). For the selected mixture, 90 percent of maximum dry density is: $(1.89 \text{ g/cm}^3)(0.9) = 1.70 \text{ g/cm}^3$. The mixture that consisted of Area 5 soil amended with 6.5 percent bentonite will be referred to in this report as amended Area 5 soil.

Porosity of the selected mixture (6.5 percent bentonite) as determined by equation (3) was determined to be 34 percent:

$$\frac{\rho_g - \rho_d}{\rho_g}(100) = \frac{2.58 - 1.70}{1.70}(\text{g/cm}^3)(100) = 34\% \quad (24)$$

Effect of Molding Water Content

For this study, the effect of molding water content on the final value of K_s of the amended soil mixture was characterized by a series of conductivity tests performed on soil samples prepared at different dry densities and molding water contents. The intent was to describe saturated conductivity curves upon the Proctor-type graphical representation of water content and density. Three densities

Figure 6. Results of compaction tests using the modified Proctor method for Area 5 soil amended with various percentages of bentonite.

and three molding water contents were chosen, and saturated conductivity tests were run on these nine combinations. Results from these tests are shown in Figure 7. For this soil mixture, the primary influence on K_s is clearly the dry density of the sample. There is a general trend toward lower values of K_s as molding water content is increased, but this effect is much less pronounced than in other studies that were performed on soils with a much higher clay content. As noted by Daniel and Benson (1990), the hydraulic characteristics of an amended soil are very sensitive to added bentonite up to about 12 percent total weight. Until that limit is reached there is still substantial grain to grain contact between sand grains and the compactive forces are not fully felt by the clay amendment. This may account for the insensitivity of K_s to molding water content in amended Area 5 soil.

This lack of sensitivity of final K_s to molding water content may have significant implications for the construction practices used to fabricate a low-permeability layer. As noted above, the engineering literature on low permeability covers contains several references to the importance of molding water content in relation to the performance of the layer in limiting infiltration. In the arid climate of the NTS, the practical problems of maintaining proper water content of the soil would be substantial. These tests performed on amended Area 5 soil indicate that maintaining optimum soil moisture contents during construction may not be a critical factor in the long-term performance of the low-permeability layer.

Shrink-swell Character

The shrink-swell character of the amended Area 5 soil was determined by measuring the length of sample cores in a fully saturated condition and then following pressure plate extraction and oven drying. The difference in core length between saturated samples and those pressurized to 1.8 MPa in a pressure plate extractor was less than the ability to resolve with a millimeter-scale rule. Following oven drying, the samples had shortened between 1 and 1.5 mm, or 2 to 3 percent of the total length.

Shear Strength of Material

The shear strength of the amended soil was tested with the use of a triaxial cell. Three samples were strained to failure at different confining pressures. Results of the three tests are shown here in Table 4.

TABLE 4. RESULTS FROM THE TRIAXIAL TESTS ON AMENDED AREA 5 SOIL.

Sample	Confining Stress (P_3)	Deviator Stress (ΔP) at Failure	Principal Stress (P_{1f}) at Failure
1	0	278	278
2	25	345	370
3	50	410	460

(all units in KPa)

The tests were performed as unconsolidated, undrained tests. Due to the unsaturated condition of the soil, it can be assumed that compression of air-filled voids during both stages of the tests

Figure 7. The effect of dry density and molding water content on the K_s of amended Area 5 soil. The contour lines connect points of equal K_s . The nine marked points represent soil samples that were tested for K_s . The values of K_s are in units of cm/sec.

caused some additional degree of compaction of the samples. The data are plotted as a Mohr circle diagram in Figure 8. The use of the Mohr circle allows visualization of normal and shear stress relationships at any angle within a sample as well as failure states at different confining pressures. The value of the Y axis intercept (C) is 80 KPa and the angle ϕ is 34° . It should be noted that the large value of the angle (ϕ) for the amended soil is a function of the degree of particle contact and is reasonable for a frictional material. The value of cohesion (C) results from the large negative pore water pressures. These values can be checked with an example using the relationship:

$$C = -\psi \tan \phi \quad (25)$$

where ψ (soil water potential, a negative value) is chosen to correspond to the molding water content ($\omega = 13.5\%$) and $\phi = 34^\circ$. Solving for C gives a value of 157 KPa, which deviates from the graphically determined intercept of 80 KPa. Fredlund and Rahardjo (1993) describe a relationship between the failure envelopes of saturated and unsaturated soils that may explain the discrepancy in values of C:

$$C = C' + (-\psi \tan \phi^b) \quad (26)$$

where C' represents the value for cohesion determined as if the sample were saturated (80 KPa), C represents the value for cohesion for the unsaturated soil (from equation (25), or 157 KPa) and ϕ^b is the angle between the saturated and unsaturated failure envelopes for the soil. Using the known values for C and C' and solving for ϕ^b gives a value of 18.2° , which is consistent with the measured values for other soils (Fredlund and Rahardjo, 1993).

SOIL HYDRAULIC PROPERTIES

Saturated Hydraulic Conductivity

The relationship between K_s and percent amended bentonite is tabulated in Table 5 and graphically shown in Figure 9. The straight line relationship on the semi-log plot of K_s versus percent bentonite allows simple interpolation of the results to determine a soil mixture that meets the screening criterion. A soil mixture consisting of Area 5 soil amended with 6.5 percent bentonite by weight satisfies the primary criterion of K_s . This mixture was chosen for further characterization.

TABLE 5. RESULTS OF THE FALLING HEAD PERMEAMETER TESTS FOR K_s ON FIVE MIXTURES OF AREA 5 SOIL AND BENTONITE.

Soil Mixture (% bentonite)	K_s (cm/sec)	No. of Samples	Std. Dev.
0%	9.8×10^{-6}	3	2.8×10^{-6}
5%	2.2×10^{-7}	3	7.9×10^{-8}
10%	2.6×10^{-9}	3	2.3×10^{-9}
15%	7.3×10^{-11}	3	4.6×10^{-11}
6.5% (selected mixture)	7.6×10^{-8}	5	1.5×10^{-8}

Figure 8. The results of unconsolidated, undrained triaxial tests performed on unsaturated amended Area 5 soil. The three circles show the results of tests at three confining pressures. The line and its angle (ϕ) describe the failure envelope of the soil. The point C indicates the Y axis intercept.

Figure 9. The effect on K_s of adding bentonite to Area 5 soils as determined by falling head permeameter.

Figure 9 indicates the effect of the addition of a relatively small percentage of a swelling clay such as bentonite to a sandy soil. The addition of 15 percent bentonite decreases the K_s by five orders of magnitude, and just 6.5 percent added bentonite achieves the required specification of 10^{-7} cm/sec. One might assume that a small addition of bentonite to a sandy soil does not necessarily increase the volume of the soil but instead occupies void space between sand grains. As the clay becomes hydrated, its volume increases up to a maximum of about 15 times the dry volume (Norris, 1983). This increase in volume by the bentonite occupies void space in the original sandy soil. When all of the void space is occupied by hydrated bentonite, the soil begins to have the appearance of sand grains in a clay matrix, and the hydraulic properties take on primarily the characteristics of the clay. These results are in agreement with other work that indicates that K_s should be very sensitive to additions of bentonite up to about 12 percent (Daniel and Benson, 1990).

Disk Permeameter

A disk permeameter was employed to give an alternate measurement of K_s of the amended soil and some estimate of the effect of scale due to a larger sample size (the radius of the disk was 10.5 cm). Figure 10 shows the results of the disk permeameter test. At any given time, the rate of infiltration is the sum of water drawn into the soil by capillary forces and by the force of gravity (equation 7). Early time infiltration data plotted against the square root of time in Figure 11 give as its slope a value for sorptivity of 4.1×10^{-3} cm²/sec. Later time, steady state, infiltration data plotted against straight time in Figure 10 give a value of infiltration under field saturated conditions of 3.1×10^{-5} cm/sec. Using equation (7) with a value for $\Delta\theta$ of 0.072 results in a value of K_s (at a tension of -0.1 KPa) of 9.1×10^{-7} cm/sec.

Water Retention Characteristics

The water retention characteristic curves for the soils were determined using three methods: hanging column, ceramic pressure plate extractor, and chilled mirror hygrometer. All three are required to describe the entire range of soil moistures. Due to time limitations, pressure plate data were not gathered for the unamended soil. Figures 12 and 13 show the retention curves for both the amended and unamended soils. Figure 13 shows that the hygrometer was used for large negative potentials (-10^3 to -10^5 KPa) and is in good agreement with the pressure plate technique in the range of -10^3 KPa. The hanging column is used to measure potentials from saturation to -20 KPa, while the range of the pressure plate extends down to about -100 KPa. Figures 12 and 13 also show the curve fit to the data by the RETC numerical estimation technique using the method of van Genuchten et al. (1991). Summarized in Table 6 are van Genuchten parameters (α and n , equation 16) as well as the air entry pressure and log-log slope (b) of the retention curve.

Figure 10. Complete results from the disk permeameter test. Long-term steady state infiltration is represented as the slope of the line.

Figure 11. Early time data from the disk permeameter test. Cumulative infiltration is plotted against the square root of time. The slope of the line represents the value of sorptivity and is primarily dependent on the capillary forces of the soil.

Figure 12. Soil water retention curve for Area 5 unamended soil. The data were obtained with a hanging water column and chilled mirror hygrometer. The curve was fit by the RETC model. RETC determined the residual water content to be 3.4 percent, which accounts for the poor fit at the very dry end.

Figure 13. Soil water retention curve for the amended Area 5 soil. Measurements were made by hanging water column, pressure plate extractor and chilled mirror hygrometer. The curve was fit to these data by the RETC model.

Table 6. THE HYDRAULIC PARAMETERS α , n , b , AIR ENTRY PRESSURE, SATURATED WATER CONTENT, AND RESIDUAL WATER CONTENT OF UNAMENDED AND AMENDED AREA 5 SOIL AS DETERMINED BY THE RETC MODEL.

	Unamended	Amended
α (KPa ⁻¹)	0.0039	0.00014
n	1.998	1.288
b	9.1	5.9
air entry pressure (KPa)	-0.8	-6
saturated water content (%)	36	34
residual water content (%)	3.2	0

A comparison of the retention curves of the two soils is instructive in understanding the differences in physical properties. The curve for the unamended soil has the characteristic shape of a sandy soil with small value for air entry pressure and relatively flat shape indicating low water retention characteristics. The addition of just 6.5 percent bentonite shows a significant effect on the curve, raising the air entry pressure and showing the retention characteristics of a fine-grained soil. This has important implications in a landfill cover application where increased water retention capacity directly affects air-filled porosity and can be linked to the reduction in vapor transport through the cover.

Unsaturated Hydraulic Conductivity

Unsaturated hydraulic conductivity of both soils was investigated by two methods, one experimental, referred to here as the evaporating column method (Rose, 1968), and the other involving use of the numerical model RETC (REtention Curve) (van Genuchten et al., 1991). The RETC code does not allow for the movement of vapor phase water, so additional calculations for vapor flow are included to supplement the calculations from the RETC code.

The evaporating column method involved a direct measurement of hydraulic diffusivity by the evaporation of moisture from one end of a 'semi-infinite' soil column (see Figure 4). Unsaturated hydraulic conductivity values were determined by multiplying the measured diffusivity at a given water content by the slope of the water retention curve at that water content (see equation 13). The evaporating column experiment was performed on both the unamended and amended soils. Figures 14 and 15 display the data at the termination of the evaporating column experiments and show the progression of the drying front down into the soil column. Included is the curve that was fit to the data using the method of Meyer and Warrick (1990) (see equations 14 and 15). Figure 16 shows the resulting values of hydraulic diffusivity derived from both evaporating column experiments. Figure 17 displays the dramatic decrease in unsaturated hydraulic conductivity with decreasing water content as calculated from equation (13). One limitation of the evaporating column method is that the initial soil water content must be such that drainage will not occur during the experiment. This limitation restricts the initial volumetric water content to between 10 and 20 percent, which does not allow description of the full range of unsaturated flow.

Figure 14. Results from the evaporating column experiment on Area 5 unamended soil. Water contents were determined at the end of the experiment and plotted against the Boltzmann variable. The curve is from the method of Meyer and Warrick (1990).

Figure 15. Results of the evaporating column experiment performed on amended Area 5 soil. These data show the progression of the drying front into the soil column. The curve was fit by the Meyer and Warrick method (1990).

Figure 16. Hydraulic diffusivity for both amended and unamended Area 5 soil as determined by the evaporating column experiments. These figures were obtained by using the method of Meyer and Warrick (1990).

Figure 17. Unsaturated hydraulic conductivity for both amended and unamended Area 5 soil as determined by the evaporating column experiments. These figures are from the method of Meyer and Warrick (1990).

The relationship of K_s to volumetric water content can also be estimated from the water retention curve (van Genuchten et al., 1991). The RETC computer model was used to perform the curve fit and calculate the α , m , and n parameters (see equation 16). Input to the RETC model for the two soils was the experimentally derived retention data plus the values for K_s and saturated water content described in this report. The results of the curve fit are tabulated in Table 6 and are graphically shown in Figures 13 and 14 along with the experimental data. The parameters determined from the curve fit are used in the model of Mualem (1976) (see equation 17) to derive the relationship between water content and unsaturated hydraulic conductivity (Figure 18).

Figures 19 and 20 show the relationship between unsaturated hydraulic conductivity and soil water potential for both soils and compares the estimations performed by the RETC method to those measured by the evaporating column technique. The results of tests on unamended soil shown in Figure 19 display reasonable agreement between the values measured by the evaporating column and those predicted by RETC. The results for the amended soil, however, show considerable deviation between the two methods (Figure 20). The two curves intersect at the very dry end where one would expect the movement of vapor to begin to dominate the flow regime. At higher potentials, the estimations by RETC consistently over-predict values of K_s . A possible explanation may be the nature of the physical model used in the van Genuchten et al. and Mualem methods employed by RETC. The model relies on a capillary tube analogy that places all of the soil water in conductive pores. In a clay-amended soil, much of the soil water may be taken by the clay particles as water of hydration and thus be less mobile.

At very dry conditions, the movement of water vapor by diffusion can dominate the flow of liquid (Troeh et al., 1982). The relative importance of vapor movement in very dry soil is demonstrated here for unamended Area 5 soil. The diffusivity of water vapor in porous media is equal to the free air diffusivity of water vapor attenuated by both the water-filled porosity and the mean tortuosity of the path caused by the presence of the grains (see equation 19). The tortuosity term used here is that of Troeh et al. (1982) and represents an empirically derived equation that was fit to several existing data sets (see equation 20). The values of the variables u and v used here in the equation of Troeh et al. are 0.03 and 1.5, respectively. Values of diffusivity in the porous media are converted to values of vapor conductivity (K_v) by equation (18) and were calculated to complement the values derived from the use of the RETC code which models only the flow of liquid. The results for unamended Area 5 soil are shown in Figure 21. Included in the graph are the measured values from the evaporating column experiment as well as the modeled liquid movement as determined by the RETC model.

Figure 22 represents a summary of the data from the unsaturated hydraulic conductivity tests and indicates the effect on unsaturated hydraulic conductivity by the addition of bentonite. The plot shows both experimentally derived data and the results of modeling efforts using the RETC code. At water contents in excess of five percent, the amended soil displays conductivities that are two to three orders of magnitude lower than the unamended soil. If one views only the modeled results which reflect the movement of liquid water only, it is apparent that at water contents lower than five percent these two curves begin to converge. This is explained when one realizes that at these very

Figure 18. Unsaturated hydraulic conductivity for both amended and unamended Area 5 soil from the application of the RETC code (van Genuchten et al., 1991).

Figure 19. The relationship between hydraulic conductivity and soil water potential for unamended Area 5 soil as determined by two techniques. The dashed line represents the application of the RETC estimation method to retention data (van Genuchten et al., 1991). The solid line represents hydraulic conductivity data from the evaporating column method combined with potential data from the RETC fit of retention data.

Figure 20. The relationship between hydraulic conductivity and soil water potential for amended Area 5 soil as determined by two techniques. The dashed line represents the application of the RETC estimation technique to retention data (van Genuchten et al., 1991). The solid line represents hydraulic conductivity data from the evaporating column method combined with potential data from the RETC fit of retention data.

Figure 21. The results of measured and modeled flow of liquid and vapor in unsaturated unamended Area 5 soil. The RETC model was used to model the liquid flow. The movement of vapor was modeled with the equation of Troeh et al. (1982). The measured values were derived from the evaporating column experiment and include the movement of both liquid and vapor.

Figure 22. Measured and modeled unsaturated hydraulic conductivity curves for amended and unamended Area 5 soil. Results from both the direct measurement experiment as well as the RETC numerical model are shown. The range of values for the experimental technique is limited to water contents that would not result in significant gravity drainage during the procedure.

dry conditions the unamended soil has virtually no water contained in conductive pores. In addition to being a discontinuous phase, the small amount of water present is found in films on the sand grains, which are not capable of conducting much water (Hillel, 1980b). Therefore, at very dry water contents a sandy soil loses much of its ability to move water as a liquid phase. In contrast, the amended soil with its fine-grained bentonite and resulting small pores maintains significant percentages of the water still present in conductive pores even at these very dry conditions.

Results from the experimental technique shown in Figure 22 indicate conductivities with significant deviations from the modeled results. Experimentally measured values of conductivity for both soils are lower than modeled results for moisture contents greater than five or six percent. At very dry conditions the measured values are larger than those from the modeled simulations. At the very dry conditions this may well be due to a limitation in the van Genuchten method of determining the relationship of hydraulic conductivity to water content, which does not consider vapor conductivity. In contrast, the experimental technique measures both with no distinction made between the movement of vapor and liquid. As air-filled porosity increases at very dry conditions, the importance of vapor movement relative to that of liquid increases and becomes the dominant factor as shown in Figure 21. Therefore, one would expect the total conductivity based on the evaporating column data to be higher at very dry conditions than that of the modeled results.

Air Permeability

A measure of air permeability ($k_{air}(\theta)$) of the amended soil was determined by measuring the volumetric flow of air through soil samples at a known pressure difference (equation 21). The conductivity of a soil to air is largely dependent on the air-filled porosity, which is directly affected by the moisture content of the soil. Prior to the $k_{air}(\theta)$ measurement, four samples of amended Area 5 soil were placed on a ceramic pressure plate extractor at a pressure of 1.8 MPa until equilibrium water content was reached. Referring to the plot of water content versus soil water potential (Figure 13) it can be seen that the volumetric water content at this pressure is 14 percent. Subtracting volumetric water content from total porosity (34 percent) gives an air-filled porosity of 20 percent. The results of tests on four samples in this study gave an average value $k_{air}(\theta=14\%)$ of 1.14×10^{-8} cm². Test results are displayed in Table 7. It is important to note that this is not a measurement of the intrinsic permeability of the soil, but is a measure of air permeability at a specified water content.

A comparison of air permeability and unsaturated hydraulic conductivity at a volumetric water content of 14 percent gives an indication of the interaction between wetting and non-wetting fluids and the soil matrix. The unsaturated hydraulic conductivity of the amended soil at a volumetric water content of 14 percent is 8.2×10^{-13} cm/sec (see Figure 18). The permeability of the soil to water at a given volumetric water content can be calculated from:

$$k_w(\theta) = \frac{K(\theta)\eta}{\rho g} \quad (27)$$

where $k_w(\theta)$ is the permeability of the soil to water at a given water content, $K(\theta)$ is the unsaturated hydraulic conductivity at that water content, η is the viscosity of water, ρ is the density of water, and

g is the acceleration due to gravity. For a volumetric water content of 14 percent, $k_w(\theta)$ was calculated to be $8.2 \times 10^{-18} \text{ cm}^2$.

TABLE 7. DATA FROM THE AIR PERMEABILITY TESTS ON AMENDED AREA 5 SOIL. Shown are core length, air pressure across the cores, the time required for 8.39 cm^3 (corrected to standard temperature and pressure) of air to flow through the cores, and calculated air permeability. The surface area of all samples was $4.93 \times 10^{-3} \text{ m}^2$. Soil volumetric water content (θ) was 14%.

Sample #	Core Length (cm)	Manometer Displacement (cm)	Time (sec)	$k_{\text{air}}(\theta)$ (cm^2)
13	5.29	0.9	10.6	1.68×10^{-8}
3	5.35	1.0	21.1	0.77×10^{-8}
2	5.29	1.1	17.8	0.82×10^{-8}
5	5.12	1.0	12.2	1.28×10^{-8}
average				1.14×10^{-8}

Effect of Wet / Dry Cycles on K_s

Long-term changes in climate may significantly alter the hydrologic conditions within a landfill cover. Of concern to this study is the affect on the low-permeability layer of several cycles of alternating wet and dry conditions with regard to K_s . To simulate wetting and drying in an actual landfill cover, K_s of the amended soil was measured by falling head permeameter for four samples both before and after three cycles of saturation followed by drying. Results are shown in Table 8.

TABLE 8. SUMMARY OF K_s VALUES BEFORE AND AFTER THREE WET/DRY CYCLES.

Sample	Initial K_s	Final K_s
1	2.56×10^{-8}	4.09×10^{-8}
2	7.01×10^{-8}	6.21×10^{-8}
3	1.17×10^{-7}	1.06×10^{-7}
4	8.86×10^{-8}	9.47×10^{-8}
average	7.53×10^{-8}	7.59×10^{-8}

As Table 8 indicates, the four samples had an average initial value of K_s of $7.53 \times 10^{-8} \text{ cm/sec}$ and an average final value of $7.59 \times 10^{-8} \text{ cm/sec}$. Within this sample set there was nearly an order of magnitude difference in K_s measurements between individual samples despite extensive attempts to standardize the procedure of sample preparation. Individual samples, however, maintained very consistent values for K_s with an average increase of just 6×10^{-10} , or less than one percent, resulting from the wet/dry cycles. It should be noted that despite the range of values for K_s within this sample set, the figures are consistent with those listed in Table 5. The standard deviation for the initial values of K_s for this sample set is 3.84×10^{-8} . The standard deviations for the 5 percent and 6.5 percent mixtures listed in Table 5 are 7.9×10^{-8} and 1.5×10^{-8} , respectively.

CHAPTER 4: LANDFILL COVER NUMERICAL MODEL

In addition to quantifying the physical properties of the soil it seems appropriate to model the performance of the proposed layer in a simulated application. For this investigation, the Soil Water Infiltration Model (SWIM) (Ross, 1990) was used. SWIM is a one-dimensional model that describes the movement of water in variably saturated soil. Precipitation and evaporation data can be specified as well as the effects of multiple plant communities. For this study, the intent of the numerical model was to stress a very simple landfill cover design with plant and precipitation parameters that may be considered rigorous. The precipitation data used here represent extremely wet conditions for the Nevada Test Site. Plant cover was kept at a value that represents sparse vegetation, and the time periods of the activity of the annual species were kept to a value that can be considered minimal.

For this simulation, a simple conceptual model of a landfill cover was chosen consisting of one meter of unamended Area 5 soil over one half meter of amended Area 5 soil. Soil parameters were based on measured data described in this report. Initial soil water potentials were set at -489 KPa, which corresponds to a volumetric moisture content of about 18 percent for the amended soil and about 5 percent for the unamended soil. The lower boundary of the simulation was described as allowing gravity drainage. Potential evaporation data are from Franklin Lake Playa about 50 km south of the NTS with climate similar to Area 5 (Czarnecki, 1990). Precipitation data were collected at Mercury, Nevada, on the NTS during 1986 (personal communication, Richard French). Precipitation for that year was approximately twice the annual average.

Plant cover at the Area 5 site is sparse and consists of fast-growing annuals and well-spaced perennial shrubs. Two types of vegetation were simulated in the model, one with the characteristics of a fast-growing annual and the other with those of a perennial shrub. The relevant characteristics of the two modeled plant species are summarized in Table 9.

TABLE 9. SUMMARY OF THE PLANT COMMUNITY VARIABLES USED IN THE SWIM MODEL TO SIMULATE A LANDFILL COVER APPLICATION.

Species Type	Annual	Perennial
Minimum xylem potential (KPa)	460	635
Depth constant for roots (cm)	30	30
Maximum root length density (cm/cm ³)	5	5
Maximum fraction of potential evapotranspiration	0.1	0.05
Begin ET date	Feb. 1	Feb. 1
Maximum ET date	Mar. 1	Mar. 1
End ET date	Apr. 1	Nov. 1

The time period of the simulation was for five consecutive years to achieve equilibrium conditions between soil moisture conditions and the applied precipitation and evapotranspiration (ET).

Minimum xylem potential represents the lowest potential that the plant can generate in root tissue to cause water to flow into the roots. Depth constant for roots is the average maximum depth of roots expected for this species. Maximum root length density is the average length of root per unit volume of soil. The maximum quantity of water that can be transpired by the plant species relative to the potential evapotranspiration is represented by the maximum fraction of potential evapotranspiration. The dates given for evapotranspiration refer to the days that the plants begin and cease to transpire and the date of maximum transpiration.

Results of the five-year simulation indicate that drainage through the cover did not occur. While the surface layers alternated between wet and dry conditions according to the precipitation, the bottom of the low-permeability layer remained at a moisture content similar to that at the start of the simulation. The results, shown graphically in Figure 23, clearly indicate that the low-permeability layer functions quite well in preventing the movement of water through the cover. Of particular interest is the interface between the two layers in the springtime following heavy winter storms. Inspection of the plot shows an increase in moisture content at the interface as the upper layer attempts to drain. The movement of this moisture is impeded by the low-permeability layer causing the volumetric water content at the interface to approach saturation. It should be noted that the computer simulation produced water contents in excess of 30 percent at the interface, which are not shown in the plot due to the smoothing effect of the contouring program. The excess moisture that would drain without the low-permeability layer is held at the boundary between the two layers to be removed by the combined efforts of the atmosphere and the plant community. Also of importance is the relatively stable moisture content of the low-permeability layer throughout the modeled year. This value is maintained at about 20 percent due to the high retention capacity of the clay-amended soil. The year-round maintenance of fairly high volumetric water contents indicates that this layer may perform well in inhibiting the movement of noxious vapors from a waste cell to the surface. This simple design can be characterized as a native soil layer which collects precipitation for its eventual removal by biological and atmospheric processes while attenuating the passage of vapors from below. This function is performed by the top meter of soil through much of the modeled year and it is only following the unusually intense winter storms used in this simulation that the presence of the lower layer is necessary to prevent drainage from the more conductive top layer.

Figure 23. The results of modeling a hypothetical landfill cover design using the SWIM model. Isobars connect points in the profile of equal volumetric water contents. The design consists of one meter of unamended Area 5 soil over one half meter of amended Area 5 soil. Precipitation data are from Mercury, NV, and represent a year of about twice normal precipitation. Evaporation data are from nearby Franklin Lake Playa. The simulation was run for five years to allow full equilibration of the cover with the environment. This graph represents the last year of the five year simulation.

CHAPTER 5: CONCLUSIONS

This report is the culmination of a research project charged with developing and characterizing a low-permeability component of a landfill cover to be used to isolate hazardous and radioactive waste at a site in the arid southwest. Such a layer might be used as part of an innovative cover design that would make use of the natural processes of evaporation and transpiration to return soil water derived from precipitation to the atmosphere. The low-permeability layer in such a design would be located beneath other soil layers that provide for the establishment of a natural plant community, as well as a storage reservoir for precipitation. As part of this type of configuration, the low-permeability layer would function as a final barrier to infiltration into the waste cells. The primary criterion for this layer is a maximum saturated hydraulic conductivity (K_s) of 10^{-7} cm/sec. The K_s of compacted native soil from the site was found to be 9.8×10^{-6} cm/sec; therefore, the soil was amended with bentonite to reduce the K_s to the required value. Initial tests for K_s were performed on native soil amended with 5, 10, and 15 percent bentonite by weight. It was found that a mixture of sandy soil from the application site amended with 6.5 percent bentonite produced a soil mixture with a K_s of 7.6×10^{-8} cm/sec. With the primary criterion of K_s thus satisfied, additional research was conducted to further characterize the hydraulic as well as basic physical parameters of the amended soil. Physical and hydraulic characteristics are summarized in Table 10.

TABLE 10. SUMMARY OF PHYSICAL AND HYDRAULIC PARAMETERS.

Soil from study site (Area 5 NTS)		
Soil type: loamy sand (USDA textural triangle), SP-SM (USCS)		
Particle density: 2.58 g/cm^3		
Amended soil mixture		
Composition: Area 5 soil amended with 6.5% bentonite by weight		
Maximum compacted density (ASTM Method D 1557-91): 1.89 g/cm^3		
Bulk density of test samples (90% of maximum): 1.70 g/cm^3		
Air permeability (14% volumetric water content): $1.14 \times 10^{-8} \text{ cm}^2$		
Shrinkage: undetected at soil water potential of 1.8 MPa		
Shear strength: $C=80 \text{ KPa}$, $\phi=34^\circ$ at 1.70 g/cm^3 and $\theta=13.5\%$		
Effect of wet/dry cycles: less than 1% change in K_s following three cycles of drying followed by re-saturation.		
Comparison of hydraulic properties		
	Unamended	Amended
Saturated hydraulic conductivity (cm/sec)	9.8×10^{-6}	7.6×10^{-8}
Air entry pressure (KPa)	6.0	8.0
<u>van Genuchten parameters</u>		
$\alpha \text{ (KPa}^{-1}\text{)}$	0.00014	0.0039
$n \text{ (} m=1-1/n \text{)}$	1.288	1.998
Saturated water content (%)	34	36
Residual water content (%)	0	3.2

Basic physical parameters are described including grain density (2.58 g/cm^3 , see Table 2), grain size distribution curve (the native soil is a loamy sand by the USDA textural triangle, and a SP-SM by the Unified Soil Classification System, see Figure 5), Proctor compaction tests (maximum dry density of the amended soil was determined to be 1.89 g/cm^3 by the modified Proctor test, all tests were performed at 90 percent of this value, or 1.70 g/cm^3 , see Table 3 and Figure 6), and strength of the material (see Table 4 for numerical results and Figure 8 for a Mohr circle representation of triaxial tests). Shrinkage was not detected in samples that had been extracted to a soil water potential of 1.8 MPa in a pressure plate extractor, and was approximately 2 to 3 percent in samples that had been oven dried.

The figures for bulk density have important implications for the performance of a compacted layer. Deep-rooted plants constitute one of the primary sources of concern for shallow land burial of hazardous waste. Not only can plants transport waste materials to the surface directly through their roots, decomposing roots can form conduits for infiltrating water. As mentioned in the introduction, several studies have shown that plant root development is inhibited by high clay content, and in soils with dry density of 1.70 g/cm^3 (Suter et al., 1993).

The results also suggest that shrinkage and the resulting desiccation cracks are not a serious concern with the amended Area 5 soil. Desiccation cracks provide ready conduits for infiltration through a compacted layer. While there was some shrinkage (2 to 3 percent) when the soil was oven dried, at reasonable field soil water potentials (1.8 MPa) shrinkage was not detected. Shrinkage is a concern both from the standpoint of long-term fluctuations in the moisture content of the compacted layer, and quality assurance during a construction project. Studies have pointed out that desiccation during construction can result in permanent damage to a compacted layer's ability to impede the downward movement of water (Daniel and Benson, 1990).

The hydraulic properties of the soils were extensively investigated. K_s of the amended soil, as mentioned above, was determined to be $7.6 \times 10^{-8} \text{ cm/sec}$ by the falling head permeameter technique (see Table 5 and Figure 9). Of particular interest to this study was the performance, in terms of K_s , following repeated cycles of wetting and drying. Four samples were subjected to three cycles of drying followed by re-saturation. There was less than one percent change in K_s following this procedure. K_s measurements with a disk permeameter verified the permeameter values.

The results of this investigation suggest that molding water content is not a critical factor in construction practice for amended Area 5 soil. The results of these tests are graphically displayed in Figure 7. This is contrary to a considerable body of published literature concerning compacted clay layers and may be quite significant in terms of construction cost and quality assurance concerns. The results indicate that dry density is the primary determinant of K_s in Area 5 soil.

The characteristic water retention curves of both the unamended and amended soils were determined with the use of a hanging water column, pressure plate extractor, and chilled mirror hygrometer. Figures 12 and 13 demonstrate that the addition of a relatively small amount of bentonite imparts much of the character of the clay to the sandy soil of the application site.

Unsaturated hydraulic conductivity was determined by two methods, one a direct measurement of hydraulic diffusivity by an evaporation technique, and the other with the aid of the numerical model, RETC (see Figure 22 for a comparison of the two techniques). The movement of vapor in unsaturated soil was modeled and compared to these two methods (see Figure 21). As with K_s , the effect of the bentonite amendment is quite distinct, with unsaturated conductivities of the amended soil being orders of magnitude lower than those of the unamended soil throughout most of the range.

The air permeability of the partly saturated soil was tested. A measure of air permeability is sometimes acquired to relate to the intrinsic permeability of the dry soil. For the purposes of this report, however, the desired figure was the air permeability of the amended soil at a volumetric moisture content of about 14 percent. This figure was determined to be $1.14 \times 10^{-8} \text{ cm}^2$.

The experimental data were incorporated into the numerical model, SWIM, to simulate in one dimension the movement of water within a simple landfill cover design (see Figure 23). Included as input into the model were actual precipitation and evaporation data collected near the application site. Precipitation data for this simulation represent a year of twice normal rainfall to highlight the performance of the cover design. Two representative plant species were modeled, one a fast-growing annual and the other a perennial shrub. Input parameters for the two plants were deliberately maintained at minimum levels to stress the design. The results of the modeling effort suggest that a very simple cover design consisting of one meter of native soil overlaying one half meter of the low-permeability soil would suffice to prevent any percolation through the cover, even under these conditions of exaggerated precipitation and minimal plant activity.

As with all laboratory studies of physical processes, care should be taken when extrapolating the results of the work presented here to the scale of field tests or actual applications. The results of the various tests presented here as well as the simulated landfill cover were done under carefully controlled conditions that one may assume are not identical to field conditions. Issues of spatial variability and the homogeneity of the soil mixture are not addressed here.

This investigation of amended Area 5 soil for use in an integrated cover design has not addressed all of the concerns for this important application. As noted in the section concerning unsaturated hydraulic conductivity at very dry conditions, there is a discrepancy between the measured values from the evaporating column experiment and the results from the combined liquid and vapor modeling efforts. The addition of the liquid and vapor model results produces a distinctly stepped function which is contrary to the smooth transition found in the laboratory experiment. This would suggest some need for an improved model of moisture movement at very dry soil conditions. There is also considerable difference between the values for hydraulic conductivity as determined by the evaporating column method and the RETC estimates. The experimentally measured results suggest a two-phase system as opposed to the smooth transition predicted by RETC. These data suggest that hydraulic conductivities at field conditions may be much lower than those predicted by conventional modeling methods. Also, this report has not addressed the effect on the clay amended layer of leachates that may be expected to form at the application site. Considering the environmental hazards and long-lived nature of radioactive waste, this aspect of long-term performance should be investigated. Although test results indicate that desiccation cracking is not

a problem with amended Area 5 soil, it should be noted that these tests were performed on relatively small soil cores. Larger-scale test plots constructed with conventional engineering methods should be used to verify these results prior to application. A larger-scale test of this soil mixture would also provide the opportunity to test the effects of molding water content at a more appropriate scale.

In closing, it seems appropriate to note that the work presented here directly addresses the questions of short- and long-term performance of a low-permeability layer in terms that are realistic for an application site in the arid southwest. The considerable body of engineering literature on the subject is largely directed toward applications in regions of vastly different hydrologic character. The detailed investigation of the movement of water in unsaturated soil reported here departs from the conventional practice of reporting only values of K_s . At Area 5 of the NTS, saturated conditions at shallow depth are uncommon and unsaturated flow presents far greater cause for concern.

The result of the research presented here is to conclude that a mixture of soil from the Nevada Test Site, when amended with moderate amounts of bentonite, possesses hydraulic and engineering properties desirable in a low-permeability component of a landfill cover. When incorporated as part of an integrated cover design, this layer can contribute to the effective containment of hazardous and radioactive waste.

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APPENDIX

This report presents results of an investigation into soil properties that combine the disciplines of soil physics and civil engineering. With few exceptions, the material is presented from the viewpoint of hydrology and soil physics with units and terminology common to those fields. For the benefit of engineers who may seek to use the information presented here, a note on terminology is appropriate. Soil water contents are usually presented here as volumetric water content or:

$$\theta(\%) = \frac{\text{volume of water}}{\text{total soil volume}} \times 100$$

whereas engineers usually prefer the gravimetric form of:

$$\omega(\%) = \frac{\text{weight of water}}{\text{weight of solids}} \times 100$$

To simplify the use of these results, this conversion is offered:

$$\omega = \frac{\theta V_T}{G_s V_s}$$

where V_T is total soil volume, G_s is the specific weight of the soil particles, and V_s is the volume of the solid grains.

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