Instrumentation of a Landfill Cover To Measure Depth of Frost Penetration

THOMAS F. ZIMMIE, HORACE K. MOO-YOUNG, WARREN A. HARRIS, AND TIMOTHY J. MYERS

Frost penetration is a major environmental concern in landfill design. Freezing and thawing cycles may cause deterioration of the liner or cap, affecting permeability. The depth of frost penetration into the paper sludge cap at the Hubbardston Landfill in Massachusetts was measured by using a frost measurement system. A thermistor probe measured the temperature at various depths. Although temperature measurements are important, soil resistivity measurements are required to accurately predict the freezing level, since soil resistivity increases greatly on freezing. A conductivity probe measured the half bridge voltage between conductivity rings and a ground rod. Data were collected in data loggers. The data collected during the winter of 1992–1993 showed that the frost level did not penetrate the paper sludge capping layer. Heavy snow cover throughout the winter decreased the depth of frost penetration by insulating the landfill. The high water content in the sludge also contributed to the lack of freezing. One-dimensional freezing tests were conducted on the paper sludge in the laboratory by using the frost measurement system. Freezing of the material did occur, since soil resistivity increased steadily as the temperature decreased. It was shown that subzero temperatures are required to freeze the paper sludge.

A major environmental problem today is waste disposal. Although several methods of solid waste disposal are available, the use of landfills is by far the most popular method of disposal. Impermeable hydraulic barriers, liners and caps, that generate leachate are integral parts of landfill design. Although regulatory requirements for the permeability of the hydraulic barrier vary from state to state, the most common maximum allowable value is 10^{-7} cm/sec, and compacted clay soils are commonly used as the cover material.

When clay is not locally available, the cost of using landfills is significantly increased. This has sparked interest in the use of unconventional material such as paper sludge as a substitute for the barrier protection layer. Paper sludges have been successfully used to cap landfills in Maine, Wisconsin, and Massachusetts (*1–3*).

A major concern in landfill design is the effect of freezing and thawing on the permeability of the hydraulic barrier. Numerous researchers have studied the effects of freezing and thawing on the permeabilities of compacted clays [Othman et al. (*4*) summarize those studies]. In general, freezing and thawing cycles cause an increase in the permeability of compacted clays of one to two orders of magnitude. In studying the effects of freeze-thaw cycles on a paper sludge, Zimmie et al. (*5*) obtained results for paper sludge similar to those obtained for compacted clay; that is, the permeability increased. However, unlike the compacted clays that show a greater increase in permeability at low effective stresses (two to three orders of magnitude), the paper sludge permeability increased about one order of magnitude, regardless of the effective stress. The better performance of the paper sludge may be due to the fibers in the sludge and the high compressibility of the sludge. Fibers give the sludge some ability to resist tension. There is a wide variety of paper sludges, and the observation on the role of fibers may be unique to the type of sludge tested. This is an area of future research.

Although there is a significant amount of data that support the detrimental effect of freezing and thawing cycles on impermeable clay and paper sludge layers, little information on the amount of frost penetration at landfills is available. However, frost action in soils has received considerable attention in the literature (*6–11*). In the study described here, instrumentation used to measure frost penetration was installed in the impermeable paper sludge layer at the Hubbardston Landfill in Massachusetts.

FROST ACTION IN SOILS

Most of the literature on frost heave action in soils pertains to highways, foundations, construction in permafrost, and chilled pipelines buried in unfrozen soils. Frost heaves are caused by the freezing of in situ pore water and by the flow of water to the freezing front. Pressure develops in the direction of crystal growth, which is determined by the direction of cooling. The active ice lens grows slightly behind the freezing front. The frozen fringe is the frozen soil between the active ice lens and the unfrozen soil that transports water to the active ice lens from the unfrozen soil. A suction gradient is responsible for the flow of water to the frozen soil. The pore water in fine-grained soils does not necessarily freeze at 0°C. In some clays, as much as 50 percent of the moisture may remain as a liquid at −2°C (*7,10,11*). The freezing temperature depends on pore size, water content, applied pressure, and solute concentration.

Extensive research has been conducted on the effects of applied pressure on frost heaves. Applied pressure inhibits frost heaves and affects the freezing temperature and permeability of the soil. When the rate of cooling is near zero, the freezing front attracts water as long as the applied load is less than the actual shutoff pressure in which no water flows to the ice lens (*11*). For all practical purposes, the shutoff pressure in fine-grained soils is quite high and would never be exceeded in landfill covers, which typically are subjected to low values of effective stress.

Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, N.Y. 12180.

Major factors controlling frost penetration in soils are soil thermal conductivity, volumetric heat, and latent heat. Thermal conductivity is the ratio of heat flow through a unit area under a unit gradient. Volumetric heat is the change in thermal energy in a unit volume of soil per unit change in temperature. It is derived from the specific heat, which is the change in thermal energy per unit weight per unit temperature change. Latent heat is the change in thermal energy in a unit volume of soil required to freeze or thaw the soil moisture at constant temperature. Sludges require more energy loss than typical soils to freeze pore water because of the high water contents of sludges. The latent heat of soil moisture controls frost penetration.

SOIL RESISTIVITY

In fine-grained material, the pore water does not necessarily freeze at 0°C. Liquid water at well below 0°C, in a supercooled crystalloidal condition, moves toward the frozen fringe to form ice lenses. Although temperature measurements are important, an accurate determination of the freezing level requires additional measurements, one possibility being soil resistivity. Soil resistivity increases greatly on freezing. The resistance of a material is defined as the voltage divided by the current and is proportional to resistivity. Good electrical conductors have low resistivities, and good insulators have high resistivities. Water is a good conductor of electricity, and ice is a good insulator of electricity. Before the pore water in the soil forms the active ice lens, the resistivity of the soil is low. As ice lenses form in the soil, resistivity increases.

INSTRUMENTATION EQUIPMENT

Hubbardston Landfill, located in Massachusetts, is a 1.6-hm^2 (4-acre) municipal waste disposal facility at which Erving paper mill sludge was used as the impermeable cover layer. Erving paper mill is conducting studies to measure the performance of its sludge that serves as the impermeable barrier in landfill covers. Two sets of the Geonor frost measurement system were installed in the Hubbardston Landfill in December 1992 to study the performance of the sludge as a cap material.

Sensor Installation

In initial tests conducted by the instrumentation supplier, the conductivity probes worked well in the paper sludge with 5.1 cm of space between the probe and the reference electrode. A spacing of up to 17.8 cm was found to be satisfactory. The reference electrode was used to make installation holes, thus minimizing the possibility of breaking the thermistor or conductivity probe during installation. A ground wire at the top of the conductivity probe was connected to the copper clamp on the reference electrode to complete the circuit.

Conductivity Probe

A conductivity probe measures the half bridge voltage between the given conductivity ring and a reference electrode when a 60-msec pulse is fed to the ring from a 2.5-V direct current (dc) source through a 10,000-Ω series resistor. The probe has a length of 79.6 cm and a diameter of 2.22 cm. The stainless steel (SS) reference electrode has a length of 94.5 cm and a diameter of 2.22 cm. Each conductivity probe has eight conductivity rings that are spaced 7.62 cm apart and that are located on the outside of a schedule 40 polyvinyl chloride (PVC) pipe. The sensors on the conductivity probe are assigned a number in a top-down way and are interleaved because of the nature of the multiplexing method (Figure 1). The top of the probe connects to the data acquisition cable, which relays the conductivity reading to the data acquisition system. For thawed paper sludge, a voltage of 0.3 to 0.5 V is typical, whereas for completely frozen material (zero liquid pore water), a voltage of about 2.5 V is common. The formation of ice lenses and subsequent freezing are indicated by a voltage increase.

In a dc excitation situation, galvanic potential is a common problem. Two techniques are used in this probe to minimize this effect: the rings and reference electrode are made of the same grade and lot of stainless steel, and the excitation pulse width is short, minimizing electromigration and other undesirable effects.

Thermistor Probe

Thermistor probes measure the temperature at various depths in the soil and consist of eight thermistors spaced 7.62 cm apart. The probe has a length of 79.6 cm. Omega copper-constantan thermistors are inside a schedule 40 PVC pipe with an outer diameter of 2.22 cm. The thermistor temperature range is between −75°C and 150°C. At the top of the thermistor, a data acquisition cable transmits the temperature readings to a data logger. An accurate correlation between temperature and conductivity readings occurs when the thermistors and conductivity rings are installed parallel to each other.

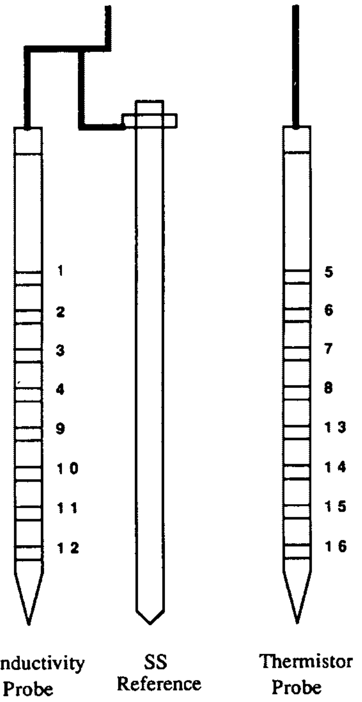

FIGURE 1 Geonor frost measurement system.

RST Data Loggers

R.S. Technical Instruments Ltd. (RST) built the data loggers and created the LE8200 Data Logger Software. The data logger (station) has three external ports: conductivity, thermistor, and data retrieval. Interface cables from the thermistor and conductivity probes connect to the data logger ports. Microprocessors collect and store the data. A 10,000-Ω series resistor located in the data logger feeds a 60-msec pulse to the conductivity rings.

Each data logger is capable of storing 32,000 bits. Each probe requires 16 bits per reading; hence, the data logger can store 1,000 readings overall. The data logger can be programmed to take readings in various modes. Typically, readings are obtained every 1 hr, and thus, 42 days of data can be stored.

Headers send preprogrammed control blocks to the data logger. The general function field allows selection of specific monitoring modes. Analogs are the monitoring modes that relate to signals, which can have a voltage of between 0 and 2.5 V. Accumulators are counter registers that keep track of the number of times a digital event has occurred. Further, a strobe is a signal that activates the station when it is in a standby mode. The strobe accumulator is a register that holds a count of the number of times a transition signal has occurred.

LABORATORY TEST CONDUCTED WITH FROST MEASUREMENT SYSTEM

Frost penetration tests on paper sludge were conducted in the laboratory by using the frost measurement system. A one-dimensional freezing test was conducted on an 84-cm-high sample compacted in a 92-cm-long and 31-cm-diameter PVC pipe. The initial water content and dry density of the sludge were 225 percent and 3.6 kN/m^3, respectively. The conductivity probe and ground rod were installed 7.6 cm apart and perpendicular to the surface, and the thermistor probe was installed near the center of the pipe and perpendicular to the surface. To achieve one-dimensional freezing, an insulation block was constructed around the pipe. Ten centimeters (4 in.) fiberglass insulation lined the wooden cabinet to simulate the PVC pipe. A warm-air line was placed at the bottom of the pipe to create a temperature gradient in the sample.

The sludge specimen was subjected to one-dimensional freezing for 20 days. Because of consolidation of the sludge, the first levels of the conductivity rings and thermistors were slightly above the final height of the sludge layer and were measuring the room temperature. The temperature of the second level dropped below 0°C after 1 day; however, the conductivity ring did not measure a voltage greater than 2.0 V. At the end of the test, the final temperature and voltage were −13.1°C and 1.96 V, respectively. When the test was ended, the conductivity rings' voltage readings were still increasing. Significant increases in voltage indicate that ice lenses were forming throughout the specimen. The final temperatures, voltage measurements, and water contents at the various levels of the specimen are given in Table 1, and Figures 2 and 3 show the voltage and temperature profiles, respectively, for each level.

The ranges in temperatures and voltages in the specimen indicate that one-dimensional freezing was achieved. The distribution of the final water content data reveals that the moisture was migrating to the freezing front. Very cold temperature and large amounts of heat loss are required to freeze the sludge because of its high water content. Freezing (the formation of ice lenses) of the paper sludge is indicated by an increase in voltage to 1.0 to 1.5 V and above and by a decrease in temperature. Levels 2–5 indicate that freezing is occurring at a pore water temperature below −5°C.

TABLE 1 Final Temperature, Voltage, and Water Content of Specimen in a Pipe Used for One-Dimensional Freezing

Level	Temperature (°C)	Voltage (V)	Water Content (%)
1[a]	-16.843	2.49	-----
2	-13.14	1.958	280
3	-10.665	1.911	272
4	-8.576	1.805	264
5	-6.632	1.327	254
6	-4.408	0.824	229
7	-2.457	0.484	206
8	-0.283	0.459	199

[a] Level 1 measured the room temperature.

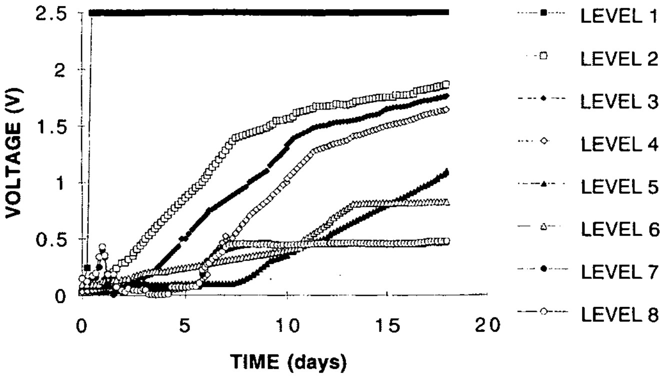

FIGURE 2 Voltage versus time profile for one-dimensional pipe freezing in the laboratory.

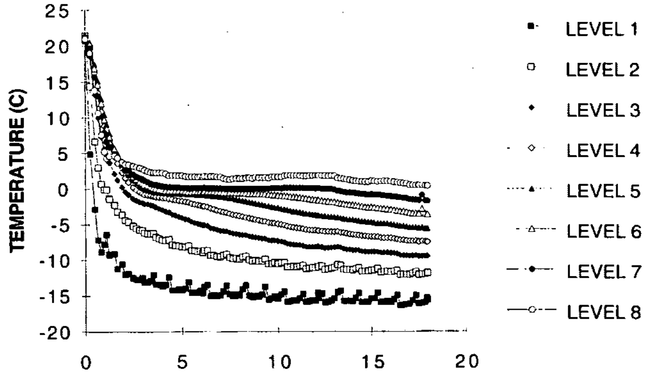

FIGURE 3 Temperature versus time profile for one-dimensional pipe freezing in the laboratory.

LANDFILL INSTRUMENTATION

Two sets of the frost measurement system were installed into the impermeable paper sludge layer at the northwest portion of the Hubbardston Landfill in December 1992. The impervious layer was overlaid with a 30.5-cm-thick topsoil layer and a 15.5-cm-thick drainage layer. The drainage layer has a permeability equal to or greater than 1 × 10^{-3} cm/sec. A frost chisel was used to remove the top 7.6 cm of frozen soil and to outline the site. The remaining soil was excavated, and the site was prepared for installation of the probes. An elevated concrete platform on which to place and store the data loggers was constructed. The frost measurement systems were placed 3.81 m to the north (Hole 1) and 3.86 m to the west (Hole 2) of the concrete pad.

Two guide holes were pierced into the sludge layer perpendicular to the surface and were spaced 7.62 cm apart on center. Electric ground rods were used to puncture the holes; two 1.9-cm-diameter water pipes were welded together to provide a guide for the two parallel holes. The conductivity and ground probes were placed into these holes. The holes were slightly smaller than the probes' diameters to allow a good soil-probe contact. A third hole for the thermistor was punctured perpendicular to the surface.

The probes were pushed by hand into the two holes made in the sludge, as shown in Figure 4. In Hole 1, the probes were placed 61 cm into the sludge. The vegetative support layer was 30.5 cm thick, the sand drainage layer was 20.3 cm thick, and the sludge layer was 76.2 cm thick (Figure 4). The top bands of the conductivity and thermistor probes were in the sand layer. In Hole 2, the probes were placed 74 cm into the sludge, which allowed all of the conductivity bands and thermistors to be contained in the sludge (Figure 4). The topsoil layer was 30.5 cm thick, the sand drainage layer was 15.2 cm thick, and the sludge layer was 76.2 cm thick.

Two trenches 7.6 cm deep were dug from the concrete pad to the holes containing the frost measurement system. The thermistor and conductivity data acquisition cables were placed in the trenches and were covered with topsoil. The data loggers were placed on top of the concrete pad [Figure 5(*top*)], and the instrumentation cables were connected to the data loggers through a hole in the middle of the concrete pad. The data loggers wee programmed to take readings every 1 hr.

To prevent vandalism and to protect the data loggers from the environment, half of a 208-L (55-gal) drum was placed over the data loggers and was secured to mounts constructed into the concrete pad with a lock [Figure 5(*bottom*)]. The sand and topsoil layers were carefully backfilled into both holes so that the instrumentation equipment was not disturbed.

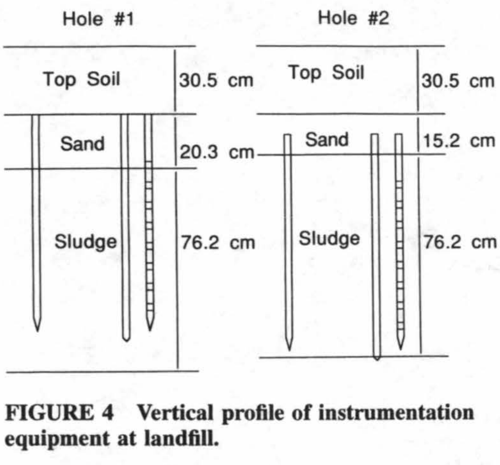

FIGURE 4 Vertical profile of instrumentation equipment at landfill.

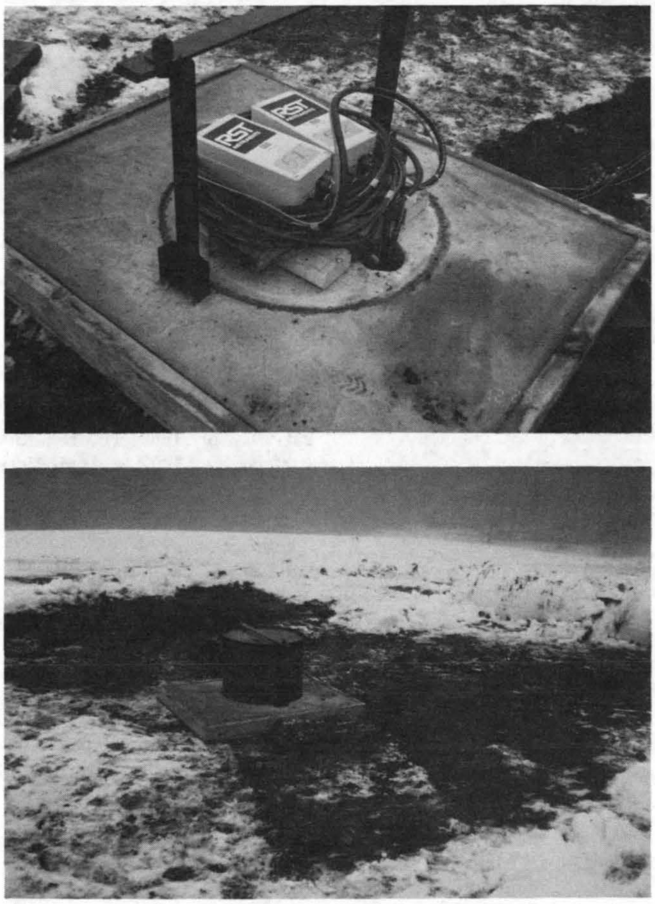

FIGURE 5 Concrete pad: *top*, with data loggers exposed; *bottom*, secured with a cover and lock.

INTERPRETATION OF FROST MEASUREMENT DATA

Data loggers were changed every month, and the data were reduced. Temperature and conductivity readings were plotted against time. For Hole 1, the first conductivity ring was in the sand drainage layer. From December 29, 1992, to February 5, 1993 (0 to 40 days), the temperature profile, as shown in Figure 6 for the top level of Hole 1, ranged from 1.9°C during installation to 0.1°C on February 5, and the voltage measured by the conductivity ring was between 0.2 and about 0.7 V. From February 5, 1993, to March 15, 1993 (40 to 78 days), there was a noticeable increase in the voltage reading and a decrease in temperature. The temperature in the sand drainage layer dropped to −0.5°C, and the voltage measurements were about 2.0 V. The increase in voltage to 2.0 V indicated that freezing occurred in the sand drainage layer. From March 15, 1993, to April 11, 1993 (78 to 102 days), the temperature measurements increased from about −0.5°C to 0.1°C, and the voltage measured by the conductivity rings decreased to 0.6 V. From April 11 to July, the temperature and con-

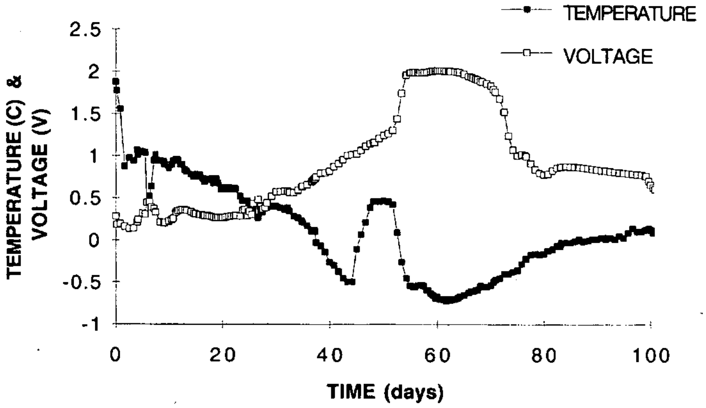

FIGURE 6 **Temperature and voltage measurements (top level, Hole 1, December 1992 to April 1993).**

ductivity measurements did not indicate frost penetration. Levels 2 to 8 in Hole 1 measured the voltage and temperature in the sludge layer. For Levels 2 to 8 from December to April, the temperature did not drop below the freezing point of water, and the voltage did not increase.

For Hole 2, all the conductivity rings and thermistors were installed in the sludge layer. For Level 1 of Hole 2 from December to February, the temperature measurements ranged from 2°C to about 0.5°C and the voltage measurements stayed constant at 0.1 V, as shown in Figure 7. From February to March, the temperature readings dropped below freezing to −1°C, but the voltage measurements stayed constant at 0.1 V. From March to April, the temperature increased to about 0.7°C and the voltage measurements stayed constant. For Levels 2 to 8, the temperature of the sludge did not fall below 0°C and the voltage remained constant. From the laboratory frost penetration tests, pore water temperatures below −5°C and increasing voltage measurements are the key indicators of freezing in paper sludge. Since the voltage did not increase even when the temperature decreased to −1°C, it can be inferred that the sludge layer did not freeze.

Heavy snow cover throughout the winter of 1992–1993 decreased the amount of frost penetration into the sludge layer. The snow created an insulation blanket over the landfill, reducing the depth of frost penetration. In analyzing the data for Hole 2 at Level 1, although the temperature dropped below 0°C, freezing cannot be inferred from the resistivity data.

The high water content might also have contributed to the lack of freezing. After 1 yr of in situ consolidation, the water content of the sludge at the Hubbardston Landfill ranged from 100 to 110 percent. For a typical sand, the in situ water content is about 10 to 15 percent, and for a clay, the in situ water content typically ranges from 20 to 30 percent. Significantly more energy loss is required to freeze the water in sludge than to freeze the water in a typical sand or clay. Another factor that may contribute to the lack of freezing is the applied stress on the sludge layer. Applied pressure affects the freezing temperatures and the permeabilities of clays. Since paper sludge consolidates considerably under a low effective stress, applied stresses may affect the freezing temperature and the permeability of paper sludge. This is an area for future research.

SUMMARY AND CONCLUSION

A frost measurement system was installed in the Hubbardston Landfill in Massachusetts to measure the depth of frost penetration into the sludge barrier protection layer. A thermistor probe measured the temperature at various depths, and a conductivity probe measured the half bridge voltage between a given conductivity ring and the ground probe.

For the winter of 1992–1993, the data collected from the thermistors and conductivity probes indicated that the frost level did

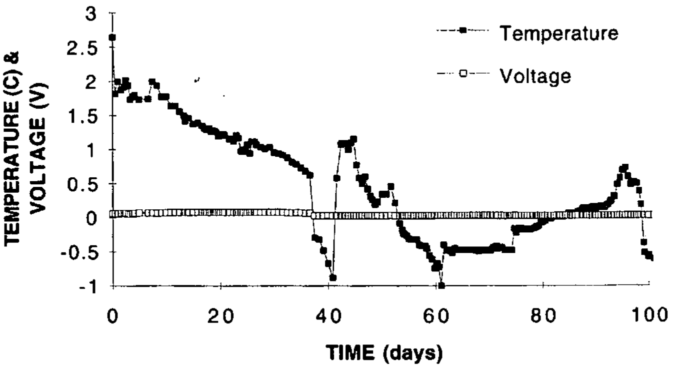

FIGURE 7 **Temperature and voltage measurements (top level, Hole 2, December 1992 to April 1993).**

not penetrate into the impermeable barrier layer. The paper sludge acted as an effective hydraulic barrier. Heavy snowfall throughout the winter covered the landfill and acted as an insulation blanket that reduced the depth of frost penetration. The high water content of paper sludge also contributed to the lack of freezing. Lower temperatures and more energy loss are required to freeze the pore water in paper sludge than to freeze the pore water in a typical sand or clay. For example, the data for Level 1 of Hole 1 indicated that freezing occurred in the sand drainage layer at a temperature of −0.5°C. Levels 2 to 5 of the one-dimensional freezing experiment indicated that freezing was occurring below −5°C. Thus, lower temperatures are required to freeze paper sludge.

Moreover, the applied stress on the sludge layer may have affected the freezing temperature and permeability of the paper sludge. The effects of applied stress on the freezing temperature and permeability of paper sludge as well as the effects of a high water content on frost penetration are areas in which further research is needed.

One-dimensional freezing tests on paper sludge were performed in the laboratory. Thermistor and conductivity probes were used to measure the temperature and voltage. The test was conducted for 20 days. The increase in resistivity indicated that ice lenses were forming and that freezing was occurring. Sludge temperature increased with depth as the sludge resistivity decreased with depth. Final water content data indicated that there was a great deal of upward moisture migration to the freezing front. Because of high water contents, cold temperatures are required to freeze paper sludge. Levels 2 to 5 indicated that the paper sludge was freezing below −5°C. The laboratory tests indicate that sub-0°C pore water temperatures are needed to freeze paper sludge in situ.

ACKNOWLEDGMENT

Funds for the research described here were provided by the Erving Paper Company, Erving, Mass., the Environmental Protection Agency, and the National Science Foundation. Their generous support and cooperation are greatly appreciated.

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