

Comparison Of Hydraulic Conductivity Test Methods for Landfill Clay Liners

Scott Purdy, *Vector Engineering, Inc.*, Joel Peters, *Vector Chile, Ltda.*

CONTACT

Vector Engineering, Inc., 143E Spring Hill Drive, Grass Valley, CA 95945
Phone: (530) 272-2448, Fax (530) 272-8533, Email: vector@vectoreng.com

Vector Chile Ltda., Malaga N° Piso 2 Las Condes, Santiago, Chile
Phone: 011 (562) 244-1452, Fax: 011 (562) 244-1457 Email: jpeters@vectorchile.cl

EXECUTIVE SUMMARY

Accurately measuring the *in situ* hydraulic conductivity (permeability) of a clay liner is a major factor in the construction of landfill containment systems. Laboratory and large-scale field test methods are often utilized on test pads constructed prior to placement of the production liner to determine the hydraulic conductivity of the clay. While these test methods provide reliable results, the time required to run the tests can be lengthy. Due to different soil types or construction methods, variations in hydraulic conductivity between borrow source test pads and production clay liner construction can occur and the ability to quickly determine the clay liner permeability in the field is critical. To avoid potential problems, it is important to be able to correlate laboratory and large-scale field test results with more rapid field test methods. These rapid methods can then be used during the production liner installation to provide quick acceptance to the contractor.

The following paper discusses in detail the standard laboratory and large-scale field permeability test methods that are commonly used on landfill clay liners. In addition, several rapid field permeability test methods are also described. Four case histories are then presented in which both long-term and rapid field permeability test methods are conducted on clay liner test pads and the correlation between the various procedures is provided. Based on the correlation between the long-term and rapid permeability test methods, the production clay liner can be evaluated using only the rapid test methods reducing the potential for construction delays. A brief discussion on clay liner quality assurance and quality control is also presented.

INTRODUCTION

Given the State and Federal regulations regarding liner systems for municipal waste landfills, the ability to quickly and accurately determine the *in situ* hydraulic conductivity of clay liners has become increasingly important. The hydraulic conductivity of a production clay liner is typically determined using laboratory test methods (ASTM D 5084). However, as described in a report by Day and Daniel (1985), the potential exists for a considerable difference between hydraulic conductivity values determined in the laboratory versus those determined in the field. In order to compensate for this potential difference, a clay liner test pad is commonly constructed to correlate the laboratory results to the actual field hydraulic conductivity.

An accepted method for determining the hydraulic conductivity in the field consists of using a sealed double ring infiltrometer (SDRI). The ability to successfully measure the *in situ* hydraulic conductivity of a clay liner using a SDRI was documented in a report by Daniel and Trautwein (1986). While the SDRI is an excellent method for determining the hydraulic conductivity in the field, it is limited by the amount of time it takes to perform a test (up to several months). For this reason, the hydraulic conductivity results from the SDRI are used as a baseline in which to compare the laboratory results. During construction of the production liner, the laboratory results are reported using the correlation factor determined during the test pad evaluation.

As the production clay liner is installed, relatively undisturbed samples are obtained and shipped to the laboratory for analysis of the hydraulic conductivity. Depending on the hydraulic conductivity of the sample, the laboratory analysis can take several weeks to complete. During the time between sampling and analysis, the potential exists for changes in material or construction procedures to occur that could result in failing hydraulic conductivity values. In order to avoid the potential removal or reworking of large failing areas of liner, the addition of short-term, field hydraulic conductivity test methods to the quality assurance program are recommended.

The sealed single ring infiltrometer (SSRI) and BAT™ permeameter have been successfully used in the field at several sites to rapidly determine the hydraulic conductivity of production liners. Both of these techniques provide results within 24 hours and have been correlated to laboratory and SDRI methods on both test pads and production clay liners.

The following report discusses the use of the SSRI and BAT™ permeameter for the rapid determination of hydraulic conductivity in the field. Included in the discussion is a description of the laboratory, SDRI, SSRI, and the BAT™ permeameter test methods, the results of several laboratory and field hydraulic conductivity studies performed on clay liner test pads, the importance of construction quality assurance during the liner installation, and the conclusions determined from the evaluations.

HYDRAULIC CONDUCTIVITY TEST METHODS AND EQUIPMENT

Laboratory Hydraulic Conductivity Testing

ASTM D 5084-90 is the standard test method currently used by the industry for determination of laboratory hydraulic conductivity. Prior to the establishment of the ASTM test, a similar method, EPA 9100, was utilized. Both of these methods operate under falling head rising tailwater test conditions using flexible wall triaxial test cells. (Other hydraulic head conditions such as constant head or constant rate of flow can be incorporated, but they are not commonly used by the industry for testing low permeability soils.)

Tests are performed on soil samples which have been remolded in the laboratory to a specified density and moisture content or performed on relatively undisturbed samples from the field obtained using a drive sampler or other method. Remolded laboratory samples are prepared directly in a flexible membrane encasement and field samples are typically extruded from fixed wall tubes before placement of the membrane. The membrane is used to limit the potential of leakage during the performance of a test. Porous stones and filter paper are placed against the ends of the samples to distribute the permeant (usually de-aired water) across the entire end-area of the sample and also minimize the washing out of soils from the sample during testing. The configuration of the triaxial permeameter and soil test specimen is shown in Figure 1.

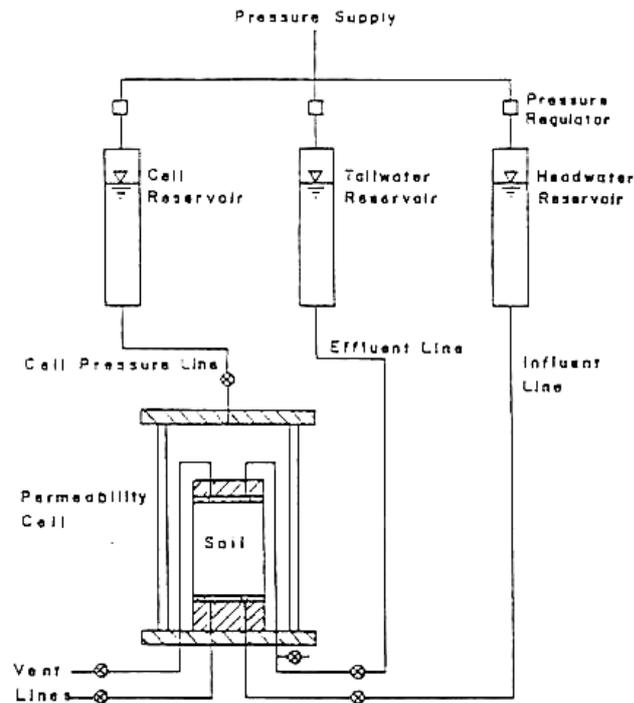


Figure 1 - Triaxial Permeameter Cell (ASTM D 5084)

Once the sample has been prepared in the test cell, the cell is filled with water and the specimen is saturated by applying pressures to both ends of the sample (backpressuring) to force water into the sample, which expedites the saturation and testing process. For soils with expected hydraulic conductivities of less than 1×10^{-6} cm/sec, the inlet pressure of the triaxial cell is typically set at 434 kilo Pascals (kPa) and 414 kPa at the outlet, which creates a hydraulic gradient of approximately 30 across a sample 7.6 centimeters (cm) in length. The cell pressure is set at a constant pressure of 21 to 69 kPa greater than the inlet pressure (the laboratory testing discussed in this report utilized a cell pressure of 483 kPa). Higher cell pressures are often utilized to determine the effects of overburden consolidation on the soil liner in question. Once testing has been initiated, saturation is confirmed when the change in the height of water in the inlet burette equals the change in the height of water in the outlet burette. Readings are performed until the calculated hydraulic conductivity has reached a relatively steady-state condition.

Sealed Double Ring Infiltrometer

All SDRI tests evaluated in this study were performed using a Trautwein SDRI test apparatus. Testing was executed in general accordance with the test methods identified by Trautwein (1989). This test method is also described in ASTM D 5093-90, Field Measurement of Infiltration Rate Using a Double Ring Infiltrometer with a Sealed-Inner Ring.

The Trautwein SDRI equipment consists of a 3.7-meter (in) square, metal outer ring and a 1.5-meter square fiberglass inner ring. The outer ring is typically embedded within a trench approximately 46 cm in depth and 15 cm in width and sealed with Volclay grout or similar material to minimize seepage along the inside walls of the outer ring. The inner ring is embedded into a trench approximately 10 to 15 cm in depth and about 2.54 cm in width. The SDRI equipment and installation is shown in Figure 2.

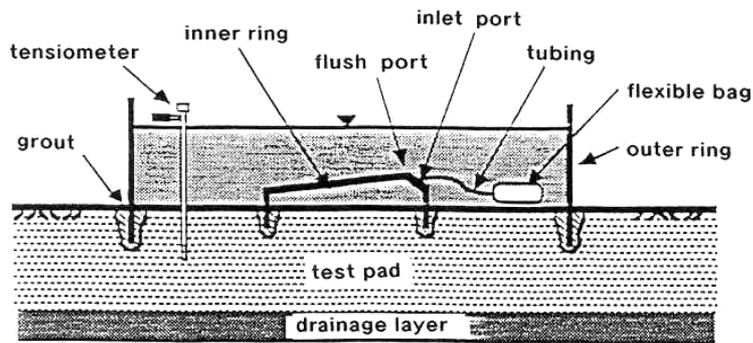


Figure 2 – SDRI Installation (Trautwein, 1989)

Soil tensiometers are used to measure the wetted front during the test. At least two sets of tensiometers are installed between the two rings (about 15 to 30 cm from the inner ring) to monitor the progression of the wetted front. Each of the sets is installed at depths varying from 15 to 46 cm below the top surface of the clay. At the conclusion of the test, the depth of the wetted front is verified by sampling the soil within the test area at various depths to determine the degree of saturation of the clay.

Prior to installation of the field hydraulic conductivity testing equipment, the surface of the clay liner or test pad is typically scraped with a motor grader so that it is free of irregularities, loose earth, and abrupt changes in grade. The prepared soil surface is protected against drying with plastic sheets until the test apparatus is in place. Once the rings and tensiometers are in place, the inner and outer rings of the SDRI are filled with water and the system checked for leaks. Infiltration is measured by determining water losses from flexible bags filled with water directly connected to the inflow port of the inner ring of the SDRI. A filled bag is initially weighed, connected to the inflow port, and set under the water within the outer ring. This ensures that the head-driving outflow of water within the inner ring is equal to the head produced for the outer ring. Over the test period the bag is reweighed to determine water losses, the bag is then filled again and the process repeated until infiltration rates have stabilized or until the wetted front advances to the bottom of the clay liner test pad.

Immediately after the test has been started, a plywood cover with foam insulation board or a similar encasement device is often placed over both rings to provide thermal insulation for the water used for the test and to minimize evaporation. Other operations during the SDRI test often include but are not limited to checking temperature variations, measuring relative moisture content versus depth with a neutron probe, measuring barometric pressure, measuring swell of the clay, and filling of the outer ring to maintain a relatively constant water level for the test.

The infiltration rate, I , is then calculated as follows:

$$I = Q / (A_i \times t)$$

Where:

$$Q = (\text{initial weight of bag in grams} - \text{final weight of bag in grams}) \times 1 \text{ cm}^3/\text{gram}$$

$$A_i = \text{area of the inner ring in cm}^2$$

$$t = \text{time between readings (seconds)}$$

The flow measurement data is used to construct a plot of infiltration versus time. For unsaturated soils, such as compacted clay liners, infiltration rates generally decrease at first, changing rapidly at the beginning of the test, and then eventually stabilize with time as the soil becomes saturated. Consequently, more frequent readings will be necessary at the

beginning of the test and less frequent readings are necessary as the flow rate decreases and stabilizes.

The depth of the wetted front, d in centimeters, is then used for calculation of the hydraulic gradient, i . The hydraulic gradient is calculated using the following equation:

$$i = (\text{total depth of water in the outer ring} + d)/d$$

The hydraulic conductivity of the soil liner is then determined by dividing the infiltration by the hydraulic gradient.

It should be noted that temperature changes of the water in the inner ring could introduce significant error in the flow measurements. A one degree Celsius drop in water temperature can result in an apparent outflow of 50 cm^3 simply due to the volume change of the water in the inner-ring itself. In order to avoid this problem, the flow readings are taken (when possible) at approximately the same time each day and the bag weighed when the water temperature is within one degree of the water temperature when the bag was initially connected.

Single Sealed Ring Infiltrometer

The SSRI test apparatus used consisted of a 0.63 cm thick steel ring nominally 30 cm in diameter by 36 cm high. A top or "seal" made of 0.95 cm thick polycarbonate plastic is clamped to the top of the ring using C-clamps. A rubber O-ring creates an airtight seal between the steel and the polycarbonate top. A center valve in the top is connected by flexible plastic tubing to a burette mounted on a post next to the ring. The post is driven into the soil liner next to the SSRI apparatus and the burette is set at a height of 1.5 to 1.8 meters above the liner surface. The burette is marked in increments to measure outflow during the test. The SSRI apparatus, flexible tubing, and burette are insulated with separate sheltering devices to maintain a relatively constant temperature of the water over the test period. The SSRI equipment and installation is shown in Figure 3.

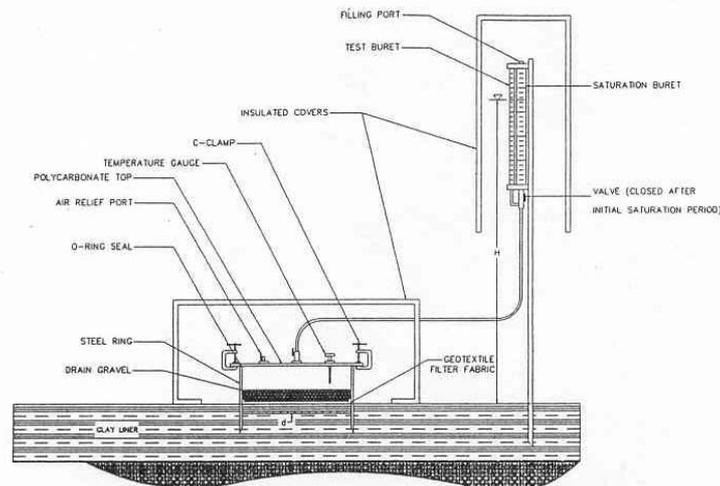


Figure 3 - SSRI Installation

Typically, the ring is hydraulically pressed into the soil about 10 to 15 cm to provide a tight seal along the soil and steel ring interface. The ring can also be set in the clay by the trenching and grouting method described for the SDRI.

The setup time, date and initial temperature of the water are recorded once the ring and burette have been filled with water to begin saturation of the test area. Any air pockets within the apparatus, which may introduce errors in the infiltration readings, are removed through ports in the polycarbonate top and burette.

The area is typically allowed to saturate for 16 to 24 hours to minimize effects of unsaturated flow and swelling of the clays. After this initial saturation period, timed infiltration measurements are recorded by monitoring the water level drop within the burette. The water temperature is also monitored to ensure that there is little or no variation over the evaluation period.

The infiltration rate, I , is then calculated as follows:

$$I = Q / (A_c \times t)$$

Where:

$$Q = (\text{initial burette reading} - \text{final burette reading}) \times A_r$$

$$A_r = \text{area of the burette (cm}^2\text{)}$$

$$A_c = \text{area of the permeameter cylinder (steel ring)}$$

$$t = \text{time between readings (seconds)}$$

Timed readings are continued until the infiltration rate stabilizes. Once the infiltration rate stabilizes, the test is complete. The final temperature is noted, the cover removed, and the water drained from the steel ring. The depth of the wetted front in the single ring is then measured. This distance, d (cm), is then used for calculation of the hydraulic gradient, i .

The hydraulic gradient is calculated using the following equation:

$$i = (\text{total height [H] of water in the burette at time zero} + d) / d$$

The hydraulic conductivity of the soil liner is then determined by dividing the infiltration by the hydraulic gradient. The effect of temperature on the infiltration of the water is obtained by multiplying the hydraulic conductivity by a temperature-viscosity correction factor to determine the final hydraulic conductivity.

BAT™ Permeameter

The BAT™ permeameter consists of a plastic or stainless steel tip containing a cylindrical porous filter. The tip is attached to a steel pipe and is driven or pushed into the clay liner to a predesignated depth. A container partially filled with water and partially filled with gas is then lowered into the steel pipe and brought into contact with the porous filter using a hypodermic needle and septum. The gas in the chamber is then pressurized.

A pressure transducer is used to monitor the changes in the gas pressure in the container as water flows out of the porous filter. The quantity of flow is computed by measuring the gas pressure change in the container and then applying Boyle's-Mariotte's law and other relatively complex flow mechanics principles. A detailed discussion of the theories and formulae utilized for calculation of the soil permeability has been provided by Petsonk (1985).

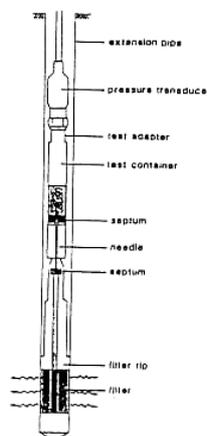


Figure 4 - BAT™ Permeameter (Petsonk, 1985)

The pressure record obtained for each increment of time is entered into a computer program for a calculation of the *in situ* hydraulic conductivity. As with the SDRI and SSRI, the BAT™ test is generally considered complete when readings stabilize often within hours of its installation.

FIELD AND LABORATORY HYDRAULIC CONDUCTIVITY STUDIES

As described in the introduction, several hydraulic conductivity studies were evaluated for correlation of short-term field hydraulic conductivity methods with the SDRI and laboratory results in order to provide timely information in the field during installation of the production clay liner. Correlations between the various test methods have been determined during the placement of clay liner test pads and production clay liners at several municipal waste landfills throughout California. This report utilizes the results from two landfill sites in Southern California and two landfill sites in Northern California.

Site A

Site A is located in Southern California at a large canyon landfill. Materials used for the test pad came from an on-site location and were classified as an inorganic silt with clay. The test pad was constructed in 15 cm lifts to a total thickness of 0.9 m using a CAT 815 padfoot compactor. The maximum dry density of the on-site material was 17,428 Newtons per cubic meter (N/m^3) with an optimum moisture of 17 percent. The material was placed at 90 percent of the maximum dry density at a moisture content between four and six percent above optimum.

After the test pad was installed, a hydraulic conductivity analysis was conducted using SDRI, SSRI, BAT™ permeameter, and laboratory (ASTM D 5084) methods. The purpose of the analysis was to determine the suitability of the on-site borrow material and correlate the various hydraulic conductivity methods to the SDRI.

A total of four SSRI tests, four laboratory tests, one SDRI test, and one BAT™ permeameter test were conducted on the test pad. As shown on Table 1, the laboratory and short-term tests correlated very closely with the results obtained from the SDRI. In this instance, the construction engineer recommended that the results obtained from both the SSRI and BAT™ be used without modification to verify the *in situ* hydraulic conductivity during production liner construction.

Site B

Site B also consists of a large Southern California landfill. A clay liner test pad was constructed at the site with dimensions of 18 m by 30 m. It was constructed in six lifts to a total thickness of 0.9 m using a CAT D8L dozer pulling a sheepsfoot compactor. The maximum dry density of the clay was 13,660 N/m^3 with an optimum moisture of 27 percent. The material was placed at 90 percent of the maximum dry density at a moisture content four to eight percent over optimum.

The hydraulic conductivity evaluation on the test pad utilized laboratory (EPA 9100), BAT™ permeameter, and SDRI methods. During installation of the production clay liner, laboratory (EPA 9100), BAT™ permeameter, and SSRI methods were employed. The test pad analysis resulted in a good correlation between the SDRI and laboratory methods, while the BAT™ permeameter tests generally ran about one magnitude of order above the other tests. During installation of the production clay liner, the laboratory and BAT™ permeameter tests had good correlation and the SSRI analyses results were within one order of magnitude. All of these results are provided in Table 1.

Site C

Site C involved the capping of a closed landfill in Northern California. At this location SDRI, SSRI, and laboratory (ASTM D 5084) methods were used. The material tested consisted of a tan silty clay with a maximum dry density of 17,428 N/m³ and an optimum moisture content of 17 percent. The clay cap was compacted in two 15 cm layers using a CAT 825 padfoot compactor to 90 percent or greater of the maximum dry density at a moisture content near optimum.

The correlation between all of the methods was within an order of magnitude. The SSRI and laboratory (ASTM D 5084) methods were very close while the SDRI indicated a slightly higher hydraulic conductivity. A total of ten laboratory tests and three SSRI tests were performed at the landfill. The results of the Site C analysis are provided on Table 1.

Site D

Site D is located in Northern California and involved the installation of a test pad for a composite liner at a municipal waste landfill. Because of the lack of available fill area and insufficient time, an SDRI was not installed. In order to obtain regulatory approval for the clay without an SDRI, a report was prepared prior to construction, which demonstrated the correlation of the SDRI with BATTM permeameter, SSRI, and laboratory test methods on other projects. Following regulatory approval, a test pad was constructed and evaluated using the BATTM permeameter, SSRI, and laboratory (EPA 9100) methods.

The test pad was constructed in 15 cm lifts to a total thickness of 61 cm using a CAT 815 padfoot compactor. The material had a maximum dry density of 17,271 N/in³ and an optimum moisture of 20 percent. The material was placed at 95 percent of the maximum dry density at a moisture content between one and five percent above optimum.

Following completion of the test pad, a total of five BATTM permeameter tests, ten SSRI tests, and six laboratory tests were conducted. The SSRI and BATTM permeameter tests conducted in the field correlated very well with each other. On average, the field tests were within a half of an order of magnitude higher than the laboratory results. The results of the test pad evaluation from Site D are shown on Table 1.

Table 1 - Summary of Hydraulic Conductivity Test Results

Location	SDRI Results (ave. cm/sec)	SSRI Results (ave. cm/sec)	BAT TM Results (ave. cm/sec)	Lab Results (ave. cm/sec)
Site A	5x10 ⁻⁸	6x10 ⁻⁸	4x10 ⁻⁸	4x10 ⁻⁸
Site B Test Pad	4x10 ⁻⁸	N/A	4x10 ⁻⁷	5x10 ⁻⁸
Site B Prod. Liner	N/A	2x10 ⁻⁷	7x10 ⁻⁸	5x10 ⁻⁸
Site C	5 x 10 ⁻⁷	1x 10 ⁻⁷	N/A	8x 10 ⁻⁸
Site D	N/A	3x10 ⁻⁸	6x10 ⁻⁸	1x10 ⁻⁹

CLAY LINER CONSTRUCTION AND QUALITY ASSURANCE

The large scale construction defects which can cause increases in the liner hydraulic conductivity can be significantly reduced by the incorporation of rigorous material specifications and a quality assurance/quality control (QA/QC) program during project development. Projects in which a detailed program is implemented have a much closer correlation between field and laboratory hydraulic conductivities.

The QA/QC program will assure the owner and engineer that proper construction techniques and procedures are used during construction and that the liner is built in

accordance with the plans and specifications. This program is typically implemented by a third party consultant contracted by the owner. The program is intended to identify and define problems that may occur during construction and to verify that these problems are corrected in a timely manner before construction is complete.

The QA/QC program should be separated into three phases during project development: (1) borrow source testing; (2) test fill construction testing; and (3) production clay liner testing. Borrow source testing is performed to determine if a soil proposed for use at a site will perform to the standards required by the specifications. The types of tests and the frequency to which they are performed are dependent on the level of confidence that the engineer has with the proposed borrow source to produce the material for liner construction. In some instances, the proposed material has been used extensively in similar applications; consequently little or no borrow source testing may be required. In other cases, the materials proposed may have never been tested for the properties necessary for determining its suitability as a clay liner.

Once borrow testing is complete, a clay test fill section should be constructed. This phase of testing and observation allows detailed QA/QC procedures to be developed prior to the clay liner installation and ensures the engineer that the proposed materials can be utilized as intended in a representative field application. The test fill is constructed using the same methods and equipment as that proposed for the production clay liner. The test fill enables the owner and its engineers to evaluate the effects that the construction procedures will have on the clay liner including but not limited to variations in compaction, moisture content, borrow material, mixing of bentonite soil additives (if required), bonding of successive lifts, size of the soil clods, and the rate of desiccation crack development.

In addition to observing procedural effects, the test pad also allows the engineer to conduct a wide range of field and laboratory hydraulic conductivity tests. Material classification properties and hydraulic conductivity of the test fill would be determined using both the *in situ* and laboratory test methods described above. Depending on the construction schedule, the engineer must decide whether an SDRI test is appropriate

After the clay liner test fill has been completed and the construction procedures approved and documented, installation of the production clay liner would proceed. The approved procedures determined from the test pad would be followed by the QA/QC monitors for the production liner installation. The QA/QC testing program for the production clay liner would be essentially the same as that described for the test fill; because of the time constraints the SDRI test would not be performed during production clay liner construction.

CONCLUSION

As described within this paper, several methods are currently available to determine the hydraulic conductivity of clay liner systems. Based on the information obtained from several solid waste landfills, all of the hydraulic conductivity methods reported can obtain realistic results.

If properly installed, the SDRI is a very reliable test method for obtaining field hydraulic conductivity. Using the SDRI, a broad area of the liner can be analyzed in one location accounting for large scale effects caused by construction. The SDRI method does, however, have limitations. These limitations include problems associated with installation, the duration of the test, and effects of temperature variations over the test period. Because

of the long duration of the test, it can only be used as a correlation for other methods on a clay liner test pad.

A typical laboratory hydraulic conductivity test can take several weeks to perform and can take much longer if the contracted laboratory is in the process of performing other tests which cannot be interrupted. During the time between sampling and analysis, the potential exists for changes in material or construction procedures to occur that could result in failing hydraulic conductivity values.

The SSRI and BAT™ permeameter field hydraulic conductivity methods have the advantage in that they both obtain results within a relatively short time frame (less than 24 hours). Therefore, many representative areas of the production clay liner can be evaluated during placement with minimal disruption of construction activities. This will enable the engineer to quickly identify and remediate problem areas due to construction or material changes.

The disadvantage of both these tests is that they provide measurements of the hydraulic conductivity of the liner over smaller areas than the SDRI. This might lead to the conclusion that they will not accurately reflect any large scale effects and variations in the liner caused by construction. However, the results of the studies evaluated provide sufficient evidence that short-term field tests may be a true reflection of the field conditions and that these tests can be used to accurately assess the *in situ* hydraulic conductivity of soil liners without the aid of an SDRI. By conducting several short-term tests over a liner, an area equivalent to that of an SDRI can be evaluated.

Using these short-term test methods to determine *in situ* hydraulic conductivity along with a rigorous QA/QC program will assure the engineer, owner, and regulatory agencies that the constructed clay liner provides an equivalent level of environmental protection to that provided by other testing methods.

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