Effectiveness of rigid insulation for thermal protection of buried water pipes in rock trenches

Daigle, L.; Zhao, J. Q.

NRCC-43093

A version of this paper is published in / Une version de ce document se trouve dans :

CSCE 1999 Annual Conference - 1st Cold Regions Specialty Conference, June 2-5, 1999, pp. 389-398

Effectiveness of Rigid Insulation for Thermal Protection of Buried Water Pipes in Rock Trenches

Lyne Daigle, P.Eng. and Jack Q. Zhao, Ph.D., P.Eng.
Institute for Research in Construction, National Research Council of Canada

ABSTRACT

Laboratory tests were conducted to investigate the effect of latent heat on frost penetration in backfill specimens. Each specimen was prepared and placed in PVC moulds, which represent a rock trench. Rigid polystyrene insulation boards and expanded polystyrene beads were used in some specimens. The specimens were then subjected to a sudden temperature drop from 22 °C to –15 °C. The preliminary study showed that high moisture content backfill materials had a lower cooling rate and a longer time plateau around the freezing point than low moisture content ones because of the low thermal diffusivity and the release of latent heat. The use of polystyrene insulation actually promoted a faster frost penetration than without the insulation. The study shows that the rigid insulation was not effective in delaying frost advance to the centre of the specimens.

Keywords: latent heat, frost penetration, insulation, buried pipe, rock trench

Des essais en laboratoire ont été réalisés pour étudier les effets de la chaleur latente sur la pénétration du gel dans des matériaux de remblayage. Les échantillons ont été préparés et placés dans des moules de PVC, utilisés comme modèles de tranchée dans le roc. De l'isolant de polystyrène et des billes de polystyrène expansé étaient inclus dans certains échantillons. Tous les échantillons ont ensuite été soumis à une baisse de température brusque de 22 °C à –15 °C. Les résultats ont démontré que les matériaux à forte teneur en eau possédaient un taux de refroidissement plus faible et un plateau de plus longue durée aux alentours du point de congélation que les matériaux à faible teneur en eau, ceci étant causé par une plus faible diffusivité thermique et par le dégagement de chaleur latente. L'utilisation d'isolant de polystyrène a causé une pénétration plus rapide du gel comparativement aux essais sans isolant. L'étude démontre que l'utilisation d'isolant rigide n'a pas été efficace pour retarder la pénétration du gel au centre des échantillons.

Mots-clés : chaleur latente, pénétration du gel, conduites enfouies, tranchée dans le roc

1.0 INTRODUCTION

A water service pipe is used to carry water from the street main to the house. In many parts of Canada, these water service pipes may freeze during harsh cold winter months. A survey (McDonald et al. 1997) found that there were recurrent problems of frozen water service pipes facing Canadian municipalities, large or small. For instance, during the unseasonably cold and dry winter of 1993/1994, 4,900 frozen services were reported in Montreal, Quebec, 900 in Winnipeg, Manitoba, 450 in St. John's, Newfoundland and 450 in Peterborough, Ontario. A total of 2,745 frozen services during that severe cold winter cost the Region of Ottawa-Carleton approximately $2.2 million (Raymond et al. 1999).

The frozen water service pipe problem is a practical representation of transient conductive heat transfer in soils involving phase changes (referred to as solidification heat transfer). Determination of frost penetration (or phase-change position) for a semi-infinite region dated back to 1860 by Neumann (Lunardini, 1991). Exact analytical solutions, however, are found only for limited and simplified cases because of the non-homogeneity and non-linear thermal properties of the soil systems (Brown, 1964; Johnston, 1981; Lunardini, 1991). Other practical difficulties include varying ground moisture content from location to location, varying thickness of snow cover and the influence of adjacent structures. Johnston (1991) concluded that more elaborate calculations do not necessarily lead to more reliable results.

The depth and type of backfill materials, trench geometry and the type of native soils all play a role in frost penetration into the ground where the pipe is buried. Water service pipes are commonly installed in a rock trench and backfilled with granular materials where bedrock is close to the ground surface. Such installations are especially prone to freezing because of high thermal diffusivity and low moisture content of the natural rock. Current practice for thermal protection of the buried water service pipe includes use of rigid polystyrene insulation boards above and below, or wrapped around the pipe. However, recent numerical thermal studies for buried water pipe (Rajani et al., 1997; Zhao, 1998) indicate that the use of rigid insulation in rock trenches does not delay the advance of frost front to the pipe location. As a consequence, laboratory tests with common backfill materials were carried out to determine the effects of thermal diffusivity and latent heat on the effectiveness of rigid insulation as used in rock trenches.

2.0 GOVERNING HEAT TRANSFER EQUATIONS

A soil trench may be represented by a two-dimensional diagram as shown in Fig. 1. Not all water in the ground freezes at a single temperature (Tarnawski and Wagner, 1993; Lundardini, 1991; Johnston, 1981). Therefore, there is a freezing zone (or phase change zone) bounded by the freezing temperature (T_m) at which water in the soil starts to freeze and a temperature (T_f) at which all water is frozen. Ignoring the thermal effect from the

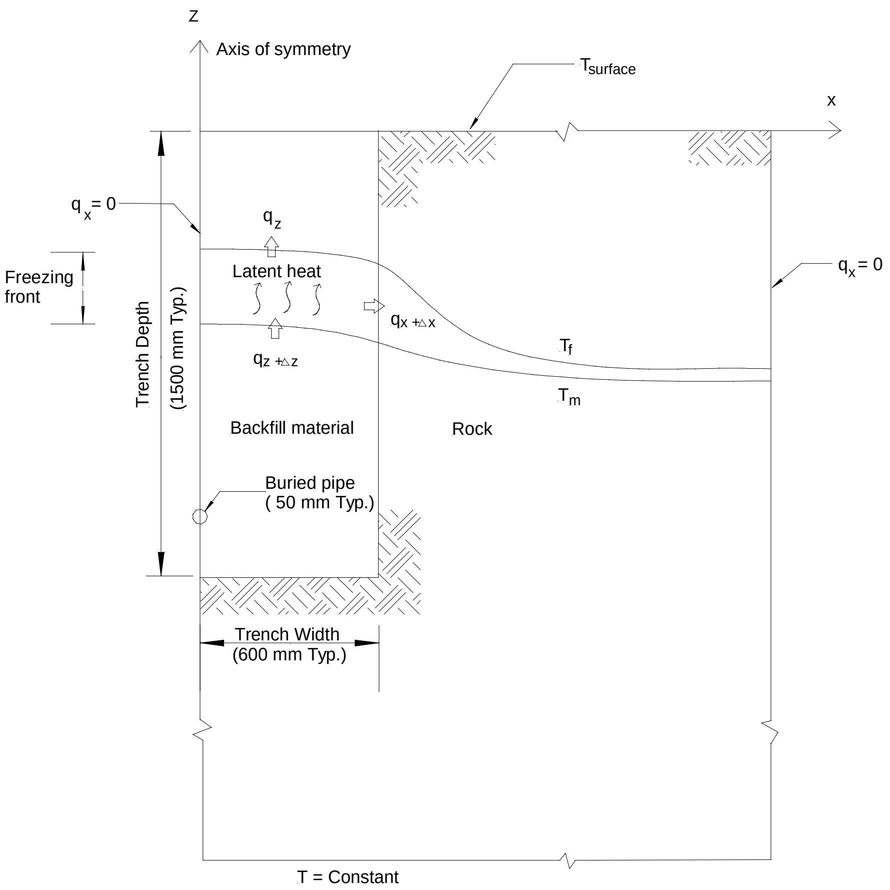

Figure 1. Schematic solidification heat transfer in and around a rock trench

small service pipe and the moisture (mass) transfer, the governing conductive heat transfer equation is:

[Eq. 1] $$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)-L(\gamma_d)\frac{\partial \xi}{\partial t}=\frac{\partial}{\partial t}(c\rho T)$$

where k_x is thermal conductivity in x-direction, k_z thermal conductivity in z-direction, L volumetric latent heat, γ_d = density of water, ξ = amount of unfrozen water, c mass specific heat, ρ density of soil, T temperature and t time. The latent heat term equals to zero for the frozen and unfrozen zones. The boundary conditions are:

$$q(0,z,t)=0 \qquad q(x_\infty,z,t)=0 \qquad T(x,0,t)=T_{surface}(t) \qquad T(x,z_\infty,t)=T_{cons\tan t}$$

Equation 1 shows that the latent heat effect is a function of unfrozen moisture content. If thermal properties of soil are assumed to be constant and homogeneous, Equation 1 then becomes:

[Eq. 2] $$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} - \frac{L(\gamma_d)}{k}\frac{\partial \xi}{\partial t} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

where $\alpha = \frac{k}{\rho c}$

and is commonly referred to as thermal diffusivity. It is a measure of the rate at which heat moves into or out of soil (Smith, 1996). Soil with high diffusivity cools (or heats) faster than one with low diffusivity. It is important to evaluate thermal diffusivity, not thermal conductivity alone, when dealing with protecting the buried pipe from freezing. The two-dimensional transient heat transfer problem represented by Equation 1 or 2 cannot be solved analytically for practical geometry and boundary conditions (e.g., transient ground surface temperature). Numerical and experimental methods are often used to obtain approximate solutions. In this study, the effectiveness of rigid insulation in a rock trench is assessed based on the laboratory tests described below.

3.0 LABORATORY TESTING

Test backfill materials were placed and compacted in polyvinyl chloride (PVC) moulds that were 200 mm in diameter (I.D.), 600 mm in height and 13 mm in wall thickness. A valve at the bottom of the moulds permitted drainage of the soil materials. Thermocouples were placed at mid-height, in the centre of the specimens and at the interior and exterior surfaces of the PVC moulds. Two configurations were considered – one without insulation and the other with rigid insulation boards immediately on top and bottom of the centre thermocouple (Fig. 2). One Granular ‘A’ specimen mixed with expanded polystyrene (EPS) beads was tested without additional rigid insulation boards. A mould filled with water was included in each test run as control (Table 1).

Test backfill materials included two samples of Leda clay from the Ottawa area, with and without polystyrene rigid insulation, Granular ‘A’ materials with and without insulation, and granular ‘A’ material mixed with EPS beads.

The specimens of Granular ‘A’ material with and without insulation were prepared to an optimum water content to obtain maximum compaction. They were compacted in the moulds and allowed to drain for 24 hours prior to the freezing cycle. The water contents of Granular ‘A’ samples with polystyrene insulation boards were higher than those without insulation because of the reduced area of drainage at the insulation boards. The specimens of Granular ‘A’ material mixed with EPS beads (2:1 volumetric ratio) were similarly prepared. Good compaction of the mix was difficult to obtain because of the buoyant property of the beads. The EPS beads, having an average diameter of 2 mm, have been used in lightweight concrete to improve its insulating properties (Baum, 1974).

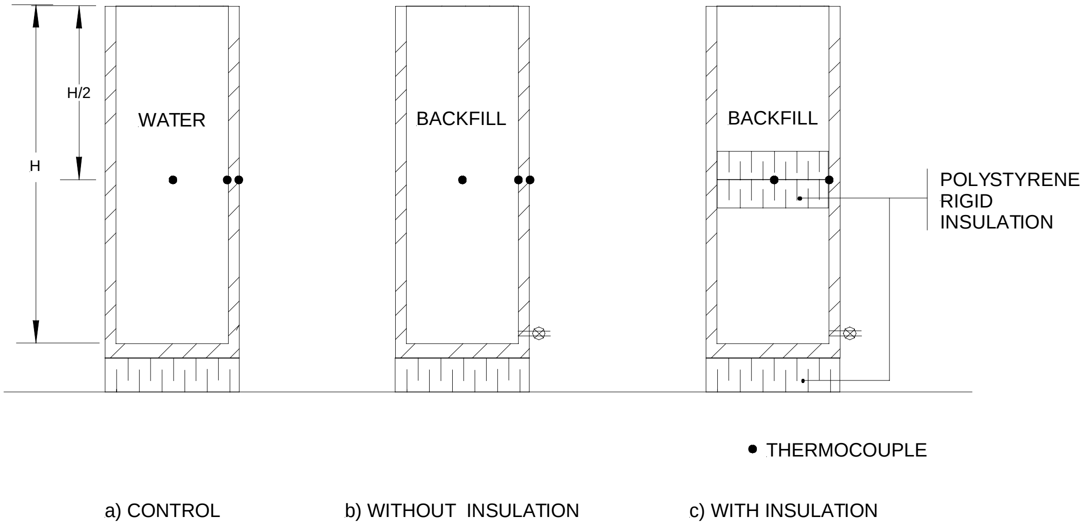

Figure 2. Test moulds and configurations

Table 1 Laboratory test specimens

Specimen #	Backfill materials	Thickness of insulation boards (mm)	Notes
1	Water	-	Control
2	Clay	-	Clay, 70 % MC
3	Clay	-	Clay, 40% MC
4	Clay	200	Clay, 39% MC
5	Granular ‘A’	-	Granular ‘A’, 3.5% MC
6	Granular ‘A’	100	Granular ‘A’, 7.5% MC
7	Granular ‘A’	200	Granular ‘A’, 6.5% MC
8	Granular ‘A’+ EPS beads	-	Granular ‘A’, 3.5% MC beads content: 1:2 (volume)

MC: moisture content. EPS: expanded polystyrene.

A total of 8 specimens were placed in a temperature-controlled room, and subjected to a sudden air temperature drop from 22 °C to –15 °C. Temperature from all thermocouples was read every 30 minutes until the temperature at the centre reached -15 °C. Specimen mixes and water content are listed in Table 1, whereas the typical thermal properties of these materials are shown in Table 2.

4.0 RESULTS AND DISCUSSIONS

Temperature vs. time curves measured by the centre thermocouples, along with the air temperature of the cold-room, are shown in Fig. 3 for clay specimens and in Fig. 4 for Granular ‘A’ specimens.

Table 2 Average thermal properties† of the test materials

Materials	Thermal conductivity, k (W/m-K)	Thermal diffusivity, α $(10^{-6}\ m^2/s)$	Mass specific heat, c (kJ/kg-K)	Latent heat, L (kJ/kg)	Density, ρ (kg/m^3)
Unfrozen					
Granular ‘A’	1.9	1.1	0.84	22.9	2091
Clay 40% MC	1.1	0.3	2.4	134	1960
Clay 80% MC	0.93	0.15	4.07	267	1519
Polystyrene insulation	0.036	1.16	1.0	0	30
Water (at 0 °C)	0.58	0.14	4.19	333.6	1000
Rock	4.0	2.20	0.7	0	2600
Frozen					
Granular ‘A’	2.4	1. 5	0.75	229	2091
Clay 40% MC	1.8	0.59	1.55	134	1960
Clay 80 % MC	1.8	0.49	2.4	267	1519
Polystyrene insulation	0.036	1.16	1.0	0	30
Ice (at 0 °C)	2.21	1.17	2.09	333.6	900

† - Values from Lunardini (1981), Smith (1996) and own laboratory testing.

Table 3 Time required to reach +2 and –2 °C

Specimen #	Initial cooling (22 °C to 2 °C)		Time required (hr)		Total time to freeze (22 °C to -2°C)
	Cooling rate, ΔT/Δt $(10^{-3}\ °C/s)$	Diffusivity, α $(10^{-6}\ m^2/s)$	From 22°C to 2 °C	From 2 °C to -2 °C	
1	0.78	0.14	7.1	56.4	63.5
2	0.69	0.15	8.1	37.4	41.5
3	0.65	0.3	8.5	25.5	34.0
4	1.98	-	2.8	3.3	6.1
5	1.21	1.1	4.6	6.0	10.6
6	1.92	-	2.9	1.9	4.8
7	3.97	-	1.4	0.9	2.3
8	1.26	-	4.4	5.2	9.6

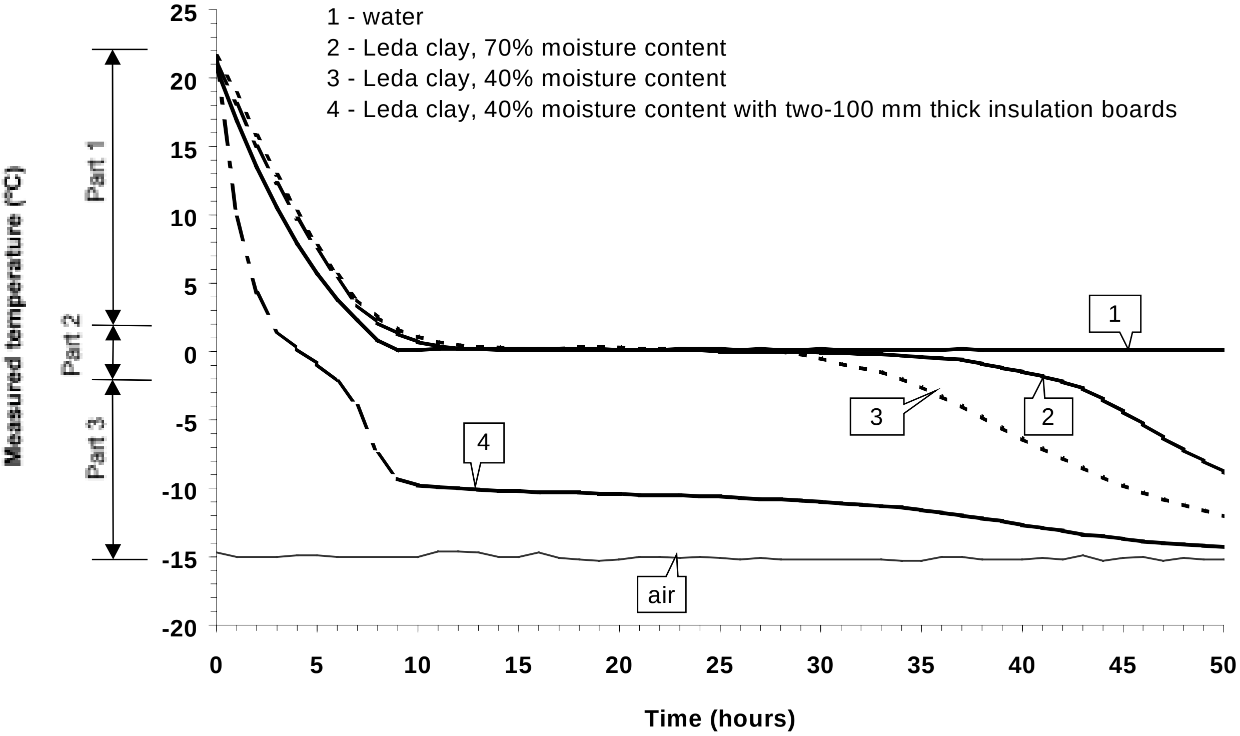

Figure 3. Freezing curves for Leda Clay specimens

The temperature curves can be divided into three distinctive parts for clay backfill materials with and without insulation and the water control specimens (1, 2, 3 and 8). The first part is the initial cooling which corresponds to the temperature range from 22 °C to 2 °C, the second part is the latent heat plateau which corresponds to the temperature range from 2 °C to -2 °C, and the third part is the frozen cooling stage which corresponds to the temperature range from -2 °C to –15 °C. The performance of different backfills is compared based on the first two parts of the temperature curves, i.e., the initial cooling and the latent heat plateau. The time for temperature change in the initial cooling is used to calculate the cooling rate and that in the latent heat plateau is used as a measure of latent heat effect (Table 3).

Different rates of cooling in unfrozen states were observed for Granular ‘A’ and clay specimens. The mechanism that governs heat transfer for this initial cooling stage is mainly heat conduction. The cooling rates of the clay specimens (specimens 2 and 3) with 40% and 70% moisture content but without insulation were 0.69 x 10^{-3} and 0.65 x 10^{-3} °C/s, which were comparable to that of the water specimen (0.78 x 10^{-3} °C/s). The cooling rate of the clay specimen (specimen 4) with 40% moisture content (MC) and 200 mm rigid insulation was 1.98 x 10^{-3}, an increase of 200% over the same clay specimen but without insulation. As a result, specimen 4 reached 2°C in 2.8 hours, whereas specimen 3 took 8.5 hours. However, the difference in moisture content did not seem to change the cooling rate of the non-insulated clay samples. The cooling rates of the Granular ‘A’ specimen without insulation (specimen 5) was 1.21 x 10^{-3} whereas those of the Granular ‘A’ specimen with

100 mm and 200 mm rigid insulation boards (specimens 6 and 7) were 1.92 x 10^{-3} and 3.97 x 10^{-3} °C/s, respectively. The use of EPS beads did not seem to reduce the cooling rate, based on a comparison of the performance of specimens 8 and 5.

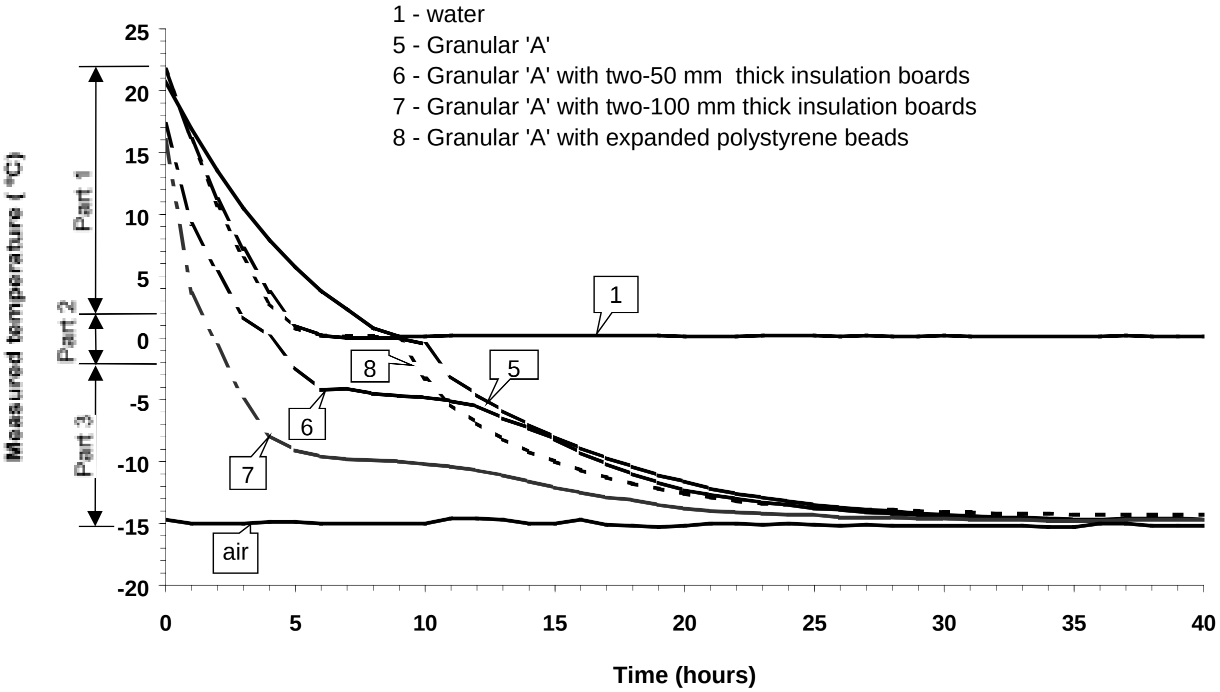

Figure 4. Freezing curve for Granular 'A' specimens

Thermal diffusivity is a measure of rate of temperature change. The cooling rates are comparable to the typical values of thermal diffusivity for three standard backfill materials and water (Table 3). Granular ‘A’ material having a higher thermal diffusivity, cools much faster than clay in the unfrozen state. The rate of cooling is also influenced by the latent heat effect. While the centre point of the specimen is still in the initial cooling stage, other points closer to the surface are experiencing phase change that is associated with the release of latent heat. Therefore, the frost penetration to the centre of the sample is slowed down. The difference in the cooling rate of the 40 % MC clay with two 100-mm thick polystyrene insulation boards and without insulation is due to two factors. First, the polystyrene insulation board has a higher thermal diffusivity than the clay (40% to 80% MC). Secondly, the board does not have the latent heat effect due to extremely low (or practically no) moisture content. Both factors promoted a faster frost penetration in the sample with the insulation material. The same explanation applies to Granular ‘A’ material. The rate of cooling increased as thicker insulation boards were used around the centre point of specimens 6 and 7.

The effect of latent heat is indicated by the length of the time during which temperature stays constant (Figs. 3 and 4). Using -2°C as the freezing temperature for ice formation inside a water pipe, the time required to reach this temperature is shown in Table 3 for all specimens. The clay specimens show that the higher the moisture content, the longer it takes to reach the freezing temperature. The time was reduced from 34 (specimen 3) to 6.1 (specimen 4) hours when a 100 mm thick rigid insulation board was placed directly on top and bottom of the thermocouple. For the Granular 'A' specimens, the reduction in time was 5.8 (time for specimen 5 minus that for specimen 6) and 8.3 (time for specimen 5 minus that for specimen 7) hours for two 50 mm thick and two 100 mm thick insulation boards used, respectively. Inclusion of the EPS beads reduced the time by about one hour (time for specimen 5 minus that for specimen 8). Figs. 3 and 4 also show that the latent heat effect seemed to take place at a temperature lower then the water freezing point for specimens with the rigid insulation (specimens 4, 6 and 7). This effect of latent heat at below freezing points would not help in preventing the water pipe from freezing. The latent heat effect has well been recognized but not quantified (Johnston, 1981; Sepehr and Goodrich, 1994; Lunardini, 1996; Rajani et al., 1997; Zhao, 1998). Although the configuration of a test specimen in the laboratory is not exactly the same as the field trench, similarities do exist. The specimens subjected to low air temperatures all around except at the bottom where a layer of insulation is placed, corresponds to the field rock trench where temperature in the surrounding rock is lower than in the trench backfill. Higher thermal conductivity and lower moisture content in the natural rock promotes faster frost penetration as indicated by a thermal diffusivity of 2.2 x10^{-6} m^2/s (1.1 x10^{-6} m^2/s for Granular 'A'). Frost advances both vertically downwards and horizontally from the sides of the rock trench, whereas frost advances both vertically downwards and radially inwards in the laboratory test specimens. While this difference is recognized, the laboratory test results are believed to provide information that is applicable to field rock trenches.

Effort has been made to model the solidification heat transfer problem with the finite element method. The model has been verified with the measured results from the water specimen. More numerical studies are under way to further quantify the effect of latent heat on the frost penetration in trenches.

5.0 SUMMARY AND CONCLUSIONS

Preliminary laboratory testing to determine the effect of latent heat was conducted with backfill specimens contained in PVC moulds. Three clay and four Granular 'A' specimens, including use of polystyrene insulation boards and expanded polystyrene beads, were tested along with a water specimen. The measured temperature data at the centre of the specimens show that use of the rigid insulation increased the cooling rate and promoted a faster frost penetration to the centre of the specimens. The cooling rate appears to increase with the increase in the thickness of rigid insulation. The results confirmed that latent heat has a big impact on the performance of the backfill materials in protecting the buried water pipe from freezing. Use of the rigid insulation seems to lower the effect of latent heat to below-freezing temperatures.

ACKNOWLEDGMENT

The authors would like to thank Dr. Balvant Rajani of the Institute for Research in Construction, the National Research Council Canada (NRC), for his comments and suggestions for the preparation of this paper. NRC provided funding and BASF CANADA Inc. in Montreal, PQ, donated the EPS beads used for this research.

REFERENCES

Baum, G. Styropor – concrete: technology, properties, and applications. BETON – Information, 5:58-67. 1974.

Brown, W.G. Difficulties associated with predicting depth of freeze or thaw. Canadian Geotechnical Journal, 1(4):215-226, 1964.

Raymond, D., Zhao J. Q., Scothorn, P., Rajani, B. B. and Daigle, L. A practical measure to prevent frozen water service lines – The Region of Ottawa-Carleton's experience. Prof. of the 27th CSCE Annual Conference, Hydrotechnical Engineering Specialty Conf., Canadian Society of Civil Engineering, Regina, SK. June 2-5, 1999.

Farouki, T.O. Thermal Properties of Soils, U.S. Army Cold Regions Research and Engineering Laboratory, CRREL, Monograph 81-1, 1981.

Johnston, G.H. Permafrost- Engineering Design and Construction. Associate Committee on Geotechnical Research, National Research Council of Canada. John Wiley & Sons. 1981.

Lunardini, V.J. Heat Transfer in Cold Climates. U.S. Army Cold Regions Research and Engineering Laboratory. Van Nostrand Reinhold Co. 1981.

McDonald, S., Daigle, L. and Felio, G. Water Distribution and Sewage Collection in Canada – Assessing the Condition of Municipal Infrastructure, Results from Questionnaires to Canadian Municipalities. Institute for Research in Construction, National Research Council Canada, Ottawa, Canada. 1997.

Rajani, B., Daigle, L. and Zhao, J.Q. Evaluation of the Insulation Specification for Water Service Lines. NRCC Client Report #: A-7029.1, Institute for Research in Construction, National Research Council Canada, Ottawa, Canada. 1997.

Sepehr, K. and Goodrich, L.E. Frost protection of buried PVC water mains in western Canada. Canadian Geotechnical Journal, 31(4):491-501, 1994.

Smith, D.W. Cold Regions Utilities Monograph, Third Edition. American Society of Civil Engineers. 1996.

Tarnawski, V.R. and Wagner, B. Modeling the thermal conductivity of frozen soils. Cold Regions Science and Technology, 22(1):19-31, 1993.

Zhao, J.Q. Determination of Freezing Potentials for Water Service Pipes under Residential Lawns. NRCC Client Report #: B-5104.1, Institute for Research in Construction, National Research Council Canada, Ottawa, Canada. 1998.