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Freeze-Thaw Effects and Gas Permeability of Utility Line Backfill

ABSTRACT: Backfill materials used in utility trenches must maintain physical and mechanical integrity when subjected to the seasonal effects of freezing and thawing. Materials used over gas utility lines must also have adequate permeability to allow any leaking gas to flow upward and out.

To help determine how soils and flowable fills might perform as backfill over utility lines, we conducted laboratory tests to measure the permeability of backfill materials before freezing, during freezing, and after thawing. The two materials investigated in this study were a silty sand, and a flowable fill made with Type F fly ash. Our work also examined the susceptibility of these materials to frost heave and thaw weakening.

An apparatus and standard test method for performing permeability during freezing and after subsequent thawing did not exist. We developed a method by adapting the ASTM Standard Test Method for Frost Heave and Thaw Weakening Susceptibility of Soils (D 5918) and the ASTM Standard Test Method for Measurement of Pneumatic Permeability of Partially Saturated Porous Materials by Flowing Air (D 6539).

Although more data are needed to confirm specific conclusions determined from this study, the test method developed here appears to be useful for evaluating the effects of freeze-thaw on backfill materials for utility trenches. Additional work is needed to demonstrate whether these laboratory results correspond to actual field conditions.

KEYWORDS: fly ash, gas permeability, freeze-thaw, utility lines, backfill, controlled low-strength material (CLSM), flowable fill

Background and Objectives

The objectives of this experimental program were to evaluate the freeze-thaw weakening and frost heave of backfills typically used as utility trench backfill, and to determine changes in their gas permeability during the freezing process.

The backfill material must maintain physical and mechanical integrity when subjected to the seasonal effects of freezing and thawing. For use over gas utility pipes, backfill must also have adequate permeability to minimize uncontrolled lateral flow of gas and to permit leaking gas to flow upward and out of the trench so that leaks can be located quickly.

The susceptibility of a soil to frost heave and freeze-thaw weakening can be evaluated in the laboratory using the ASTM Standard Test Method for Frost Heave and Thaw Weakening Susceptibility of Soils (D 5918). In this test, a soil specimen of 5.75-in. (14.6 cm) diameter and 6-in. (15.2 cm) height is subjected to two freeze-thaw cycles using specified temperatures and vertical heat flow. Temperature at points along the specimen height as well as vertical

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deformation of the specimen, are monitored over time. At the end of the second thawing cycle, the bearing strength of the specimen is evaluated by ASTM Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils (D 1883).

The effect of freeze-thaw cycles on the mechanical properties of flowable materials has not been well documented or studied. The ASTM Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666) has commonly been used to evaluate flowable fills; however, this method is an indirect measure of durability that is difficult to use in performance prediction. Some researchers have modified the ASTM C 666 method to attempt to better simulate actual field freezing conditions on flowable fill by forcing freezing and thawing to occur from the top only, and at a much slower rate than the one specified in ASTM C 666. Results using this test method on flowable fill have shown that the dynamic modulus of elasticity (E) declined with additional cycles of freezing and thawing (Gress 1996). Such loss of durability was mainly attributed to the excessive pore water pressure developed in the saturated samples during freezing (Gress 1996).

Unconfined compression tests on unsoaked specimens of flowable fill that had been subjected to various freeze-thaw cycles showed strength loss from freeze-thaw effects (Stewart 1999). However, Stewart concluded that the testing conditions did not realistically represent those experienced by flowable fill in the field.

For this study, we adopted ASTM D 5918 because it was developed specifically for soils used in pavement systems. The method consists of placing a surcharge weight on top of the specimen to simulate the overlying pavement. Cooling/heating plates on both the top and bottom of the specimen produce freezing and then thawing from the top of the specimen down. Specimens are subjected to two freeze-thaw cycles. The amount of heave and the penetration of frost into the specimen are measured. CBR, a common strength-index of roadway materials, is also measured without freeze-thaw and after the test to provide an indication of the degree to which freeze-thaw weakened the material.

Scope of Work

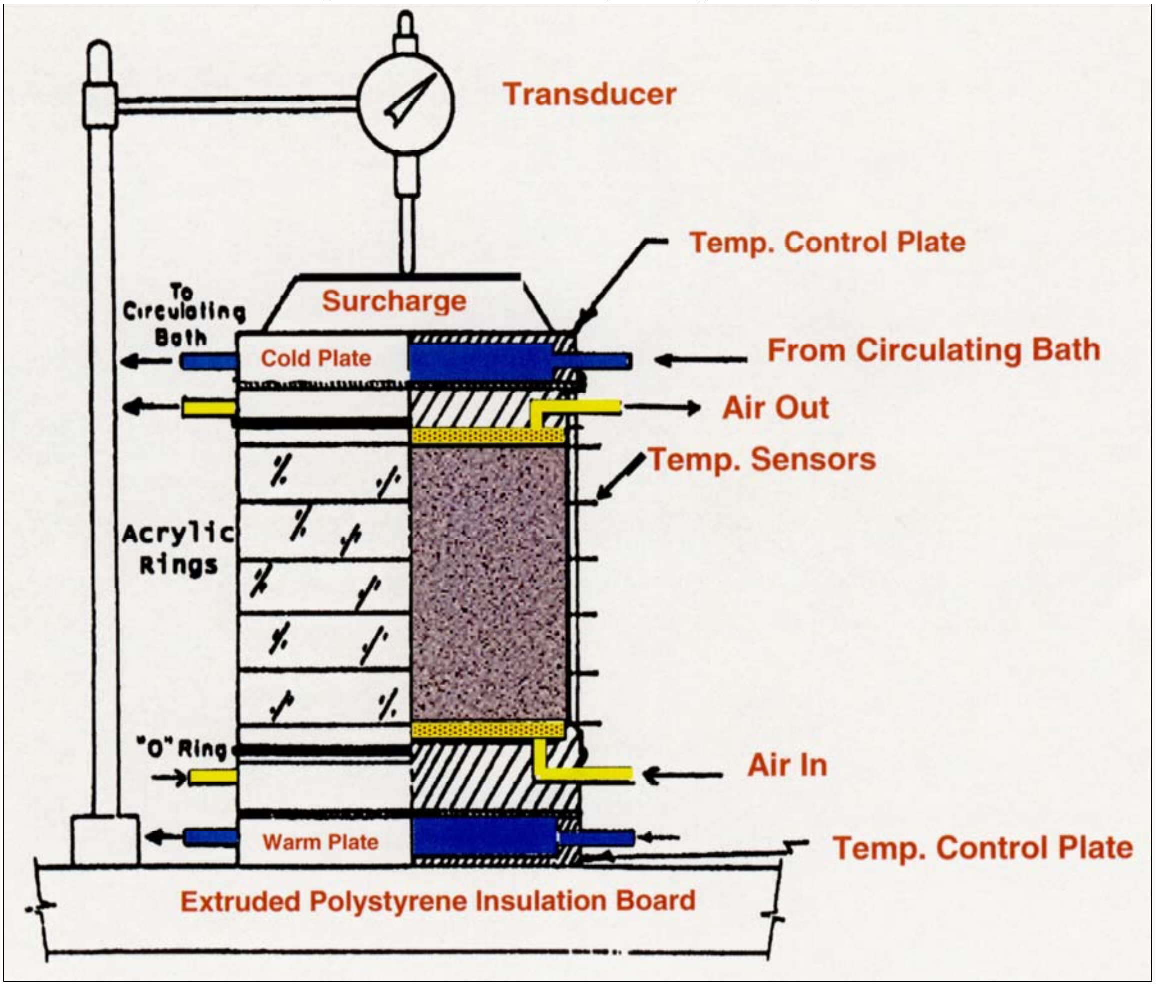
The materials selected for evaluation included a silty sand, and a flowable fill mix containing Type F fly ash. The silty sand is typical of indigenous soils that might be found in the New England area. The flowable fill was targeted to meet Massachusetts Highway Department (MHD) specifications.

In order to meet our objectives, we needed to subject the materials to freeze-thaw cycles while measuring gas permeability at specific times during the test. An apparatus and standard method for doing this did not exist. We developed a method by combining and adapting ASTM D 5918 and the ASTM Standard Test Method for Measurement of Pneumatic Permeability of Partially Saturated Porous Materials by Flowing Air (D 6539) into one method. ASTM D 5918 provides a comparative measure of frost heave and thaw weakening susceptibility of a material subjected to freeze-thaw cycles. Although, it does not predict specifically how a material will perform in the field, this method provides a basis for comparison as well as a classification of a material that can be used in pavement design methods. ASTM D 6539 was specifically developed to measure the coefficient of gas permeability for unsaturated porous media such as materials used as backfill in utility trenches.

In this study, permeability tests were conducted on the trench backfill materials at ambient temperatures (e.g., 20° C) prior to freeze-thaw cycling, at sub-zero temperatures (e.g., -5° C) during the freeze cycle, and at ambient temperatures (e.g., 20° C) after freeze-thaw cycling.

Test Apparatus

ASTM D 5918 uses a 5.75-in. (14.6 cm) inner-diameter, 6-in. (15.2 cm) high specimen encased with a rubber membrane that is surrounded by six 1-in. (2.54 cm) high acrylic rings (See Figure 1). Each acrylic ring contains a hole at its mid-height for insertion of a temperature probe. The top and bottom-most rings contain additional holes at the extreme top and bottom so probes can be placed at the ends of the specimen. A total of eight temperature probes are



(Figure adapted from ASTM D 5918)

FIGURE 1—*freeze-thaw test cell.*

positioned vertically from top to bottom of the specimen. Liquid silicone rubber is used to form an impermeable seal between the probes and rubber membrane. A porous metal plate is placed on the bottom of the specimen and another on the top. For cases where the specimen is to be tested in a saturated condition, one port on the bottom porous plate is connected to a water source (a Mariotte bottle). A heat transfer plate is placed outside of each porous plate. Each heat transfer plate is connected to a controlled temperature bath that circulates an ethylene-glycol-water mixture at specified temperatures. A 5.5-kg surcharge intended to simulate a 6-in. (15.2 cm) thick pavement is placed on the top plate. A displacement transducer is located directly on top of the surcharge weight. The entire sample cell is contained within a temperature control chamber that maintains the ambient air temperature around the cell to within 2° C. The entire cell within the temperature control chamber is surrounded by vermiculite to insulate the system. Data generated from the temperature probes and displacement transducer are recorded by GeoComp data loggers.

ASTM D 6539 describes a permeameter cell consisting of a set-up similar to the freeze/thaw apparatus. The specimen is encased in a rubber membrane with porous plates connected to the top and bottom of the sample. (See Figure 2.) Ports on the bottom plate lead to a desiccant tube, which vents to the atmosphere. The desiccant removes moisture from the gas before it enters the flow meter. Each plate has two directly opposing ports: one for gas flow, and the other for monitoring pressure. The cell required by ASTM D 5918 for freeze-thaw prevents application of a confining pressure. Consequently, applying positive gas pressure to create flow and measure permeability is not possible in the ASTM D 5918 test chamber. The positive internal gas pressure would separate the membrane from the specimen and produce short circuit flow of gas outside the specimen. However, the ASTM D 6539 test could be performed by using a vacuum to create a differential pressure in the specimen at less than atmospheric pressure. This presses the membrane tight against the specimen and prevents short circuit flow. The vacuum, equal to ($H\gamma_W$-P_a), is created in a large sealed reservoir with an adjustable Mariotte tube. The Mariotte bottle is connected to the top porous plate. The bottom is open to atmospheric pressure. The pressure difference of $H\gamma_W$ causes gas to flow upward through the sample and into the reservoir. Gas flow into the reservoir is automatically compensated by water flow out of the reservoir. The pressure difference stays constant. The displaced water from the reservoir is measured to determine gas flow rates. Different vacuums and thus gas flow rates are applied by adjusting the height of the tip of the Mariotte tube. Figure 3 shows the actual test cell. Figure 4 shows the complete gas permeability – freeze/thaw test apparatus.

Materials

The silty sand was selected because it is typical of indigenous soils that might be found in the New England area and therefor used as a trench backfill. Results from tests on this soil will be compared with results on the flowable fill mix to obtain a relative comparison of material performance. As shown in Table 1, the silty sand has properties that classify it as an AASHTO A-4 type soil.

The flowable fill mix was made with Type F fly ash, and designed to meet Massachusetts Highway Department specifications for a mix classified as 'Type 2E'. Table 2 summarizes the mix design and mix properties. Flowable fill samples were cured in a high humidity environment.

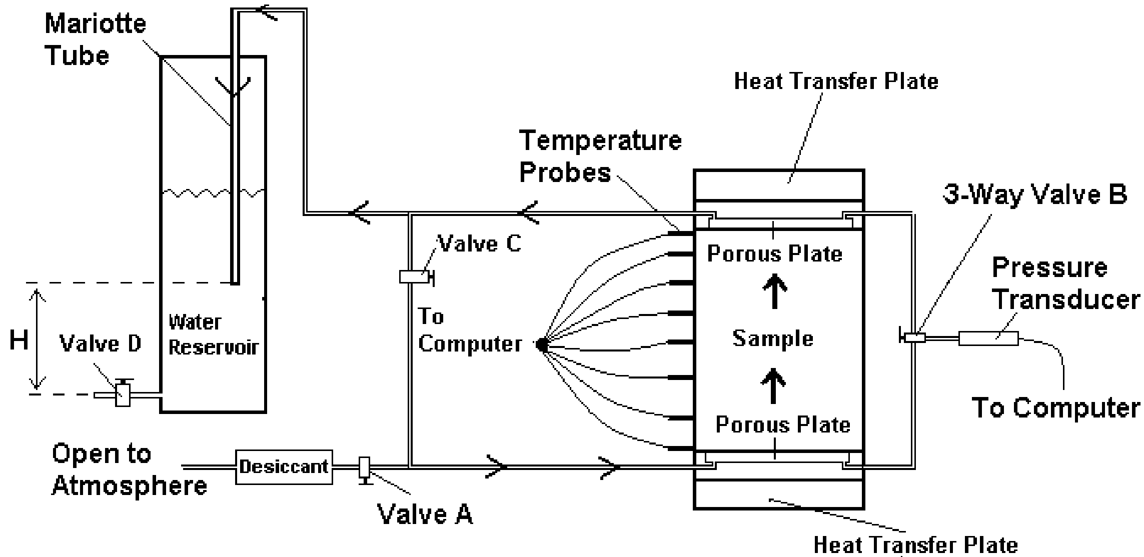


FIGURE 2—*schematic of freeze-thaw / gas permeability test apparatus*.

FIGURE 3—*actual freeze-thaw / gas permeability test cell.*

FIGURE 4—*entire freeze-thaw / gas permeability test apparatus.*

TABLE 1— *silty sand properties*.

Sieve Size / Parameter	Silty Sand (% Passing)	AASHTO A-4 Classification Criteria (% Passing)
3/8-inch (9.5 mm)	---	---
No. 4	100	---
No. 8	89	---
No. 10	---	---
No. 16	81	---
No. 20	---	---
No. 30	73	---
No. 40	---	---
No. 50	67	---
No. 60	---	---
No. 100	58	---
No. 200	47	36 minimum
Plasticity Index, %	Non-Plastic	10 maximum
Optimum Moisture, %	15.1	---
Max. Density, PCF (N/m^3)	114.2 (17.9)	---

TABLE 2—*fly ash flowable fill properties.*

Material / Property	Fly Ash Flowable Fill Mix lbs/yd^3 (kN/m^3)	MHD Type 1E & 2E Specification (M4.08.0)
Cement	56 (0.33)	---
Sand	2871 (16.71)	---
Water	510 (2.97)	---
Fly Ash	276 (1.61)	---
Entraining Agent, oz/yd^3	0	---
Air, %	0.6	---
Flow, inches (cm)	10.5 (26.7)	**9–14 (22.9-35.6)**
Unit Weight of Fresh Mix, pcf (kN/m^3)	145 (22.8)	---
Compressive Strength, psi (Pa):		
7-day	30 (207)	---
28-day	52 (359)	**30–80 (207-552)**
56-day	---	---
90-day	67 (462)	**30–100 (207-689)**
135-day	---	---

'---' = not measured or specified.

Test Specimen Preparation

A 6-in. (15.2 cm) inner-diameter steel mold was used for compaction of the silty sand. Prior to placing the soil in the mold, the six acrylic rings were placed inside the steel mold, with a rubber membrane placed on the inside of the rings. The soil was compacted inside the rubber membrane to the required density at the optimum moisture content. The resulting outer diameter of the compacted specimen was 5.75-in. (14.6 cm), with a height of 6-in. (15.2 cm). The steel mold was fabricated to split in half to allow it to be removed. The compacted specimen inside the acrylic rings and membrane was placed into the freeze-thaw/gas-permeability set-up.

The flowable fill mixture was poured into a 5.75-in. (14.6 cm) inner diameter mold, 6 in. (15.2 cm) high. This mold was constructed of a single, 5.75-in. (14.6 cm) inner-diameter, 6-in. (15.2 cm) high acrylic tube which had been split vertically on one side to allow for easy sample removal after curing. No rubber membrane was placed on the inside of the acrylic tube. The acrylic tube was placed on the inside of a standard plastic concrete mold that had also been split down one side and taped to hold the mold together during curing. After pouring fresh flowable fill mix into the mold, the material was allowed to cure for about 1 week in a high humidity chamber. Then the mold was removed and the sample was cured with all sides exposed to a high humidity environment. After the requisite amount of curing time (e.g., 28 days) the sample was tested for gas permeability and freeze-thaw.

Test Procedure

System Check

Prior to all permeability tests, a system check was run to insure a gastight (closed) system. (Please view Figure 2 for reference.) Valve C was opened, valve A was closed, and valve D was opened to allow water to flow from the reservoir. The water flowing out of the reservoir induced a vacuum to the system. Valve D was then closed and the pressure of the system was monitored at valve B. (Valve B is a 3-way valve allowing measurement of pressures at both the top and bottom of the specimen with one transducer.) If the pressure (vacuum) of the system stays constant over time, the system is considered gastight (closed).

Gas Permeability

For each specimen, data were collected at six different vacuum pressures. The different pressures were produced by varying the height of the Mariotte tube hence changing the head of water that gravity was acting upon. For each test, the pressure transducer offset was adjusted by current atmospheric pressure such that true pressure differences across the specimen could be determined. Permeability data were taken by closing valve C, opening valve A, and opening valve D to allow water to flow from the reservoir and induce a vacuum in the system. The vacuum in turn creates a pressure difference across the specimen that induces flow of gas through the specimen from bottom to top. Placing valve B in the up position allowed the monitoring of the pressure at the top of the sample. Once the pressure reached equilibrium, pressures were recorded at the top and bottom of the specimen. Concurrent with pressure readings, the volumetric flow rate was recorded by collecting the water displaced from the reservoir over a measured period of time. The weight of water was then converted to the corresponding volume of gas that had flowed through the specimen.

The pressure and flow data are used to calculate the volumetric flow rate (at average pressure and temperature) as follows:

$$Q_{AV} = (Q * P_B)/(P_I+P_B-(\Delta P/2)) \quad (1)$$

where,
Q_{AV} = Volumetric flow rate at average pressure and temperature, m^3/s
Q = Exit flow rate of gas, m^3/s
P_B = Barometric Pressure, Pascals
P_I = Specimen inlet gage pressure, Pascals
ΔP = Specimen Pressure Drop, Pascals

To satisfy Darcy's Law, the gas flow rate must be linearly related to the pressure difference across the specimen. ASTM D 6539 requires measured data fall within +/-25 % of the slope of a best-fit line passing through the origin. Due to the large differences in flow and ΔP, the data are plotted on a log-log plot (Figure 5).

The average gas permeability was then calculated in units of Darcy or square meters, as follows:

$$K_p = (Q_{AV} * \mu * L * 1.013 \times 10^{12})/(\Delta P * A) \quad (2)$$

where,
K_p= average gas permeability, Darcy or m^2
Q_{AV} = volumetric flow of gas through the specimen, m^3/s
ΔP = pressure difference across specimen, Pascals
L = specimen length, m
A = Specimen cross-sectional area, m^2
μ = viscosity of gas at test temperature, Pascal-seconds

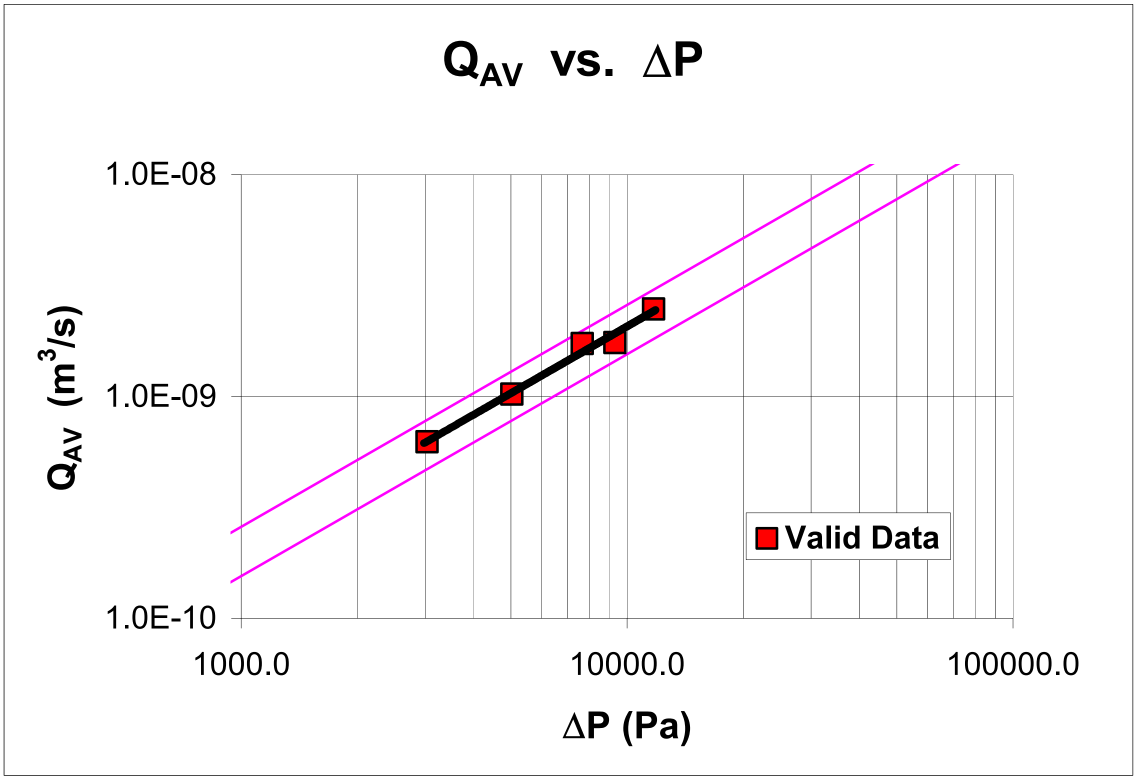


FIGURE 5—*log-log plot of volumetric flow rate vs. differential pressure.*

Testing Samples

Unsaturated Condition—Prior to initiating freeze-thaw, specimens were tested for gas permeability. After permeability testing, the freeze-thaw test was begun. The freeze-thaw test (ASTM D 5918) consists of cooling and warming the top and bottom heat transfer plates to the temperatures given in Table 3, while measuring frost penetration and heave of specimen. ASTM D 5918 requires the specimen be subjected to two freeze-thaw cycles. After approximately one-half hour into each freeze cycle, nucleation at the top of the specimen is initiated by tapping the surcharge weight. This prevents the water in the sample from super-cooling. The idea is to freeze the specimen from the top down, to realistically simulate field conditions.

TABLE 3—*boundary temperature conditions (from ASTM D 5918).*

Day	Elapsed Time (hours)	Top Plate Temperature (C)	Bottom Plate Temperature (C)	Comments
1	0	3	3	24-hr Conditioning
2	24	-3	3	First 8-hr freeze
	32	-12	0	Freeze to bottom
3	48	12	3	First thaw
	64	3	3	
4	72	-3	3	Second 8-hr freeze
	80	-12	0	Freeze to bottom
5	96	12	3	Second thaw
	112	3	3	
	120	Room	Room	End Test

Gas permeability was measured both in the frozen state at the end of the second freeze-cycle, and in the fully thawed state after the specimen had undergone the two freeze-thaw cycles. The displacement transducer, surcharge weight, and temperature probes, etc. were removed from the cell. The specimen was then tested for CBR to provide an index of strength. A surrogate sample that had not been subjected to freeze-thaw cycling was also tested for CBR. Specimens were not soaked prior to conducting CBR. After running CBR on the freeze-thaw specimen, moisture contents were determined for 1-in. (2.54 cm) thick slices of the specimen from top to bottom. An example of typical results is plotted in Figure 6. Assuming the moisture distribution through the specimen prior to freeze-thaw testing is constant (e.g., 15.1% for sample in Figure 6), this presentation provides an indication of moisture movement occurring as a result of freezing and thawing.

ASTM D 5918 suggests the amount of heave be plotted versus time and examined in conjunction with a plot of frost penetration (Figure 7). It is helpful to view the plots in conjunction with the boundary temperature settings of the cooling/heating plates (Table 3). The top plot shows that during the 24-hour conditioning period at 3° C there is no heave of the sample and the bottom plot shows that there is no frost penetration. However, once the top plate goes to negative 3° C, the sample heaves (top plot) and the frost penetrates the sample down to about 60-mm from the top (bottom plot). Once the top plate is set at negative 12-degrees, the frost penetration goes almost immediately through the entire 160-mm (6-in.) of the specimen (bottom plot), and the specimen heaves at a high rate up to a maximum height (top plot). When the top plate is then set at positive 12° C and the bottom plate it set at positive 3° C, the heave of the sample is almost immediately relaxed (top plot), and at about 48 hours the sample begins to thaw at both the top and bottom of the specimen (bottom plot). The specimen remains frozen at the middle of the specimen (~100 mm from the surface) until about 55 hours into the test (bottom plot). After about 20 hours of thawing, the second freeze cycle is initiated. According to ASTM D 5918, the heave rate from the second cycle, as well as CBR results after two freeze-thaw cycles are compared with the values in Table 4 to classify the materials' susceptibility to frost heave and thaw weakening.

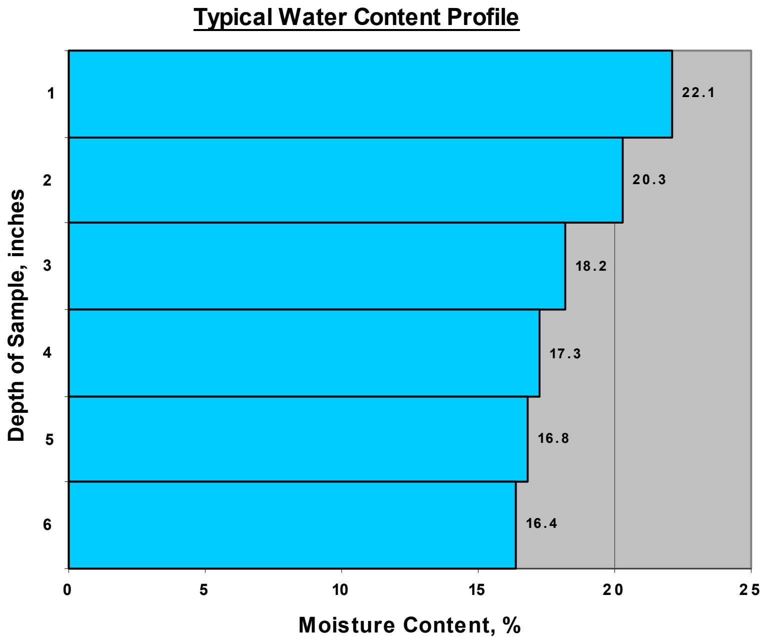


FIGURE 6—*typical water content profile of specimen after freeze-thaw cycling.*

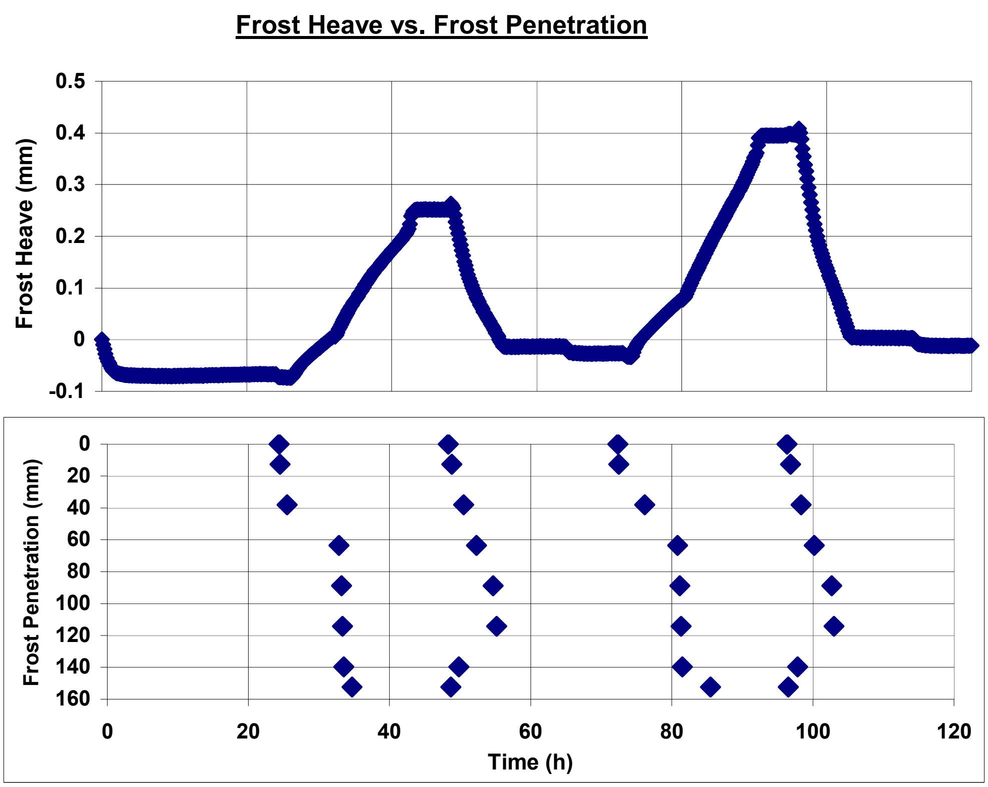


FIGURE 7—*frost heave vs. frost penetration over freeze-thaw cycles.*

TABLE 4—*ASTM D 5918 classification table for freeze-thaw results.*

Susceptibility Classification		Heave Rate mm/day	Thaw CBR %
negligible		<1	>20
very low		1-2	20-15
low		2-4	15-10
medium		4-8	10-5
high		8-16	5-2
very high		>16	<2

Saturated Condition—ASTM D 5918 suggests testing specimens in a saturated condition if the material is likely to be used in a high water-table area. Saturation of the specimen is accomplished by connecting the water outflow tube from the Mariotte bottle to one of the ports on the bottom porous plate (with the other port plugged). The water head is then raised at a rate of 25-mm per hour (by setting the Mariotte tube) until standing water is visible on the upper surface of the sample or until 8-hours have past. The water supply head is then lowered to the level of the upper surface of the specimen and held for 16 hours. Then the water supply is lowered to 10-mm above the bottom of the sample, and the upper porous plate is secured into place. The specimen is then subjected to the same freeze-thaw cycling described previously with the Mariotte water supply remaining in place and open to provide a continuous supply of water to the specimen.

When gas permeability tests were attempted on the specimens before and after freeze-thaw cycles, water flowed out of the specimens. This indicates essentially zero gas permeability.

In order to measure gas permeability of the sample when the saturated specimen is in the frozen state, the top and bottom porous plates must be carefully removed and dried. To avoid disrupting temperature probes and thus losing subsequent thaw data, the gas permeability was measured during an additional (third) freeze cycle.

Results and Discussion

Silty Sand

Results of the silty sand are shown in Table 5.

Heave Rate—Testing the silty sand under saturated conditions resulted in a doubling of the heave rate from unsaturated conditions.

Thaw Weakening—The unsaturated silty sand maintained its CBR-strength after freeze-thaw cycling. According to ASTM D 5918 (see Table 4), the thaw-weakening classification of this material was ‘very low’. For the sample tested under saturated conditions, there was a significant change in CBR resulting from freeze-thaw cycling. The CBR before freezing was 18% and after freezing and thawing was 1%. The thaw-weakening classification of this material in the saturated condition was subsequently ‘very high’.

Permeability—The permeability of the silty sand tested under unsaturated conditions increased one (1) order of magnitude from pre-freeze-thaw values when subjected to freezing temperatures. Once thawed, the permeability decreased to about ½ order of magnitude below the value prior to the freeze-thaw test. Silty sand tested under saturated conditions did not have measurable permeabilities.

TABLE 5—*freeze-thaw and gas permeability results for silty sand*.

Property	Silty Sand Unsaturated	Silty Sand Saturated
FROST HEAVE SUSCEPTIBILITY		
2nd Heave Rate (mm/day)	4.40	9.50
Frost Heave Susceptibility	Medium	High
THAW-WEAKENING SUSCEPTIBILITY		
CBR Before Freeze/Thaw (%)	11	18
CBR After Freeze/Thaw (%)	16	1
Thaw-Weakening Susceptibility	Very Low	Very High
GAS PERMEABILITY RESULTS:		
Pre-Freeze/Thaw (m^2)	1.5×10^{-14}	**
During Freeze/Thaw (m^2)	1.6×10^{-13}	***
Post-Freeze/Thaw (m^2)	6.4×10^{-15}	**

Notes:
**Sample became fully saturated through the entire height of sample. When gas permeability test was attempted, significant internal transport of pore water was induced such that water was drawn into the permeameter tubing.
***Flow was less than system capability.

Fly Ash Flowable Fill

Results of the fly ash flowable fill are shown in Table 6.

Heave Rate—The heave rate for the fly ash flowable fill was negligible for both saturated and unsaturated conditions.

Thaw Weakening—According to ASTM D 5918 (see Table 4), the fly ash flowable fill tested under unsaturated conditions is classified as having ‘negligible’ thaw-weakening susceptibility. Saturation lowered the CBR-strength by over a factor of two (from 40% to 17%) resulting in a thaw-weakening susceptibility classification of ‘very low’.

Permeability—Permeabilities of the fly ash mix tested in the unsaturated condition decreased about one (1) order of magnitude when subjected to sub-zero temperatures, but returned to original values once thawed. The fly ash mix tested at above freezing temperatures under saturated conditions did not have measurable permeabilities. However upon freezing, the permeability increased into the 10^{-15} m^2 range.

Conclusions and Recommendations

Although more data are needed to confirm specific conclusions from this study, the test method developed here appears to be useful for evaluating the performance of materials for backfilling utility trenches.

TABLE 6—*freeze-thaw and gas permeability results for fly ash flowable fill*.

Property	Fly Ash Flowable Fill Unsaturated	Fly Ash Flowable Fill Saturated
FROST HEAVE SUSCEPTIBILITY		
2nd Heave Rate (mm/day)	0.36	0.47
Frost Heave Susceptibility	Negligible	Negligible
THAW-WEAKENING SUSCEPTIBILITY		
CBR Before Freeze/Thaw (%)	42	23
CBR After Freeze/Thaw (%)	40	17^
Thaw-Weakening Susceptibility	Negligible	Very Low
GAS PERMEABILITY RESULTS:		
Pre-Freeze/Thaw (m^2)	6.4×10^{-16}	**
During Freeze/Thaw (m^2)	3.1×10^{-17}	9.2×10^{-16} ^^
Post-Freeze/Thaw (m^2)	7.7×10^{-16}	**

Notes:
**Sample became fully saturated through the entire height of sample. When gas permeability test was attempted, significant internal transport of pore water was induced such that water was drawn into the permeameter tubing.
^This is the CBR after three (3) freeze-thaw cycles.
^^Frozen gas permeability measured during a third freeze cycle.

For silty sands like AASHTO A-4 types and flowable fill mixtures containing fly ash, the degree of saturation appears to affect the amount of frost heave, thaw-weakening, and gas permeability. Subjecting these materials to a high water table or a significant level of moisture may result in increased heave rates, increased thaw weakening, and the flow of gas may be significantly limited during both freeze and thaw conditions. Other backfill materials (e.g., high fly ash content flowable fill, air entrained flowable fill, sandy soil, etc.) are currently being evaluated.

Additional work is needed to demonstrate how the laboratory results correspond to actual field conditions.

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