Sealing Leaks in Geomembrane Liners Using Electrophoresis

By Glenn T. Darilek,[1] Member, ASCE, M. Yavuz Corapcioglu,[2] Fellow, ASCE, and Albert T. Yeung,[3] Member, ASCE

Abstract: An innovative method was demonstrated to seal leaks in geomembrane liners by attracting clay particles to the leaks using electrophoresis. Electrophoresis is the movement of electrically charged particles suspended in a liquid by the action of an electric field. A direct-current voltage impressed across the liner causes electrical current to flow through the leaks. The current produces a strong electric field at leaks. When a clay slurry is dispersed into the liquid in the impoundment, electrophoresis attracts the clay particles to the leaks, thereby sealing them. The method can seal leaks in liquid impoundments without removing the liquid or locating or accessing the leaks. The laboratory and full-scale test results were remarkable in that electrophoresis sealed the leaks completely when a layer of geofabric was under the liner, and electrophoresis reduced the leakage rate through holes as large as 10 mm in diameter by a factor of 1,600 in the field test with gravel under the liner, and by a factor of 1,667 in the laboratory basin with geonet under the liner.

INTRODUCTION

Geomembrane liners are sheets of impermeable flexible synthetic material that are installed in surface liquid impoundments and tanks to prevent the migration of contaminated water to surface or groundwater resources. However, many of these installations leak due to physical damage and inadequate installation techniques. Laine and Darilek (1993) found an average of 22.5 leaks per 10,000 m^2 (9.1 leaks per acre) in installations surveyed using an electrical leak location method. The usual method for repairing leaks in geomembranes reported by Landreth (1989) includes removing the waste, locating the leaks and cleaning the liner material near them before they are sealed. Because the liner material has aged and been contaminated, extrusion welding or solvent bonding of patches at the leaks may be difficult. A cost-effective, reliable, and safe leak sealing method is needed to improve these storage systems.

Electrophoresis is the movement of suspended particles through a liquid under the action of an electric field in the liquid. The electrophoretic leak sealing method is to put a voltage across a geomembrane liner so electrophoresis can attract suspended clay particles to leaks, thereby sealing them. Darilek (1990) reported on the feasibility investigations of the electrophoretic effect to seal leaks in geomembrane liners. The bench scale tests in small shallow basins were a remarkable success in that clay, which concentrated at leaks in the liner, sealed the leaks. Furthermore, in several instances, the clay formed a relatively hard crust in the leaks that sealed them. The electrophoretic leak sealing method was patented by Darilek and Laine [U.S. Patent No. 4,950,374 (1990)].

ELECTROPHORETIC LEAK SEALING METHOD

Fig. 1 shows the principles of the electrophoretic leak sealing method. A direct-current voltage is put across the electrically insulating liner using a d.c. power supply connected to one electrode in the liquid and another electrode in electrically conductive material under the liner. This causes electrical current to flow through leaks in the insulating synthetic liner, creating a strong electrical field near the leaks. Particles such as bentonite clay platelets in a colloidal suspension carry a high surface charge because of their molecular structure. A dilute clay slurry is dispersed into the liquid in the impoundment. With the proper d.c. voltage polarity, electrophoresis attracts the clay particles to the leaks. The clay accumulates on the leaks and is trapped in the media immediately beneath the leaks, thereby sealing the leaks. Because the geomembrane liner is an insulator, electrical current flows only through the leaks, so the electrical power requirement is small.

THEORETICAL ELECTRIC FIELD NEAR A GEOMEMBRANE LEAK

The electric field strength close to a leak can be modeled as the electric field caused by a point current electrode in a conductive infinite half-space. The radial electric field strength can be derived from Ohm's Law as

$$\mathbf{E} = \frac{\mathbf{i}\rho}{2\pi r^2} \tag{1}$$

where $\mathbf{E}$ = electric field vector; $\mathbf{i}$ = current density vector; ρ = resistivity of the conducting medium; and r = distance from the point current source. In practice, the electric field is quantified by measuring the voltage difference between two closely spaced points in the medium. By definition, this voltage difference is

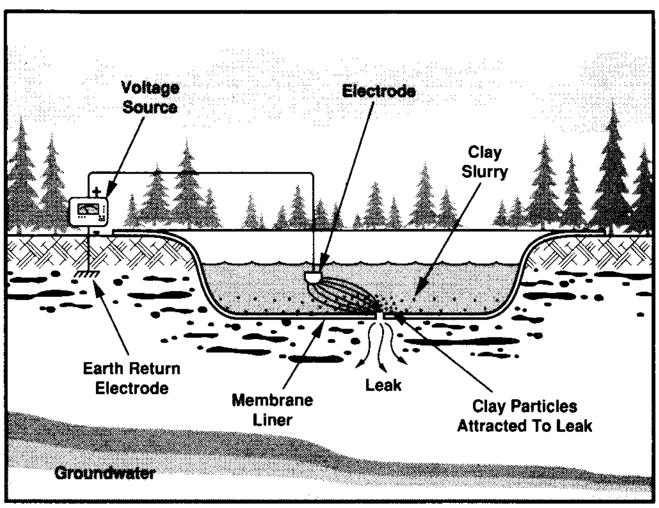

FIG. 1. Principles of Electrophoretic Leak Sealing Method

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[1]Prin. Engr., Leak Location Services, Inc., 7028 Bandera Road, Suite 228, San Antonio, TX 78238-1201.

[2]Prof., Dept. of Civ. Engrg., Texas A&M Univ., College Station, TX 77843-3136.

[3]Asst. Prof., Dept. of Civ. Engrg., Texas A&M Univ., College Station, TX.

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$$V_{1,2} = \int_2^1 \mathbf{E} \cdot \mathbf{dl} \tag{2}$$

where $V_{1,2}$ = voltage difference between points 1 and 2; and $\mathbf{dl}$ = incremental distance vector. Performing the integration, the potential difference is expressed as

$$V_{1,2} = \frac{I\rho}{2\pi}\left[\frac{1}{r_2} - \frac{1}{r_1}\right] \tag{3}$$

which can be expressed as

$$\frac{\Delta V}{I\Delta r} = K\frac{1}{r(r + \Delta r)} \tag{4}$$

where ΔV = potential difference; $\Delta r = r_1 - r_2$; $K = \rho/2\pi$; and $r = r_1$.

These equations are developed under the assumption that the current return electrode is also distant (at infinity). Because (4) shows the potential difference decreases approximately inversely proportional to the square of the distance r from the current source, this assumption is valid within 1% if the current return electrode is ten times more distant than r.

MEASUREMENTS OF ELECTRIC FIELD NEAR A GEOMEMBRANE LEAK

Test Procedure

Potential gradient measurements versus distance from a leak were made in a test basin with a 4 mm diameter leak at the center of the bottom. Fig. 2 shows the dimensions of the test basin and the geometry for the measurements. The basin was filled to a depth of 600 mm with water from a test impoundment. A potential gradient probe was built by encapsulating carbon electrodes onto the ends of rigid, insulated wires. Immediately after each measurement sequence, the polarization potential of the probe was measured by making a potential measurement with the impressed voltage turned off. This polarization potential was subtracted from the readings and the readings were normalized to the leak current. This quotient was divided by the potential electrode spacing of 100 mm to obtain a potential gradient measurement normalized to the leak current.

The potential gradient measurements were made along lines at 0, ±30, ±60, and ±90 degrees from the vertical axis for a vertical plane passing through the leak and perpendicular to one side of the basin. The power supply voltage for the measurements was 100 V d.c. The resistivity of the water was measured using a four-electrode linear (Wenner) electrode array with an electrode spacing of 100 mm.

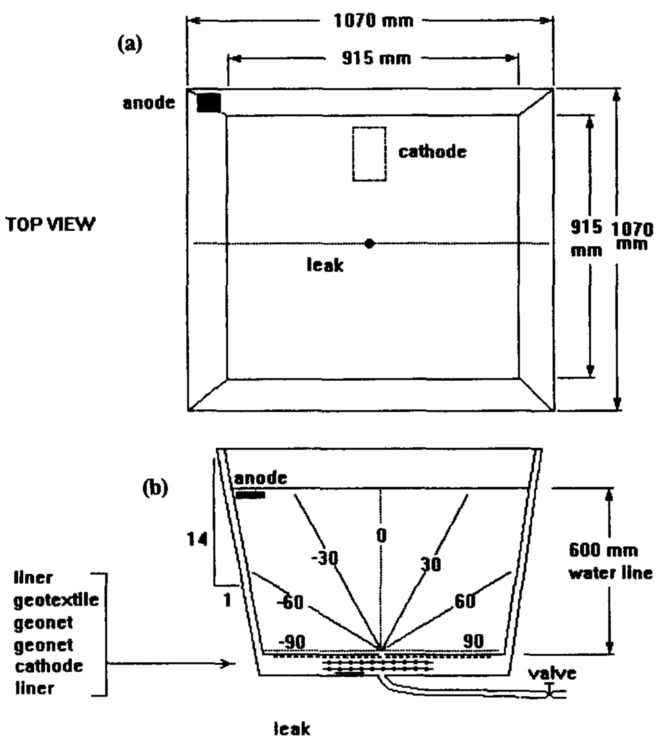

FIG. 2. Test Basin Showing Geometry for Potential Gradient Measurements

Test Results

Fig. 3 shows the potential gradients for the measurements taken in the quarter-plane closest to the anode. Fig. 4 shows the measurements taken in the quarter-plane more distant from the anode. Because the amplitude of the measurements made at the leak was very large and had extreme variations with minor variations in the positioning of the measurement probe, those measurements were not plotted. The average measured resistivity of the water was 22.3 ohm-meters. The left-hand part of (4) is the quantity plotted in Figs. 3 and 4. The electrical current through the leak was typically 8.8–9.0 mA.

The measured resistivity value of 22.3 ohm-meters corresponds to a K value of 3.55 ohm-meters. Figs. 3 and 4 also show the theoretical field strength calculated with this value. The measured data is in close agreement with the theoretical values. The data follows the shape and magnitude of the calculated values. The slight deviations from the theoretical values for the data taken toward the anode may be attributed to the effect of the proximity of the anode.

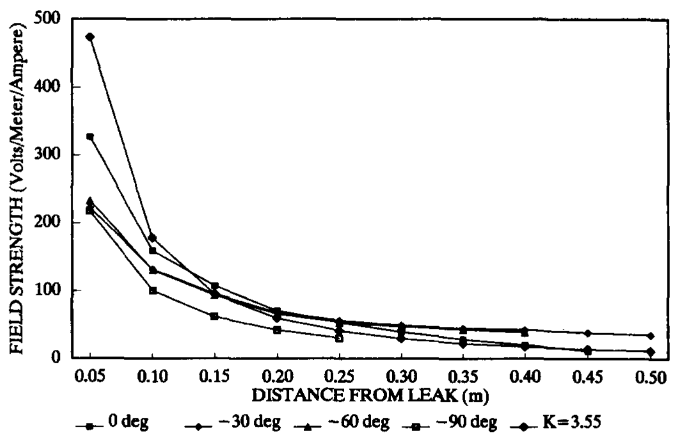

FIG. 3. Potential Gradient Measurements for Quarter-Plane Nearest Anode

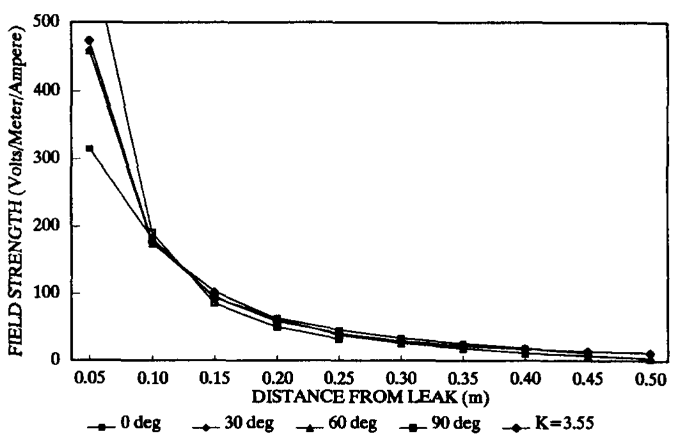

FIG. 4. Potential Gradient Measurements for Quarter-Plane Farthest from Anode

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TABLE 1. Results of Electrophoresis Tests

(1)	Basin A (2)	Basin B (3)	Basin A (4)	Basin B (5)	Basin A (6)	Basin B (7)
Leak size	4 mm	4 mm	8 mm	8 × 10 mm	15 × 19 mm	8 × 10 mm
Leak shape	Circle	Circle	Circle	Ellipse	Ellipse	Ellipse
Underlayment	Fabric	Fabric	Fabric	Fabric	Fabric	Geonet
Leakage with no treatment (mL/min)	29	469	87	70	55	4,000
Leakage after electrophoresis (mL/min)	0	0	0	0	0	2.4
Diameter of clay cake (mm)	28	32	33	34	37	40

LABORATORY ELECTROPHORESIS TESTS

Test Procedure

Laboratory tests of the electrophoresis leak sealing method were conducted with various sizes of leaks. The dimensions of the test basins were previously shown in Fig. 2. Two identical test basins each constructed in a plywood form were used. Double Hypalon liners were used. This scrim-reinforced liner material was very flexible, which allowed it to be shaped to fit the plywood form. The center of the bottom liner had a drain hose attached to a drain fitting. The bottom sloped toward the drain. Two layers of Gundnet geonet covered the drain. A layer of Trevira 1120 nonwoven geofabric covered the layers of geonet. The primary liner was placed on the geofabric. The leak in the primary liner was at the center of the bottom. The sizes and shapes of the leaks ranged from a 4 mm diameter circle to a 15 × 19 mm ellipse. One of the laboratory tests was conducted with only geonet under the liner.

A 50 V d.c. power supply provided voltage to a cathode embedded in the water between the liners and an anode in the water in an upper corner of the basin. Fifty-five grams of Baroid Aqua Gel bentonite were used for each of the tests. The bentonite was mixed in approximately 1 L of water using a food blender for approximately 15 s. The basins were filled to a level of 600 mm with water from a test impoundment. The water was San Antonio, Texas well water that had been stored in the test impoundment for several months. The water had a slight concentration of fine algae and slight amounts of sediment, primarily from residual amounts of caliche soil washed into the impoundment. The combined amounts of these residues were estimated to be less than 5% of the volume of the dry clay added for the test, so the residues could not have clogged the leaks. The steady-state water flow from the leak detection zone between the double liners was measured before the clay was added and after the electrophoretic treatment. Because the two liners were not sealed together at their edges, the hydrostatic head was released between the liners. After 5 d the leak detection zones of the basins with the 4 mm diameter leaks were opened and allowed to drain while the electrophoretic treatment was continued. The suspension was stirred in irregular intervals of 1–28 d to reintroduce settled clay particles into the slurry so they could be attracted by the electric field again. The electrophoretic treatment was maintained for periods ranging from 9 to 39 d.

Test Results

During two preliminary tests in basin B with a 4 mm leak, a reliable leak seal was not obtained. The power supply voltage was decreased from 50 to 25 V d.c., but this produced no improvement. One reason for the failure was probably that the leak detection zone was being drained during the treatment and the force of the flowing water was clearing the clay from the leak. Another probable reason was excessive periodic stirring of the clay slurry. The test was restarted and left unattended for 28 d, during which time the clay was not stirred and the leak detection zone was not drained. Then the leakage was zero. These procedures were repeated in the subsequent reported tests to obtain a reliable seal. At one time, basin A was accidently disturbed and the clay seal leaked a few mL. However, the electrophoretic treatment was continued and the leakage returned to zero again.

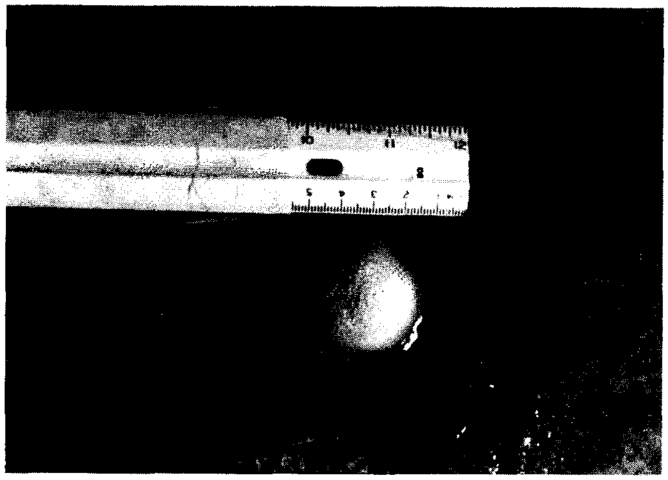

FIG. 5. Clay Seal on 15 mm by 19 mm Elliptical Leak

Table 1 tabulates some of the test conditions and the results of the electrophoresis tests. Fig. 5 shows the accumulation of clay after one of the tests. The flow rates before the electrophoretic treatment did not correlate with the leak area. This is probably because of differences in how the leak area was in contact with the underlying geofabric. The leaks were in the center of the geomembrane liner, which was the area on the liner where two folds intersected. The folds had been made for shipment. When the folds prevented the geofabric from contacting the geomembrane in an area around the leak, the geofabric impeded the flow less, so the leakage rate was much more than when the leak area closely contacted the geofabric. The power requirement for the laboratory tests ranged from 150 mW to 1.3 W. The cost of power for the electrophoresis treatment was insignificant.

Analysis of Results

The best results were obtained under the conditions when (1) a geofabric was under the liner; (2) the clay was allowed to settle fully with no agitation; and (3) a power supply voltage of 50 V d.c. was used. This combination resulted in the complete sealing of all of the leaks tested. The leakage rate for the extreme case of an 8 × 10 mm elliptical leak with only geonet under the liner resulted in a reduction of the flow rate of the leak by more than three orders of magnitude.

The electrophoretic forces are much smaller than the hydraulic force of water flowing freely through a leak. Therefore, the electrophoretic leak sealing process must be applied with little or no water flow through the leaks. Prior to the electrophoretic treatment for double liner systems, the leak detection

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zone between the liners should be flooded to the same level as the water in the impoundment so that water will not flow through the leaks. For single geomembrane liners, the subgrade is usually constructed of compacted clay or other relatively impermeable soil. The clay will contain the leakage, and the leak rate will approach zero which will allow the application of the method.

Geotextile placed under the geomembrane liner improves the electrophoretic leak sealing compared to the sealing with only a geonet under the liner. The previous laboratory tests conducted by Darilek (1990) showed that sand under the liner also provides a strong base for a tighter clay cake. The clay incrustation penetrates the geotextile or sand, which serves as a matrix to further strengthen the seal.

The level of the impressed voltage must be selected to provide the strongest field strength without causing excessive electrolytic decomposition of the water. Electrolysis causes gas to bubble through the leak, which dislodges the clay from the leak, thereby reducing the sealing efficiency. The voltage level at which decomposition occurs is primarily determined by the ionic content of the water and the current density. The current density with a given voltage level is a function of the size and geometry of the leaks. The best way to determine the proper voltage level to use will be an experimental method on a bench scale using the actual waste liquid and representative leaks. The tests in this study showed that a voltage of 50 V d.c. caused no noticeable electrolytic decomposition for the test conditions.

The quantity of the clay that is attracted to the leak is a small percentage of the total clay. To come into the influence of the electric field, the clay particles must settle within a few cm of the leak. Therefore, stirring the water after the clay particles have completely settled will reintroduce some clay particles to the electric field near the leak, thereby aiding the sealing action. The tests showed that excessive stirring can dislodge the clay seal as it forms. Very good seals formed when the water was not stirred.

FULL-SCALE TESTS

Impoundment Preparation

A geomembrane test impoundment at Southwest Research Institute in San Antonio, Texas was prepared for a full scale test. The test impoundment has a total area of 4,500 m^2 and is lined with a single high-density polyethylene (HDPE) liner. The bottom area is 49 × 52 m. Almost all of the sand and clay sediment in the pond was removed manually prior to the test.

Fig. 6 is a cross section of the leak detection zone that was installed in the southeast corner of the impoundment. A 5.5 × 5.5 m portion of the liner was removed and a leak detection sump was dug in the gravel under the liner. An existing drain pipe was leaking, so it was retrofitted with a polyethylene pipe. A 1.5 mm HDPE liner was welded into the sump area and the sump was welded to the polyethylene drain pipe to form a secondary containment system. The sump area was tested for leaks using the electrical leak location method for water-filled liners described by Laine and Darilek (1993).

A square 100,000 mm^2 stainless steel plate electrode was placed in the sump. A 100 mm monitor and vent pipe was placed down the side slope into the sump. The sump was filled with washed pea gravel. A 1.5 mm HDPE liner was welded over the sump area to form a primary liner. The monitor and vent pipe were covered with a strip of liner that was welded to the secondary liner to prevent rainwater from entering the leak detection zone. A complete electrical leak location survey was conducted with the impoundment filled with 600 mm of water. All the leaks were repaired and the impoundment was refilled with water to the 600 mm depth.

A 10 mm diameter circular hole was drilled in the primary liner near the center of the area equipped with a leak detection zone. The leak drained directly into the underlying gravel.

Electrophoretic Treatment

Batches of clay slurry were prepared by mixing approximately 15 kg of dry Baroid Aqua Gel bentonite with 150 L of well water in a 200 L barrel. A 50 mm construction pump circulated the slurry in the barrel. The gasoline-powered pump had a rated head pressure of 30 m of water with a flow rate of 560 L/min. The slurry was mixed by directing the flow of the pump into the barrel through an irrigation nozzle rated at 100 L/min at a pressure of 310 kPa.

The mixed clay slurry was uniformly sprayed onto the surface of the water in the impoundment. The pump and nozzle could spray the slurry approximately 22 m. A total of 225 kg

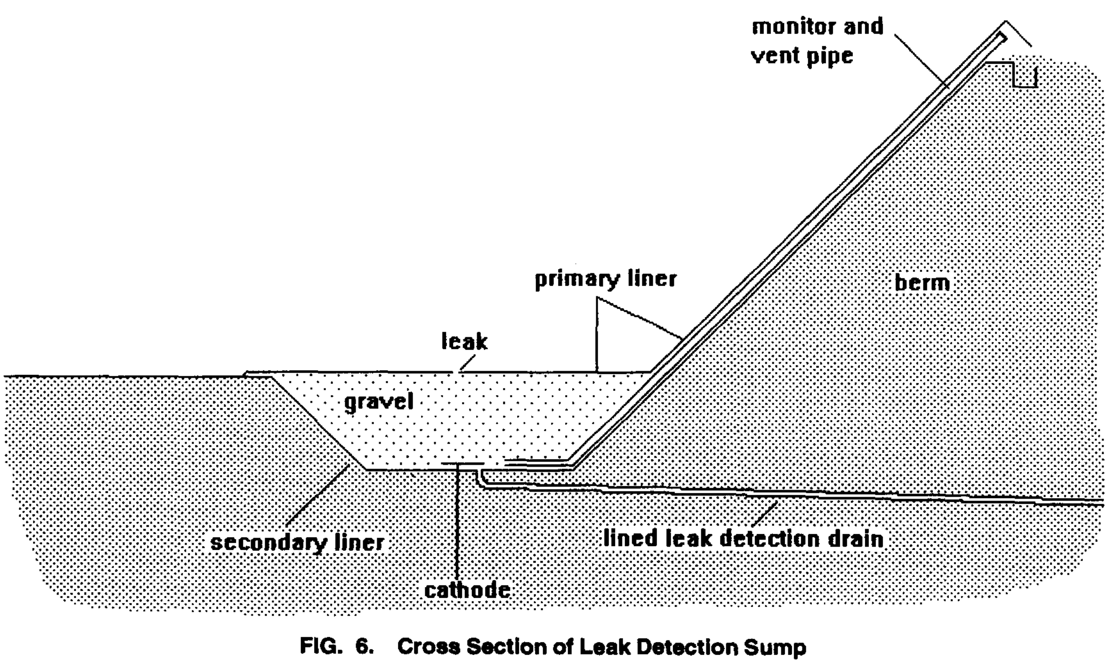

FIG. 6. Cross Section of Leak Detection Sump

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(dry weight) of bentonite was introduced into the impoundment which had approximately 1,400 m^3 of water.

The power supply voltage of 50 V d.c. was connected with the correct polarity to the electrode in the leak detection zone and another similar electrode in the pond. The positions of the electrodes are not critical in most cases where there are no very large leaks. With no large leaks, the current flow in the pond is small so the voltage drop in the water will be small and the voltage across the liner will be relatively uniform. This is indicated by the low potential gradient at larger distances from the leak previously shown in Figs. 3 and 4.

Full-Scale Test Results

The steady-state leakage rate with the clay slurry in suspension was measured to be 1,120 mL/min. The drain valve for the leak detection zone was closed for the first 27 d of the electrophoretic treatment. After 27 d of the electrophoretic treatment, the leak rate was measured. After the water in the leak detection zone drained, the leakage rate was 189 mL/min. The electrophoretic treatment was continued and after an additional 7 d the leakage rate was 2.1 mL/min. An accumulation of dead algae covered the leak area. To examine the clay seal this sediment was fanned away from the leak area using a paddle. This evidently moved some of the clay seal away because the leakage rate increased to 105 mL/min. However, after an additional 19 d the leakage rate had decreased to 0.7 mL/min. With only gravel for a substrate for the clay electrophoresis reduced the leakage by a factor of 1,600.

The power requirement for the electrophoresis never exceeded 500 mW. If additional leaks were present, more power would have been needed, but the worst case scenario is anticipated to take less than a few hundred watts.

CONCLUSIONS

The full-scale test and laboratory tests confirmed the practicality of using electrophoretic sealing in geomembrane liners. Electrophoresis attracted a remarkable amount of clay to the leaks in the geomembrane liner thereby sealing the leaks. Geotextile or other fine pore substrate placed under the geomembrane liner was found to help the sealing action. The clay penetrated the geotextile fabric under the liner, which provided a matrix to add strength to the seal. With geofabric under the leaks, the laboratory tests were successful in completely sealing even the largest leak tested, which was an elliptical leak with dimensions of 15 mm × 19 mm. With only geonet under the 8 × 10 mm elliptical leak, electrophoresis reduced the leakage rate by a factor of 1,667.

The full-scale test demonstrated that electrophoresis reduced the flow from a 10 mm diameter leak by a factor of 1,600 with gravel under the liner. Applying the electrophoresis treatment was a straightforward process that required no special equipment. Treating a 2,500 m^2 impoundment required 2 person-d of labor. The cost for the bentonite and power supply was minor.

Only a small portion of the total clay is attracted to the leaks. Some agitation of the water such as natural wave action in an impoundment can stir the settled clay to put it into suspension again so more clay can be attracted to the leaks by the electrophoretic forces. In areas or periods with low wind speeds, mechanical stirring of the water may help. However, to be effective, stirring should be conducted cautiously, and only after the clay has completely settled. Maintaining the electrophoretic treatment can allow the leaks to be sealed further.

Strong concentrations of acids, alkalies, chlorides, and organics may deteriorate the sealing properties of clays. However, strong acids and alkalies are not usually stored in geomembrane lined impoundments. The electrophoretic leak sealing method will probably not be applicable to some impoundments such as salt brine impoundments and impoundments containing high concentrations of organics. For further full-scale applications, the effect of the chemical characteristics of the waste in the water should be evaluated in a laboratory-scale test prior to the application.

ACKNOWLEDGMENT

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

$\mathbf{dl}$ = incremental distance vector;
$\mathbf{E}$ = electric field vector;
$\mathbf{i}$ = current density vector;
K = $\rho/2\pi$;
r = distance from point current source;
ΔV = potential difference;
π = 3.14159 . . . ; and
ρ = resistivity of conducting medium.

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