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Response of landfill clay liners to extended periods of freezing

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Abstract

This paper presents the results of a physical model study of the performance of landfill clay cover liners subjected to extended freezing periods. Three proposed designs for a prototype cover liner were evaluated with a primary objective being the determination of frost penetration resulting from the sub-freezing temperatures imposed as an upper boundary condition to the model. The ultimate performance of the three liner designs were compared on the basis of frost penetration, leakage through the liner, and frost heave. The observed depth of frost penetration was compared to that predicted using a simplified analytical solution of the thermodynamic problem, in addition to measured field behavior.

The laboratory experiment utilizes a 1.8 m^2 tank, of ca 2.1 m depth. The tank is loaded with clay to the specifications required for landfill liners. Three different landfill cover liner designs were modeled in the experimental tank. The performance of the three designs, as measured by a variety of observations, were compared. Frost heave was measured for each design and was found to vary between 3.8 and 4.3 cm. The results indicate the depth of frost penetration was similar for all designs tested (29.2–31.7 cm), although the design which included a soil drainage layer had superior leakage performance.

Keywords: Freezing; Frost action; Frost heaving; Frozen ground; Landfills; Permeability; Thermal conductivity

1. Introduction

One of the primary mechanisms of landfill clay cover liner failure in cold regions is the freeze/thaw phenomena. This failure may include cracking, soil heaving, permeability increase and/or strength decrease. There have been many investigations of the soil/water processes involved in freeze/thaw. In 1929, one of the pioneers, Taber, reported that pressure increases are associated with freezing due to the growth of ice crystals and that excessive heaving is explained by the segregation of water as it freezes (Taber, 1929). Segregation of water on freezing causes shrinkage cracks below if the supply of water is limited or if the soil is very impermeable. Laboratory studies have cited increases in permeability of one to two orders of magnitude following freeze/thaw (Chamberlain and Gow, 1979; Chamberlain et al., 1990; Zimmie and LaPlante, 1990). The total effect is dependent on soil type, moisture content, freezing duration, and possibly, rate. Konrad (1989) found that freeze/thaw caused significant changes in the soil structure of a saturated clayey silt consolidated to

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various overconsolidation ratios. Jessberger (1980) investigated the mechanical failure of frozen soil and related this failure to the influence of the duration and temperature of the freezing condition. Penner (1986) studied the ice lensing phenomenon in layered soils and the impact of lensing on frost heaving. The heaving noted for fine-textured (clay) soils was much more significant than for coarse-textured (silt) soils. Such fine-textured soils are the type typically used in landfill cover liner construction. Landfill clay cover liner conditions are much different than those investigated in many of the previous freeze/thaw studies. The landfill problem is not represented well by a single cell of monolithic soil, as various soil layers are incorporated in a typical landfill cover liner. Moreover, many of the laboratory studies have been limited to small samples and are typically of the scale used in triaxial testing and permeability testing. Therefore, the applicability of the results to landfill cover liners can be questioned. The present investigation utilized large scale laboratory testing with the actual depth of a cover liner, layered soil profiles, and boundary conditions similar to those encountered in the landfill.

2. Background

When air temperatures are below freezing, frost penetrates the ground surface, causing the upward migration of soil moisture. A significant body of literature is available describing the mechanisms of moisture migration through frozen soil. Various theories attribute movement to a thermal gradient where capillary flow is in the direction from higher to lower temperatures, and to osmotic flow. Ferguson et al. (1964) reported that water moves to a frozen zone when water in the unfrozen zone is held at low tensions. However, the amount of movement may depend on the available soil/water, the temperatures of the frozen zone, the duration of freezing and the physical and chemical properties of the soil. The freezing effects on soil are primarily dependent on the soil's chemical and physical properties and moisture conditions as well as on the freezing rate. Chamberlain and Ayorinde (1991) studied the effects of freeze/thaw cycles on clay layers and the compaction requirements for minimizing the effect of freezing and thawing on permeability. They observed that freeze/thaw had an effect of increasing the permeability of compacted clay by a factor of two orders of magnitude or more. The actual effect was dependent on the type of clay and the initial condition of the clay sample. As part of their research, compaction criteria were developed to address the permeability changes. In general, the more densely compacted a soil, the less permeability change that occurs. Kim and Daniel (1992) also report on the effects of freezing on hydraulic conductivity of compacted clay. In that research, the focus was on the influence of freeze/thaw for soils of varying moisture content and the subsequent change of soil structure. As in previous studies, the hydraulic conductivity was shown to increase for all soil samples after freezing and thawing. Benson and Othman (1993) report that freezing and thawing affects the structure and hydraulic conductivity of compacted clay both on laboratory samples and in the field. When they froze the clay at a rate of 0.3 h, the reported increase in hydraulic conductivity was in the range of one order of magnitude or more. Benson and Othman (1993) also studied the development of cracks associated with the freeze/thaw phenomena.

As revealed in this literature review, there is wide consensus that cyclic freezing and thawing can be detrimental in numerous ways to the integrity of any soil structure, especially fine-textured (clay) soils. This has lead to serious concern regarding the integrity of landfill covers constructed with clay soil. Cover liner design guidelines (e.g. US EPA, 1991) have recently included freeze/thaw as an area of focus. Most standards stipulate a minimum thickness and depth of cover liner to accommodate the possible action of freeze/thaw. This thickness criteria is expected to allow for some degradation of the upper portions of the cover liner, while ensuring that a portion of the cover liner is beyond the influence of freeze/thaw. However, there has been only very limited research into the depth of frost propagation into cover liners. Most guidelines rely on frost penetration data and prediction methods used in the construction industry, such as the US Department of

Commerce Weather Bureau data (Jumikis, 1966). This source suggest the depth of frost penetration in the Detroit area is 127 cm (55″). Typical construction projects, such as the placement of buried pipelines and foundation design utilize such data. However, frost penetration through cover liners at landfills may be quite different than observed in other fields of the construction industry. In fact, measured frost penetration depths at a landfill site maintained by City Management Corporation (CMC) in southeastern Michigan registered a maximum depth of frost penetration of 32 cm (Song, 1992), significantly less than the published depth of frost penetration (127 cm). This variation may be attributed to the soil layers and elevated temperatures at the lower boundary of the landfill cover system (i.e. decomposing waste). Benson et al. (1995) measured similar depths of frost penetration (maximum depth of 45 cm) at a site in the midwestern USA.

Thermodynamic numerical simulations and analytical methods can be used to estimate the depth of frost penetration in soil. Analytical methods generally rely on the freezing index as a necessary input parameter. The freezing index is the sum of the degree-days of frost for a given period and is usually evaluated from the mean daily temperature. The present research provides a study of the utility of the analytic approach to prediction of frost penetration in landfill cover liners, while also indicating changes in gross performance measures attributed to frost penetration.

3. Experimental design

3.1. Experimental tank

The experimental tank consists of two structural components; a steel frame and Plexiglas walls. The steel frame supports the Plexiglas walls that are insulated with 5.1 cm of styrofoam and 15.2 cm of fiberglass (*R*-value 22). The tank has a surface dimension of 0.76 m × 2.4 m, and a depth of ca 2.1 m. Tank space is reserved for the temperature controlled regions at the upper and lower boundaries of the tank. The tank is used to simulate closed system freezing, meaning there is not access to a continuous water supply during the freezing process. The details of the experimental tank are shown in Fig. 1.

3.2. Liner designs

Three different cover liner configurations were investigated. These designs were selected jointly by CMC and the research team. The three designs are indicated in Fig. 2(a–c). Design No. 1 corresponds to the most simplistic cover system, while design No. 2 includes a protective barrier layer between the topsoil and clay. Design No. 3 involves the most complex system of layering and includes a lateral drainage layer above the clay liner to limit fluid pressures above the clay.

3.3. Thermodynamic conditions

The simulations were required to reproduce thermodynamic conditions at a central location within the cover, that is, near the crown of the cell. At a central location, the heat flux is primarily in a vertical direction. Therefore, the outer boundaries of the test cell were insulated to provide a "no-flow" thermodynamic condition. The upper boundary condition was reflective of a severe Michigan winter, providing a worst case analysis. Although the objective was to maintain a temperature of -12.1°C in the air space above the cover liner, it fluctuated slightly over time. The lower boundary condition was an applied temperature of ca 20.9°C, approximating temperature measurements at the liner/waste interface of landfills operated by CMC in metropolitan Detroit, MI (USA) (Lee, 1994). Older landfills, with a reduced level of biological activity, would exhibit a lower waste temperature, increasing the predicted depth of frost penetration. Thermocouples manufactured by Yellow Springs Instruments Company, YSI Series 701, were located at three different sites within the clear space above the cover liner to assess the uniformity of temperatures within this space. Additional thermocouples were used to monitor the temperatures along a vertical cross-section within the cover liner (Fig. 2).

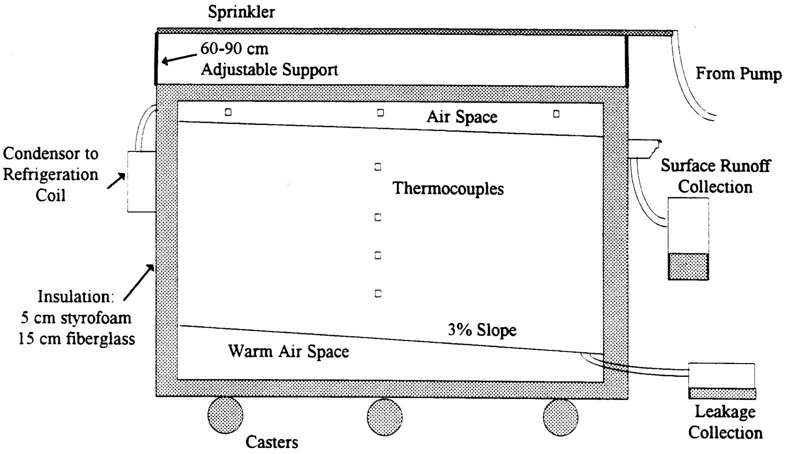

Fig. 1. Insulated tank for freeze/thaw investigations.

3.4. *Rainfall simulations*

The primary function of a landfill cover liner is to limit the influx of atmospheric and surface moisture to the deposited waste. Influx through the cover liner is termed "leakage" while the resulting liquid in the landfill is termed "leachate". Minimization of leakage generally leads to the minimization of leachate, and hence a reduction in groundwater contamination potential. One of the objectives of this project was the determination of the change in leakage through the clay cover liner attributed to freeze/thaw degradation of the cover system. This required the simulation of rainfall, and the measurement of the resulting surface runoff and leakage. A double length of perforated PVC pipe, as shown in the schematic of Fig. 1, was used to apply the simulated rainfall. A submersible pump provides the energy to pass the water through this system, at a preset application rate. The remainder of the design details are presented in Fig. 1.

4. Materials and placement

4.1. *Materials*

All soils were obtained from borrow areas maintained for clay liner construction at landfills operated by CMC in southeastern Michigan. The mineralogical compositions of the clay, silt and sand fractions were determined by X-ray diffraction analysis with a Rigaku (Danvers, MA) RU200 rotating anode powder diffractometer with monochromatic Cu Kα X-radiation, after pretreatment to remove soluble salts, carbonates, organic matter and Fe oxides (Kunze, 1965). The clay fraction of the cover liner material was predominately illite (64%), with approximately equal amounts of kaolinite and chlorite (10%). The remainder was comprised of smaller quantities of quartz, hornblende, microcline and plagioclase. The clay liner was also characterized in terms of the soil-to-water hydraulic conductivity using ASTM standard D 5084-90 (ASTM, 1994a), resulting in a value of 10^{-8} cm s^{-1}. The optimum moisture content was ca 13%, with a maximum dry density of 1928 kg m^{-3}, as determined following ASTM standard D 698-91 (ASTM, 1994b). Analysis of the particle size distribution (ASTM, 1994c) resulted in a Unified Soil Classification of CL-ML.

4.2. *Compaction*

Compaction of the clay lifts was accomplished external to the tank, in a 1.2 m by 0.76 m wooden tray of 0.152 m height. Compaction utilized a power hammer with a 0.09 m^2 head. The average thickness of each compacted lift was 10.1 cm. Moisture content and density determinations were made for each of the six lifts placed in the tanks.

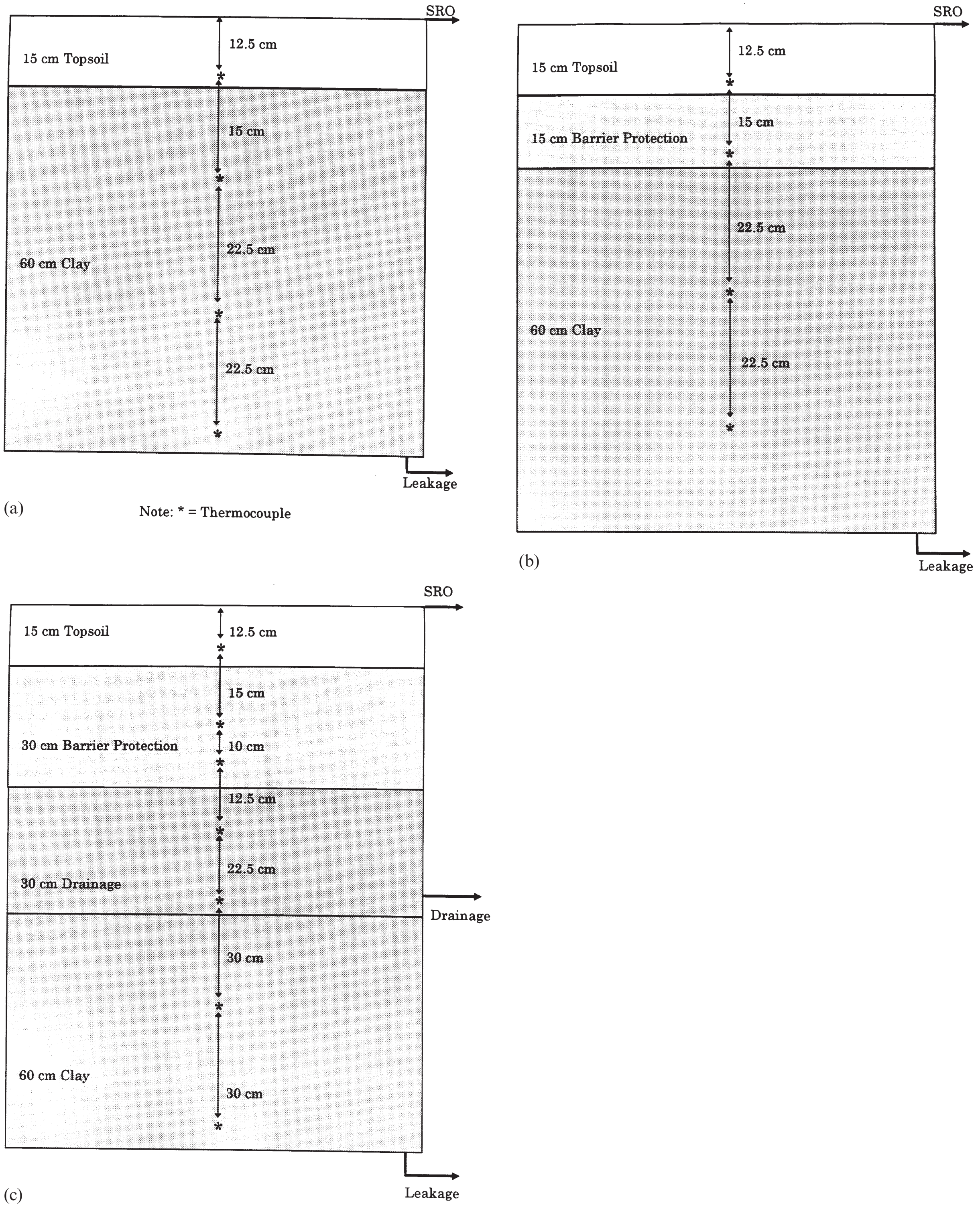

Fig. 2. (a) Design No. 1 for cover liner simulations. (b) Design No. 2 for cover liner simulations. (c) Design No. 3 for cover liner simulations.

The density exceeded the 90% modified Proctor density (ASTM, 1994b), at moisture contents slightly greater than optimum. The final moisture contents at the conclusion of each experiment were sampled to provide the necessary data for a water balance, as provided in the following section.

5. Experimental results

The overall performance results for the three cover liners appears in Table 1. Detailed analysis of the experimental results in the areas of flow measurement and frost penetration appears in the following sections.

5.1. Flow measurement

Four rainfall events, separated by freeze/thaw cycles, were simulated for each of the three designs. Fig. 3(a–c) displays the time history of rainfall inputs and leakage outputs for each of the designs. In this application, leakage is defined as the amount of fluid collected in the leakage collection system at the base of the tank (Fig. 1). At a prototype landfill, this leakage would mix with the waste deposited in the landfill, emerging as potentially hazardous leachate. The leakage performance is defined as the percentage of available inflow that exits the system as leakage. The available inflow is the value of the applied rainfall less the surface runoff, representing the moisture available to migrate through the cover liner. Surface runoff was measured using the collection system shown in Fig. 2. Designs Nos 1 and 2 were very similar in regards to the leakage performance (ca 19% for both cases) while design No. 3 had significantly less leakage (ca 3%). This suggests the drainage layer included in design No. 3 was very effective in removing potential leakage from the system before it had an opportunity to migrate through the clay. It may also be true that the clay liner of design No. 3 was more effective at "holding-up" the leakage because the frost had not propagated into the clay layer of this design.

Other elements of the system water balance shown in Table 1 include evaporation, drainage, moisture increase and excess moisture. Evaporation was determined by measuring condensation on the refrigeration coil external to the tank. Drainage was measured as the lateral outflow from the drainage layer of design No. 3 (Fig. 2). A second collection system, similar to the surface runoff collection system of Fig. 2, was included to provide this measurement. Moisture increase represents the difference in moisture retained by the clay cover liner before and after the simulation. A positive value indicates that the overall moisture content of the cover liner increased during the simulation.

Table 1
Performance based comparison of three clay cover liner designs

Characteristic	Cover liner No.		
	1	2	3
Average air temperature (°C) during freezing cycle	−11.6	−12.6	−13.0
Depth of frost penetration (cm)	29.0	31.0	32.0
Frost penetration into clay (cm)	13.9	1.2	0.0
Frost heave (cm)	4.4	3.8	3.8
Water balance (l)			
Rainfall	1490.0	1131.7	1234.9
Surface runoff	1107.5	760.5	904.0
Leakage	75.5	71.4	8.5
Evaporation	26.3	38.5	36.9
Drainage	—	—	62.2
Moisture increase (1)	262.0	255.8	193.3
Excess moisture (1)	18.7	5.5	30.0
Leakage performance (%)	19.7	19.2	2.6

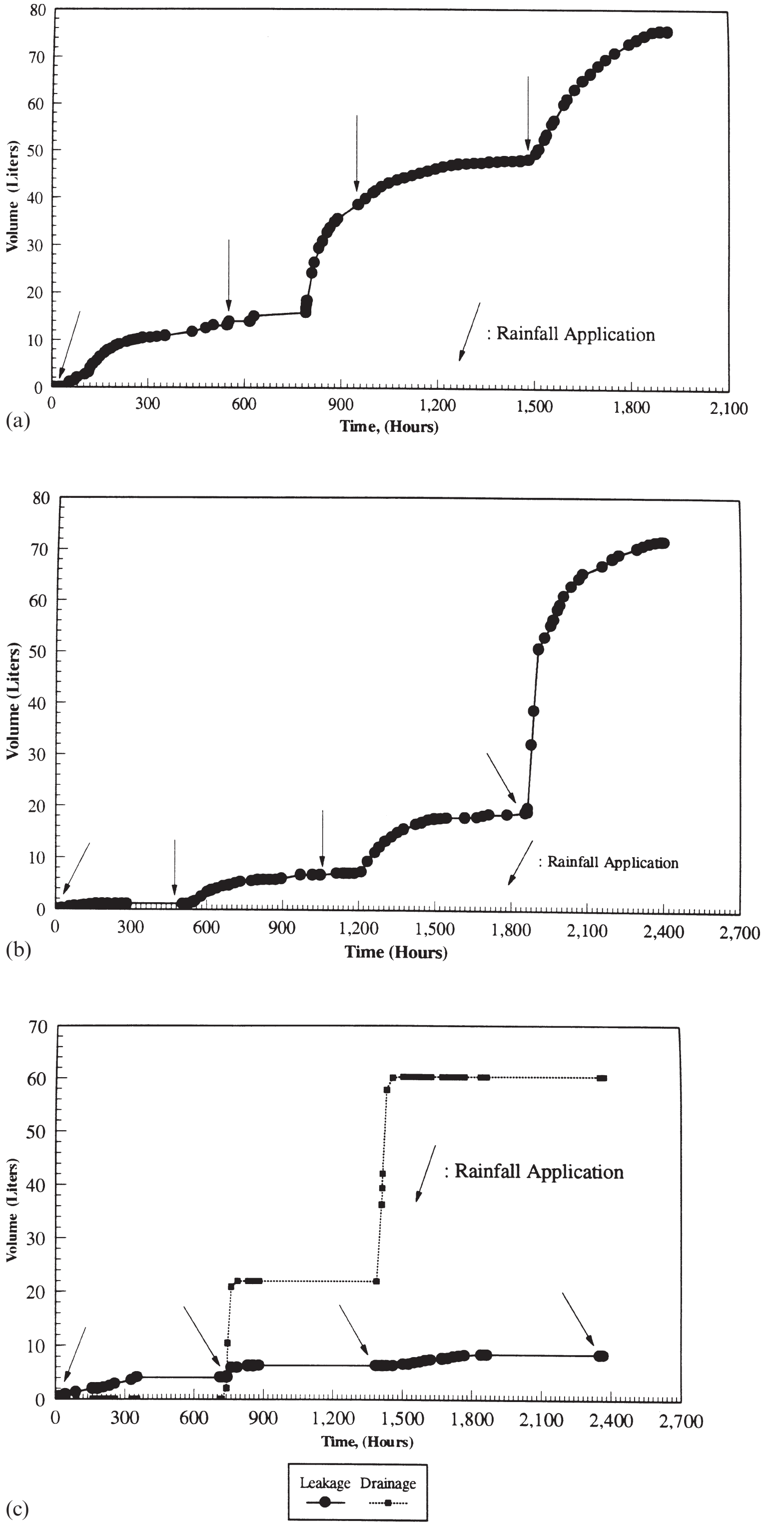

Fig. 3. (a) Measured leakage through the clay liner for design No. 1. (b) Measured Leakage through the Clay Liner for design No. 2. (c) Measured drainage above the clay liner and leakage through the clay liner for design No. 3.

One measure of the experimental error associated with the flow portion of the study is the unaccounted moisture (termed excess moisture in Table 1) from the water balance. This moisture can be determined as:

Rainfall–Surface Runoff–Leakage–Evaporation

–Drainage–Moisture Increase

The percentage error, calculated as the percent of rainfall unaccounted in the water balance, varies between 0.50 and 2.43% for the three cover liner simulations. The unaccounted moisture is a relatively small fraction of the total incoming precipitation, indicating close control of the flux measurements.

5.2. *Frost penetration*

A primary focus of this project was evaluation of the depth of frost penetration resulting from continuous freezing periods. Fig. 4(a–c) displays the temperature history for each of the three designs. The thermocouple locations for each design were indicated earlier, in Fig. 2. The depth of frost penetration recorded in Table 1 can be determined for each design by evaluation of the depth of the lowest probe registering freezing conditions.

The average air temperature maintained for each design was similar. Design No. 3 was run at the coolest average freezing period temperature, −13.0°C. The depth of frost penetration was similar for all designs, ca 30 cm. This resulted in freezing of a portion of the clay liner of designs Nos 1 and 2. However, the freezing zone was not able to penetrate the clay liner of design No. 3, due to the additional depth of cover materials used in design No. 3 [Fig. 2(c)].

The temperature profile for each of the three designs is nearly linear, as shown at the selected times of Fig. 5(a–c). The profile associated with design No. 3, which has the most complex layering of soil types, deviates most significantly from a linear variation. This deviation can be attributed to the change in thermal conductivity in moving from layer to layer.

The frost penetration observations of this investigation can be compared to previous research, both analytical and field-based. One analytical technique frequently used for the prediction of frost penetration is the Stefan equation (Jumikis, 1966). However, because it is an analytical technique, it requires significant assumptions be made that render it much less applicable for the cover liner problem. One such assumption, of a semi-infinite domain, limits the allowable boundary temperatures to one. Therefore, the only thermodynamic control that enters the problem is air temperature at the landfill surface. For the landfill problem, the temperature at the interface between the cover soils and the waste may be vastly different (typically warmer) than the temperature in the atmosphere. Therefore, one would expect the Stefan formula to overpredict the depth of frost penetration. An application of Stefan's formula under design No. 1 conditions results in a frost penetration depth of 53 cm (Miller and Lee, 1997), as opposed to the 29 cm observed experimentally. This comparison supports the hypothesis that the Stefan formula, and other analytical solutions based on similar assumptions, are conservative approaches.

Benson et al. (1995) reported on the results of a field investigation designed to evaluate the effectiveness of a newly developed geosynthetic insulation product. The site of the investigation was a landfill in metropolitan Detroit, USA, with winter temperatures similar to those simulated in the present experimental study. As part of their investigation they measured the depth of frost penetration in both insulated and non-insulated zones of a simulated cover liner of fine-textured soil. The maximum depth of frost penetration measured was 45 cm. This is significantly greater than the values measured in the present experimental investigation, likely due to the absence of the liner/waste interface. Therefore, their set-up did not simulate the thermodynamic control afforded by decomposing waste beneath the cover liner.

In field measurements at an instrumented landfill cross-section, the CMC investigation (Song, 1992) reported a maximum depth of frost penetration of ca 32 cm for an average daily air temperature of −25.3°C for a duration of ca 30 days. The cover

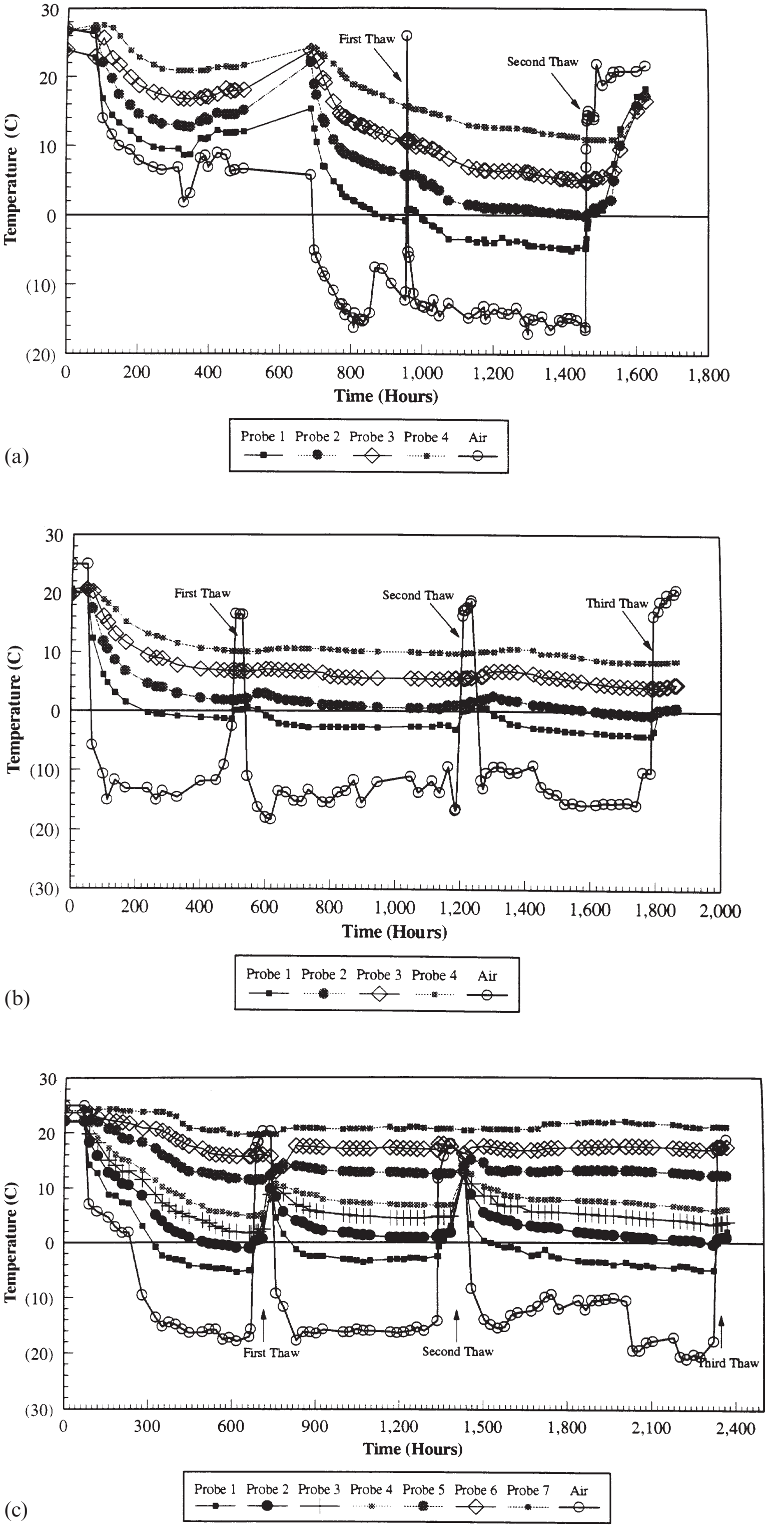

Fig. 4. (a) Soil temperature history for design No. 1. (b) Soil temperature history for design No. 2. (c) Soil temperature history for design No. 3.

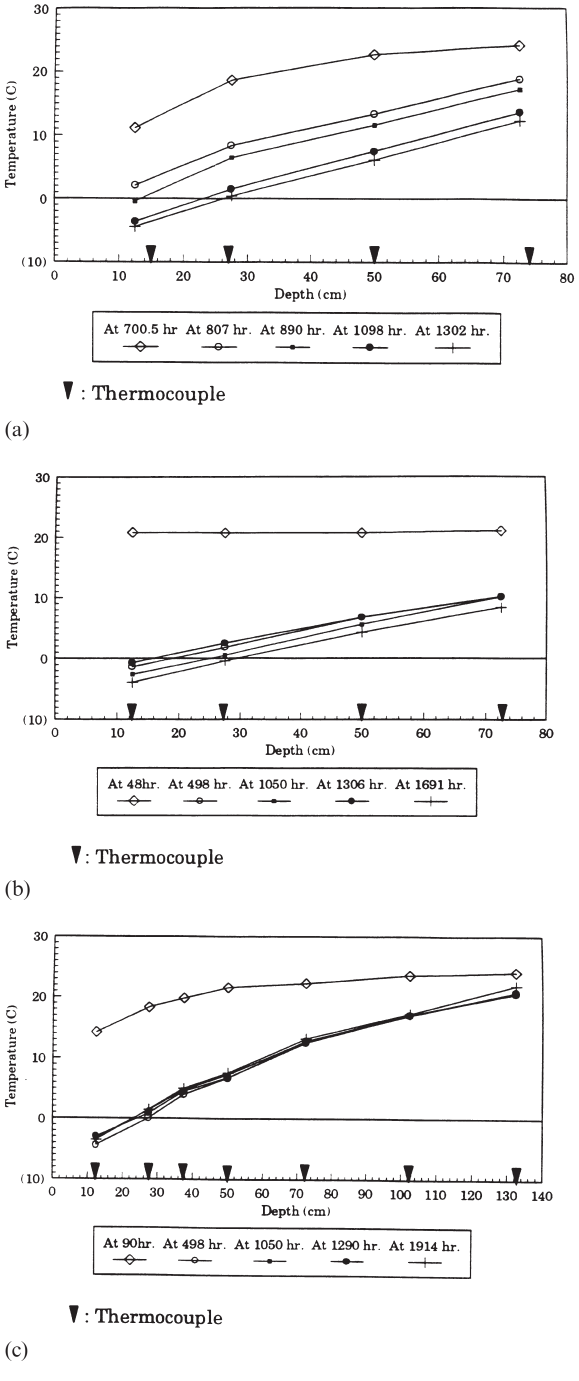

Fig. 5. (a) Soil temperature profile for design No. 1. (b) Soil temperature profile for design no. 2. (c) Soil temperature profile for design No. 3.

liner was similar to that of design No. 1. The field measured frost penetration depth is comparable to measurements of the present study.

5.3. Frost heave

Several locations of frost heave appeared with corresponding disruption of the surface. The magnitude of frost heave varied between 3.8 and 4.4 cm as shown in Table 1. Design No. 1, with the clay material closest to the ground surface, registered the greatest frost heave. This finding supports the theory that frost heave is more significant in fine-textured soils. The observed frost heave was highly variable over the cover liner surface, with some regions experiencing negligible heave. This may reflect the inherent difficulty in achieving uniform placement conditions (density and moisture content) throughout the cover liner. The observed locations of frost heave appeared to remain unchanged following multiple cycles of freeze/thaw. In landfill cover liner applications, the primary concern associated with frost heave of this magnitude relates to the increase in permeability associated with frost heave. It is expected that infiltration to the waste will be greatest at locations of the cover liner affected by frost heave. The drainage system of this experimental set-up did not allow isolation of the portion of flow through the heaved region. However, the observations indicate that the damage due to frost heave is limited to the upper 5 cm of the clay liner. The total depth of the compacted clay liner in this experimental simulation, as well as at many landfill facilities, is on the order of 60 cm. Therefore, an extensive buffer of non-damaged clay remains between the surface of the liner and the base of the liner. There is not expected to be an immediately discernable correspondence between rainfall and leakage observed at the base of the liner, due to this buffer. However, over a period of many years and numerous freeze/thaw cycles, the moisture will make its way to lower regions of the liner, increasing the depth associated with frost heave damage. Subsequently, there is expected to be noticeable increases of leakage at the base of the liner due to fluid migration through the damaged portion of the liner.

6. Conclusions

It was the purpose of the research described herein to provide a comparative analysis of three different landfill cover liner designs. The primary basis for the comparison is the frost penetration characteristics of the liners. Therefore, the average air temperature maintained for each design was similar. Although the depth of frost penetration was similar for all designs tested, the freezing zone never propagated into the clay of Design No. 3 because of its depth. It appears that even had the test been performed for a much greater period of time, the clay would have remained unfrozen, with a steady state condition having been achieved. Table 1 provides a performance-based comparison of the three liner designs.

An additional objective of this research was to evaluate the correspondence between observed frost penetration depths with those predicted analytically and those measured in the field. The frost penetration observations of the experimental set-up were found to correspond closely to measurements at local field sites. However, the analytical model used in the study significantly underpredicted the depth of frost penetration. It is recommended that more sophisticated models that incorporate more features of the field problem (including a lower boundary condition that simulates the temperature of the decomposing waste) be used in future applications.

The magnitude of frost heave measurements varied throughout the surface of each of the three liners, although the locations of maximum disruption for each liner recorded similar heaves — to the order of 4.0 cm. It did not appear that the frost heave affected the magnitude of leakage collected at the base the clay liner, suggesting that the damage was limited to surficial disruption that was buffered by the extensive clay depth associated with each liner design. However, it is expected that the presence of multiple freeze/thaw cycles over many years would impact the measured leakage, with the damaged liner regions acting as high permeability conduits for by-pass flow.

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