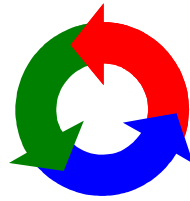


**Manhattan College**



**Center for Geotechnology**

**Geomaterials Research Project**

**Non-Earth Subgrade Materials and Their  
Thermal Effects on Pavements: An Overview**

**Report No. CGT-2001-2**

**by**

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## The Manhattan College School of Engineering *Center for Geotechnology* and Its Mission

The Manhattan College School of Engineering *Center for Geotechnology* (CGT) is a unique organization that strives to be more than the typical academic research center or institute. It was founded in 2001 at the initiative of Prof. John S. Horvath, Ph.D., P.E. of the Civil Engineering Department who serves as its first Director. The CGT is the result of Prof. Horvath's evolutionary realization after almost 30 years of geotechnical engineering practice that the explosive growth in geotechnical and geoenvironmental engineering technology has made it difficult for the engineering practitioner to keep abreast of new technical developments. The traditional academic approach of simply publishing research results in narrowly disseminated technical reports and papers (a philosophy of "if you print it, they will learn") has proven to be an increasingly ineffective way of reaching practitioners and moving the state of art to the state of practice. The critical need for a total rethinking of how life-long continuing education is achieved not only for engineering practitioners but academicians themselves is evidenced by the appearance of "teach-the-teacher" training courses in drilled shaft foundations and geosynthetics beginning in the late 1980s. If even academicians cannot keep up with new developments by reading journal papers and conference proceedings, how can practitioners be expected to? The stagnation of geotechnology also affects current engineering students and perpetuates the cycle. The desirability of involving the practitioner in the process of formulating research programs so that they may have a more direct and immediate benefit to practice is also something that is now recognized more and more.

The CGT seeks to address the current need for effective, meaningful continuing education by recognizing that the cycle of growth for any technology has three interdependent components, what can be called the "trilogy of technology". Like a three-legged stool, each of these components must be of equal length and strength if a given technology is to succeed. Thus the CGT has adopted a holistic strategy of supporting geotechnology growth by recognizing the need to concurrently address:

- *Technology advancement* through research and development that involves not only the engineering practitioner but also other end users of geotechnology such as construction contractors and material manufacturers to the greatest extent practicable.
- *Technology transfer* through education of engineers, contractors and manufacturers in a multi-faceted, proactive way.
- *Technology documentation* through standards development so that all end users (practitioners, contractors and manufacturers) of a given technology work to a common set of guidelines.

This trilogy of technology growth is the cornerstone of all activities of the CGT. It is important to note that the interaction of these three components, which is embodied in the CGT logo that is shown on the cover of this report, is never completed but assumes a constant cycle that leads to continuous growth of a technology.

The CGT receives no direct financial support from Manhattan College for any of its activities. Thus the success and growth of the CGT is totally a function of outside funding from individuals and organizations whose philanthropic philosophies are consistent with the stated goal of the CGT to treat technology growth in a more holistic fashion than is typically done in academia and considers the entire process from research to standards with end-user input at all stages. In addition, as part of its mission to promote technology transfer through education to the greatest extent practicable the CGT is willing to partner with industry and other academic institutions not

only in research but also technology transfer and standards activities on any topic relevant to geotechnical or geoenvironmental engineering. The new Manhattan College School of Engineering William J. Scala Academy Room, which is located on the main floor of the Leo Engineering Building and available for CGT activities, offers modern facilities for hosting technology transfer activities. One benefit of Manhattan College's location on the northern edge of New York City is that it is quite accessible (including free off-street parking adjacent to Leo Engineering Building) from both within and outside the City. More information about the CGT can be found on the Internet at <[www.engineering.manhattan.edu/civil/CGT.html](http://www.engineering.manhattan.edu/civil/CGT.html)>.

## Preface

The basic elements of this report appeared originally in a preprint paper that was researched and prepared by me for the 74<sup>th</sup> Annual Meeting of the Transportation Research Board (TRB) that was held in January 1995 in Washington, D.C., U.S.A. This paper formed the basis of my keynote presentation at a technical session titled *Thermal Effects on Pavements of Non-Earth Materials*. I had conceived the need for and proposed this session that was ultimately co-organized and co-chaired with Ms. Maureen Kestler of the U.S. Army Corps of Engineers (USACE) Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, U.S.A. Unfortunately, the TRB did not deem my paper (or several others from this session) worthy of subsequent formal publication in their *Transportation Research Record* series so dissemination of the contents of my paper was quite limited (that was back in the days when TRB made available to the public only about 100 paper copies of each preprint).

Since my presentation in 1995, I have come to realize that the contents of my TRB paper are more relevant than ever as a result of the growing use of various types of non-earth materials (especially block-molded expanded polystyrene (EPS) geofoam) as backfill and fill in various types of transportation-related earthworks and earth retaining structures. Therefore, I felt it would be a worthwhile to make the contents of my TRB paper more readily available by issuing a Manhattan College *Center for Geotechnology* (CGT) research report. Although the contents of the original preprint paper have been extensively edited, updated and expanded in this report, they are still essentially those presented at the TRB annual meeting in 1995. I feel that what I had to say when I prepared the original paper in 1994 has stood the test of time pretty well.

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May 2001

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## Executive Summary

Non-earth materials, both manufactured new and recycled waste products, are seeing increasing use as backfill and fill in various types of transportation-related earthworks and earth retaining structures. An issue that does not appear to be considered routinely in design at the present time is that non-earth materials have thermal properties (thermal conductivity, heat capacity and latent heat of fusion) that differ, in some cases significantly, from natural earth materials (soil and rock). Consequently, the surface of a pavement underlain by non-earth material will, in general, have a temperature different than that of an otherwise identical adjacent pavement underlain by soil or rock. The pavement underlain by non-earth material will, in most cases, be relatively warmer in summer and cooler in winter. This is because most non-earth materials are, whether intentionally or by happenstance, more thermally insulative than soil or rock.

The phenomenon of greater summer warmth can affect the service life of the pavement if it is made of asphalt concrete (AC) because the Young's modulus of AC decreases with increasing temperature. Thus live-load-induced strains within AC are always larger in summer than in winter even if traffic loads remain the same. If the presence of non-earth material beneath the pavement makes the AC even warmer in summer than would otherwise occur, live-load-induced strains would concomitantly be larger than if the subgrade were soil or rock. In addition, the fact that most non-earth materials are inherently less stiff than soil or rock reduces the stiffness of the overall pavement system which also adds to the strain increase. These cumulative sources of larger strains with a non-earth subgrade could hasten the fatigue failure of AC (a common mode of AC-pavement failure whether insulated or not) and thus result in a shorter-than-anticipated pavement life. This could be a significant maintenance issue given the predominance of AC pavements worldwide.

However, it is the colder winter temperatures of a pavement underlain by non-earth material that is more critical because it can result in a phenomenon called *differential icing*. This is traditionally defined as ice formation on the surface of a pavement underlain by non-earth material when an adjacent, otherwise identical pavement underlain by soil or rock is ice free. This somewhat restrictive definition can be broadened to include ice developing to a greater extent (thicker and/or more difficult to melt using road salt) on an pavement underlain by non-earth material compared to an adjacent pavement underlain by soil or rock.

The primary occurrence of differential icing is when precipitation is falling and near-surface air temperatures are below freezing. But what is perhaps more troublesome is that differential icing can occur even when the air temperature is greater than 0°C (+32°F). This is because the surface temperature of any pavement can drop below the near-surface air temperature during the night as heat is radiated into the atmosphere (clear nights in the autumn are especially conducive for this). Pavements underlain by non-earth materials can have an increased nocturnal heat loss and concomitant surface-temperature drop compared to pavements underlain by soil or rock. Also, differential icing can occur even if there is no precipitation falling because natural water vapor in the air can condense as dew on a pavement surface that is colder than the near-surface air and then freeze if the pavement surface is below freezing.

Unlike accelerated pavement fatigue failure caused by warmer summer temperatures and/or decreased pavement-system stiffness (a maintenance issue), differential icing is considered to be a safety hazard. This is because motor-vehicle operators do not expect to encounter sudden pavement icing when a road is otherwise ice-free. In addition, unlike the related phenomenon of bridge-deck icing which can be anticipated by drivers by the obvious visual change to a structure (especially if warned by appropriate signage as is common in the U.S.A.), differential icing of otherwise identical on-ground pavement surfaces tends to be sudden and unrecognizable until the vehicle is upon it.

This report provides an overview of how using non-earth materials in transportation earthworks and earth retaining structures affects the thermal balance at and near the surface of the Earth. It

also provides an overview of techniques developed to overcome differential icing problems for pavement systems insulated using EPS- and XPS-geofoam. This information is expected to be of use in evaluating the geothermal implications of using a broader spectrum of non-earth materials in a wider variety of transportation applications.

## INTRODUCTION

Earthworks such as fills and embankments as well as earth retaining structures supporting roads, airfields and railroads are traditionally underlain by, constructed of or backfilled/filled with natural earth materials (soil and rock). However, non-earth materials are being used increasingly in such applications. These alternative materials can be categorized in a number of ways. In the author's opinion, the most useful categorizations are by:

- material source (manufactured new versus recycled waste) and
- material composition<sup>a</sup> (particulate (i.e. soil-like) versus solid).

Table 1 lists the non-earth materials most commonly used for transportation earthworks and earth retaining structures categorized using these variables. Good technical summaries and overviews of virtually all materials shown in this table can be obtained by combining material found in *Matériaux* (1997) and Elias et al. (1999). These are summary reports that also list primary references that contain more-detailed information for each of the various materials.

**Table 1. Non-Earth Materials Used in Transportation Applications**

material composition	material source	
	manufactured new	recycled waste
particulate	expanded shale/clay aggregate	coal ash (various types) demolition debris (variable composition) rubber tires (various forms) slags (various types) wood fiber (various forms)
solid	geofoams (polymeric, glass, cementitious) geocombs	-

There are several reasons non-earth materials are used increasingly in transportation applications:

- *As lightweight material.* Most non-earth materials have densities less than that of natural soil, in some cases as little as 1% of the density of soil. This means that an earthwork consisting of non-earth material will produce vertical gravity stresses on the underlying ground and have seismic inertia forces that are often much less than those of an equivalent earth structure. This can dramatically reduce settlement and increase stability of the earthwork. Frequently, using non-earth material (which is often more expensive than soil when compared on a strictly unit volume basis) is a more cost-effective choice overall for reducing settlement, increasing stability and reducing construction time compared to traditional design alternatives using staged construction and vertical drains, or building a structure supported on deep foundations.

<sup>a</sup> Material *composition* should not be confused with material *texture*. For the purposes of this report composition refers to how a material derives its strength from a Mohr-Coulomb perspective, i.e. through inherent strength due to true cohesion (solids) or through stress-dependent, inter-particle friction (particulates). For example, geofoams are considered to be solids even though up to 99% of a geofoam material may be voids filled with air.

- As *thermal insulation* to prevent or limit subgrade freezing beneath pavements or railway tracks. The pavement application is discussed in detail later in this report.
- As a way of utilizing waste materials in a productive manner. In recent years, this has sometimes been dictated by legislation, for example, the use of shredded rubber tires in road construction.

## PURPOSE AND SCOPE OF REPORT

An issue that does not appear to be considered routinely at present in designs involving the use of non-earth materials beneath paved areas such as roads and airfields is that these materials have thermal properties that differ, in some cases significantly, from natural earth materials. Experience indicates that this can result in safety related problems as well as increased maintenance costs. This is not to imply that all non-earth materials have negative effects in all applications. However, experience dating back to the 1960s with some non-earth materials and applications indicates that there is at least a potential for problems in most applications. This suggests that a consideration of thermal effects is at least warranted when non-earth materials are used.

The purpose of this report is to foster a greater awareness of and interest in the thermal effects of using non-earth materials in transportation applications. The scope of the report is to present a summary of key points concerning the relevant thermal phenomena and an overview of what has been learned to date concerning thermal effects of some non-earth materials in some applications. Detailed discussion of the geothermal properties and implications of all non-earth materials is beyond the scope of this report.

## BASIC THERMAL REGIME FOR PAVEMENT SYSTEMS

### Thermal Parameters

There are two thermal parameters that are important to this discussion:

- *thermal conductivity* and
- *heat capacity*.

Thermal conductivity relates to the rate at which heat can flow through a material. It is conceptually and mathematically identical to the well-known phenomenon of liquid flow in soil. In some calculations, the reciprocal of thermal conductivity, *thermal resistivity*, is used instead (an example is the familiar *R-value* of construction materials). The relevant parameters used to quantify thermal conductivity in a particular application are the:

- *coefficient(s) of thermal conductivity* of the material(s) through which the heat flow is occurring,
- thickness(es) of the material(s) through and in the direction in which heat flow is occurring and
- thermal gradient (temperature difference) imposed across the material(s) in the direction which heat flow is occurring.

Each of these parameters has a direct analogy with liquid flow in soil.

Heat capacity refers to the amount of heat energy associated with a change in temperature of one degree of a unit quantity of a material. Heat capacity can be expressed in either a mass/weight or volume basis. Thus heat capacity can be expressed as how much energy (in British Thermal Units (BTUs), calories or joules) it takes to change one kilogram/pound or cubic metre/foot of a material one degree Celsius, Kelvin or Fahrenheit.

There is also a thermal material property called *latent heat of fusion* or simply *latent heat*. From a practical perspective it is not really an independent material property but is related to heat capacity. Latent heat is the amount of heat energy it takes to cause the water within a unit quantity (mass/weight or volume) of a material to undergo the phase change from the liquid to solid (ice) state or vice versa. Therefore, latent heat can be visualized as a spike or surge in heat capacity required to cause this phase change. Note that by definition the latent heat of a material that does not contain water is zero. Also, it is of interest to note that the phase change of water in the ground always occurs over a range of temperature, typically at least a few degrees, rather than at a single temperature as is often assumed for standing water. Thus the latent heat of water-bearing materials in the ground is always spread out over a range in temperature.

### Thermal Balance

The Earth's surface represents a complex thermal interface at which there must always be a thermal balance between heat energy in its three fundamental forms of transmission (conduction, convection and radiation) and from many different sources entering and leaving the Earth. Description of the various sources and mechanisms of heat generation and transfer can be found in numerous texts and papers. Examples include Lunardini (1985) and Zarling and Braley (1988).

A result relevant to this report is that the temperature at the Earth's surface,  $T_s$ , is usually different from the near-surface air temperature,  $T_o$ , which is typically measured several metres (feet) above the surface. In general, the Earth's surface is warmer than the near-surface air during the day and cooler at night. On an annual-aggregate basis, the average daily temperatures of the surface and near-surface air will also differ. Because meteorological data are generally collected only for near-surface air temperatures, this makes it necessary to calculate the surface temperature using air-temperature data in geotechnical problems.

While the Earth's surface-heat balance is conceptually simple, there are several heat transfer mechanisms and numerous heat sources, even in the absence of human activity, that must be considered and evaluated individually. This renders the problem of calculating surface temperatures extremely complex to solve theoretically. As a result, an empirical approach using the concept of *n-factors* is generally used in geothermal-analysis practice. An *n-factor* is a positive, dimensionless parameter that is determined experimentally by field measurement and relates seasonal-aggregate differences between surface ( $T_s$ ) and near-surface air ( $T_o$ ) temperatures either above or below freezing<sup>b</sup>. Thus there are always separate *n-factors* for the annual freezing and thawing seasons. Specifically:

$$n = \frac{\text{theoretical number of degree - days of freezing or thawing at ground surface}}{\text{actual number of degree - days of freezing or thawing measured in near - surface air}} \quad (1)$$

To interpret the physical meaning of an *n-factor*, note that an *n-factor* less than one means that the heat energy, usually expressed in degree C- or degree F-days<sup>c</sup>, causing freezing or thawing at

<sup>b</sup> It is important to note that *n-factors* are not simply the difference between  $T_s$  and  $T_o$  at some instant in time. This is a misconception that appears at times in practice.

<sup>c</sup> A degree-day is an average daily temperature of one degree Celsius or Fahrenheit above or below freezing as appropriate for one day. For example, if the average temperature on a given day is  $-7^{\circ}\text{C}$  ( $+19.4^{\circ}\text{F}$ ) there

the ground surface is less than that in the near-surface air. Conversely, an  $n$ -factor greater than one means that the freezing or thawing energy at the ground surface is greater than that of the near-surface air.

Tables of  $n$ -factors appear in numerous geothermal texts, manuals and technical papers. Examples include Lunardini (1985) and Esch (1988). Values are primarily a function of:

- the nature of the material covering the ground surface (e.g. type of pavement or vegetation),
- degree of latitude,
- geographic location,
- surface-slope angle and
- compass orientation if the surface is sloped.

With so many variables, it can be seen that it is difficult to generalize  $n$ -factors or, more importantly, to reliably use results from one area in another.

In the U.S.A., by far the largest body of  $n$ -factor data that has been accumulated to date is for the State of Alaska. There,  $n$  is generally less than one for the freezing season and greater than one for the thawing season. This means that the ground surface is overall warmer than the near-surface air during the winter and warmer during the summer which is a typical condition in many parts of the world.

### Subgrade Effects

It would be expected that the material immediately underlying the ground surface would also influence  $n$ -factors. This is because the thermal conductivity of near-surface material influences the rate of heat exchange between the ground and atmosphere which is very important for transient phenomena such as daily and seasonal temperature changes. In addition, the heat capacity of the near-surface material is important because it can act (or not) as a *heat sink*, literally a storage reservoir of heat energy. This is especially true if the near-surface material contains water which has a relatively large heat capacity and significant amount of latent heat associated with the phase change from liquid to solid and vice versa.

Unfortunately, there does not appear to have been any systematic study to date of the effect of near-surface subgrade material on  $n$ -factors. This is probably because this would add another variable to what is already a complex problem and, in most cases, subgrade materials are earth materials and, therefore, reasonably consistent given all the other variables that affect  $n$ -factors. However, there is some published information that suggests subgrade effects can be important when non-earth materials are used in the near-surface zone. This involves lessons learned using *insulated pavement systems* and is discussed in detail in the following section.

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would be 7 degree C-days (12.6 degree F-days) of freezing. By adding up all the degree-days in the freezing or thawing season, the total degree-days of freezing or thawing for the year at a given location is determined. Tables or figures showing degree-days (usually of the freezing season only) for different locations appear in geothermal texts and design manuals and even some geotechnical engineering texts. When using these data, note that the number of degree-days of freezing or thawing for a given location is not a fixed number but varies with probability, e.g. there are different values for an average year, a "100-year" winter, etc. in the same way as different water elevations are quoted for a "100-year" flood versus a "500-year" flood in a body of water.

## EXPERIENCES WITH INSULATED PAVEMENT SYSTEMS

### Background

Seasonal freezing of a soil subgrade beneath a road or airfield pavement often causes surface heaving due to the fact that many soils expand in volume, sometimes substantially, as they freeze. Subsequent seasonal thawing then results in settlement (which can exceed the magnitude of heave) due to *thaw consolidation* as well as a temporarily weakened subgrade due to excess porewater that can lead to the development of the classical *pothole*. The effect of the combined freezing and thawing phenomena is a pavement surface that is at best variable in its profile and at worst physically deteriorated. This affects trafficability and pavement life, and requires the seasonally ubiquitous pothole-patching that is never effective at fully restoring the pavement to its original condition. Furthermore, because pothole-patching treats a symptom (surface deterioration) and not the cause (a *frost-susceptible* subgrade) of the problem it is fundamentally incorrect and completely ineffectual at preventing the reoccurrence of potholes and concomitant pavement deterioration during a subsequent winter. Pothole patching, while well intentioned and expedient, is a classic example of applying a non-engineering solution to an engineering problem.

A better-engineered solution to this problem that evolved in the early 1960s is that of more fundamentally correct problem prevention. This is achieved by incorporating non-earth material within the pavement system as thermal insulation to prevent or at least significantly limit seasonal freezing and thawing of the soil subgrade underlying the insulation layer. The resulting pavement system is termed an *insulated pavement system* or, more simply, an *insulated pavement*. Use of insulated pavements prevents or at least limits pavement deterioration altogether and thus improves the long-term performance of pavements.

The way in which the synthetic thermal insulation works in this application is by decreasing the overall thermal conductivity of the pavement system. It drastically slows down the rate at which cold temperature (colloquially referred as the *freezefront*) penetrates the ground vertically from the pavement surface and removes ground heat which would eventually cause a frost-susceptible subgrade soil to freeze and heave. Thus to be effective materials used as the thermal insulation layer must have a relatively low coefficient of thermal conductivity compared to natural earth materials. At the same time, the insulation material must be sufficiently strong to withstand traffic-induced stresses with acceptable levels of strain so that the overall pavement-system stiffness is not significantly compromised. In addition, the insulation material must be reasonably robust to survive construction and not be environmentally deleterious to the air, ground or groundwater.

These design criteria for pavement insulation materials are very demanding. The insulation material of choice that evolved during initial research into insulated pavements in the 1960s was relatively thin (up to 100 mm (4 in) thick) panels of *rigid cellular polystyrene* (RCPS). There are two types of RCPS:

- *Expanded polystyrene* (EPS) which is inherently white in color (although outside the U.S.A. it may be colored otherwise for marketing purposes) and is sometimes referred to colloquially as *beadboard*. This is the same familiar plastic foam used for coffee cups and cushioning packaging.
- *Extruded polystyrene* (XPS) which, depending on the manufacturer, is colored blue, green, pink or yellow in the U.S.A. for marketing purposes.

One must be careful outside the U.S.A. using color as a guide for differentiating between EPS and XPS. For example, in the U.K. there is an EPS product that is colored pink and should not be

confused with the pink-colored line of XPS products made by Owens-Corning that is available in the U.S.A. and other countries.

Another practical note is that in the U.S.A. at least it is common for all types of plastic foam to be referred to colloquially as *styrofoam*. This is incorrect and should be discontinued, especially in civil engineering practice, as Styrofoam® is the tradename of a line of blue-colored XPS products manufactured by The Dow Chemical Company. It is also of interest to note that plastic foams such as EPS and XPS when used in geotechnical applications have, since the early 1990s, been considered to be part of a geosynthetic product category called *geofoams*. However, contrary to what has been published in some places the terms "geofoam" and "EPS" are not synonymous. Geofoams are defined as any closed-cell foam used in a geotechnical application and thus include all types of polymeric (plastic) foams as well as glass and cementitious foams as noted in Table 1. Therefore EPS is but one of many types of geofoam.

### Overall Observed Behavior

Although there has not been any systematic study to date of the effect of subgrade materials on *n*-factors, there has been some research for insulated pavements. As noted previously, it would be expected that the presence of a thermally insulative synthetic material such as EPS- or XPS-geofoam placed relatively close to the ground surface as occurs with insulated pavements would affect the surface thermal balance. However, available information suggests that this was not anticipated when the concept of insulated pavement was first developed and eventually patented (in the U.S.A. interestingly (Leonards 1966)) in the 1960s.

The effect of the geofoam insulation for insulated pavements can be seen by comparing average *n*-factors for roads with *asphaltic cement concrete* (ACC, more commonly called simply *asphalt concrete* (AC)) pavement given in Lunardini (1985):

**Table 2. Comparison of AC-Pavement *n*-Factors as a Function of Subgrade Insulation**

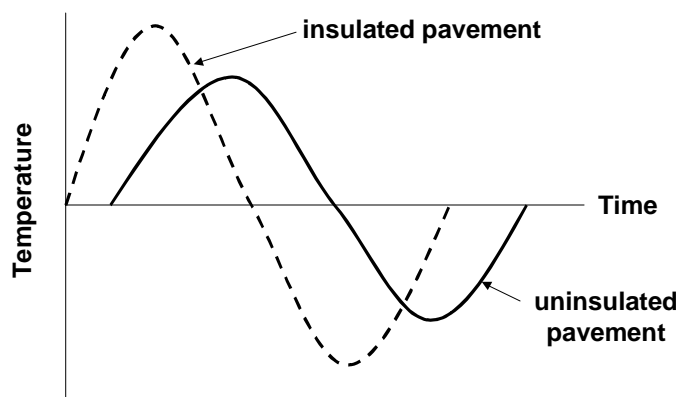
type of pavement system	<i>n</i> -factor	
	freezing season	thawing season
uninsulated	0.71	1.70
insulated	0.94	1.82

The implication of these numbers is that insulated pavements are, overall, cooler during the freezing season and warmer during the thawing season compared to uninsulated pavements. The reason for these thermal differences is because the insulation layer effectively isolates the pavement surface from the underlying ground. In winter, not only does the insulation restrict the downward propagation of the freezefront into the subgrade soil (as intended) but it also restricts the perpetual upward flow (flux) of geothermal heat of approximately 60 milliwatts/m<sup>2</sup> (0.02 BTU/hour/ft<sup>2</sup>) from the Earth's interior. In summer, the insulation traps heat from daytime solar radiation within the pavement system rather than allowing it to propagate into the ground.

It should be noted that important additional details concerning the type, thickness and depth of the thermal insulation material for the pavement systems on which the numbers in Table 2 were obtained are not known. However, fairly detailed thermal measurements made in recent years for two very different applications (but both with AC pavements) confirm these trends:

- A project reported by Kestler and Berg (1992, 1995) involved an airfield pavement in the State of Maine that was insulated using 50 mm (2 in) of XPS geofom that was placed only 368 mm (14.5 in) below the pavement surface<sup>d</sup>.
- A project reported by Jutkofsky (1998) involved a road embankment in the State of New York containing EPS-block geofom lightweight fill approximately 3 metres (10 ft) thick and buried approximately one metre (3 ft) below the pavement surface.

In addition to the aggregate, seasonal differences reflected in the  $n$ -factors shown in Table 2, field observations in Norway (*Sikring* (1976), with an updated English-language summary in Refsdal (1987)) showed that there could be significant differences even on a daily basis. A typical result is shown qualitatively in Figure 1. Note that the surface of the insulated pavement gets warmer during the day and cooler at night compared to the uninsulated pavement.



**Figure 1. Daily Temperature Cycles**

In summary, insulated pavements will experience both:

- more aggregate thawing-season heat energy (= more "warmth") as well as higher daily temperatures and
- more aggregate freezing-season heat energy (= more "cold") as well as lower daily temperatures

than for a corresponding uninsulated pavement. Each of these outcomes has significant impact on pavement performance as well as safety that require further detailed discussion in the following sections.

<sup>d</sup> It is of interest to note that this depth is comparable to early insulated-pavement practice but would be considered relatively shallow and marginally acceptable by current design standards (discussed subsequently) that were in effect when this project was designed and constructed in the mid-1980s. A possible explanation is that the groundwater table at this site was very shallow which governed how deep excavation could be performed.

## Accelerated Fatigue Failure of AC Pavements

The overall warmer conditions experienced by an insulated pavement during the thawing season may affect the service life of the pavement itself if it is made of AC. This is because the Young's modulus of AC decreases with increasing temperature. Given the more or less linear relationship between stress and strain for AC, this means that live-load-induced strains within an AC pavement, whether insulated or not, are always larger in warmer weather than in cooler weather for the same traffic load. Field measurements of overall pavement-system stiffness reported by Kestler and Berg (1992, 1995), for example, show this clearly. If the presence of synthetic thermal insulation within a pavement system makes the AC even warmer than would otherwise occur, live-load-induced strains would concomitantly be larger than if no insulation were present. Again, results shown by Kestler and Berg (1992, 1995) support this hypothesis. These larger strains with an insulated pavement system could hasten the development of fatigue failure of the AC (a common mode of AC-pavement failure whether insulated or not) and thus result in a shorter-than-anticipated pavement life. This could be a significant issue given the predominant use of AC pavements over other types worldwide.

## Differential Icing

While accelerated pavement failure is a potential maintenance problem, it is the colder freezing-season temperatures (especially the daily variations shown in Figure 1) experienced by an insulated pavement that can result in a more-critical, safety related problem called *differential icing*. This is traditionally defined as ice formation on the surface of an insulated pavement when an adjacent, otherwise identical uninsulated pavement is ice free. The author suggest that this somewhat restrictive definition be broadened to include ice developing to a greater extent (thicker and/or more difficult to melt using road salt) on an insulated pavement compared to an adjacent uninsulated pavement.

The most obvious potential for differential icing is when precipitation is falling and near-surface air temperatures are below freezing. But what is particularly troublesome is that extensive research, most of which was conducted in Norway in the late 1960s to early 1970s, demonstrated clearly that differential icing can occur even when the near-surface air temperature is greater than 0°C (+32°F). This can occur because the temperature of any pavement surface can drop below the near-surface air temperature during the night as heat is radiated into the atmosphere (clear nights are especially conducive for this). The presence of synthetic thermal insulation within the pavement systems simply increases this natural tendency for nocturnal heat loss and concomitant surface-temperature decrease. Remarkably, differential icing can also occur even if there is no precipitation falling. This can occur because natural water vapor in the near-surface air can condense as dew on any pavement surface that is colder than the near-surface air and then freeze if the pavement-surface temperature is below freezing forming *hoarfrost*. In Norway, hoarfrost formation was found to occur routinely with some early insulated pavements with near-surface air temperatures up to approximately +4°C (+39°F) and, in an extreme case, at a near-surface air temperature of +11°C (+52°F) (Refsdal 1987). In general, it was observed that the potential for hoarfrost formation with insulated pavements and the resulting differential icing tends to be greatest in the autumn when the otherwise uninsulated ground still retains some of summer's heat (Refsdal 1987).

The phenomenon of differential icing is sometimes called the *bridge-deck problem* in reference to the well-known phenomenon that the pavement surface on a bridge will generally ice before adjacent pavement sections on the ground. Like bridge-deck icing, differential icing is considered to be a safety issue. This is because motor-vehicle operators do not expect to encounter sudden pavement icing when a road is otherwise ice free. However, unlike bridge-deck icing which can be

anticipated by drivers by the obvious visual change to a structure (especially if warned by appropriate signage as is common in the U.S.A.), differential icing of otherwise identical pavement surfaces tends to be sudden and unrecognizable until the vehicle is upon it. For airfields, unexpected icing can be a problem especially for landing aircraft.

### **Other Observed Phenomena**

There are at least two additional phenomena attributed to insulated pavements that are worth noting. The first is related to temperature. Kestler and Berg (1992, 1995) suggested that the greater summer-to-winter temperature range experienced by insulated pavements compared to traditional uninsulated pavements may result in a greater tendency to develop thermal cracks in AC pavements due to greater-than-typical temperature-induced horizontal expansion and contraction of the AC. This thermal cracking is separate from the fatigue-related cracking discussed earlier. The consequences of thermal cracking include a direct contribution to structural failure of the pavement itself as well indirect contribution to overall pavement system failure by allowing water into the pavement subgrade where it can be trapped above the insulation (which could reduce the strength of the unbound materials within the pavement system) or wet the insulation (which would increase its coefficient of thermal conductivity and thus reduce its thermal insulative value).

The other phenomenon is not thermal related so, strictly speaking, is not relevant to this report. However, it is noted here because it is associated with insulated pavements and was also discussed by Kestler and Berg (1992, 1995). This relates to the fact that the materials typically used to insulate pavements (and railways for that matter), EPS- and XPS-geofom, are relatively less stiff than materials typically incorporated into pavement systems. EPS- and XPS-geofom typically have California Bearing Ratio (CBR) values in the single-digit range which is comparable to a medium-stiff clay. As a result, the overall pavement-system stiffness of an insulated pavement is typically less than that of a traditional uninsulated pavement as measured with a Falling-Weight Deflectometer (FWD) or other, similar device. As a result, insulated pavements deflect more under live loads regardless of pavement temperature which could contribute to accelerated fatigue failure of AC pavements.

### **Problem Solutions**

Historically, only differential icing of insulated pavements has been considered a real potential problem in practice and is the only issue discussed in detail in this report. However, before discussing the solutions to differential icing for the sake of completeness the other problems hypothesized for insulated pavements will be discussed briefly.

It does not appear that sufficient research has been conducted to quantify the hypothesized accelerated fatigue failure of insulated AC pavements. If this is indeed an issue, it should simply be accepted as a fact of life and considered during design by thickening the pavement system. The fact that insulated pavements are typically not as stiff overall as uninsulated ones should also be dealt with simply as a design consideration. It should be kept in mind that insulated pavements provide significant benefits and as such, their pluses and minuses need to be considered together as part of the overall system design rather than focusing on just the negatives (the negatives of an uninsulated road with potholes should be kept in mind as well). An excellent example of an integrated system design approach for insulated pavements that considers mechanical (stress-strain) and thermal behavior along with both construction and life-cycle costs to come up with an insulated pavement design that offers the lowest overall cost was presented by Doré et al. (1995).

Getting back to differential icing of insulated pavements, the reaction worldwide in the late 1960s/early 1970s to this unanticipated problem was varied and reflected the societal philosophies of different industrialized countries using this then-new technology. Most states in the U.S.A. were

driven by legal concerns for liability and discontinued further use of insulated pavements, a policy that largely remains in force to the present time. Other states significantly restricted future use of insulated pavements. The one exception to both of these policies seems to be the State of Alaska.

While the policies of non-use or severe restriction may eliminate or minimize problems with differential icing it does not eliminate the problems that result from freezing and thawing of uninsulated pavements. Pavement damage due to the effects of freezing and thawing and the resulting potholes has significant economic consequences and, in extreme cases, also produces safety problems. This suggests that a better approach is to develop a technical, not legal, solution that allows continued use of insulated pavements but in a way that eliminates or at least minimizes the potential for differential icing. This is the course taken in the late 1960s/early 1970s by most countries other than the U.S.A. It also turns out that development of a technical solution to differential icing was necessary for the use of non-earth materials for other applications, especially EPS-block geofoam lightweight fills, that began to develop in the 1970s.

The most detailed study of technical solutions to differential icing was performed in Norway (Refsdal 1987). It was recognized that in early applications of insulated pavements, the insulation was placed relatively close to the pavement surface. In a hyperbolic-but-illustrative statement made to the author, a geotechnical engineer who was heavily involved with the early insulated pavements commented that they practically placed the AC on top of the EPS or XPS geofoam layer in many cases. Thus as a general strategy to prevent or at least minimize differential icing, it was found beneficial to place the geofoam insulation layer deeper in the pavement section. The benefit of doing this comes almost solely from the heat capacity of the unbound material(s) in the pavement system above the insulation layer acting as a heat sink<sup>e</sup>. Essentially, the material between the insulation layer and pavement surface is relied on to provide sufficient retained heat to (ideally) keep the pavement surface as warm as an adjacent uninsulated pavement. It is important to note that the goal here is not to prevent all icing of insulated pavement but to limit ice formation to the same extent as adjacent sections of uninsulated pavement, i.e. to equalize the potential for icing. From a practical perspective, this suggests that the unbound base/subbase materials used in an insulated pavement must have sufficient "fines" (minus #200 sieve soil particle sizes) to hold water which has a relatively high heat capacity. However, the material chosen must not contain too many fines or else it may itself be susceptible to freezing and thawing problems.

In summary, the important conclusion of the Norwegian research into differential icing of insulated pavements was that the more important consideration is the type of unbound material used in the pavement section above the insulation layer, not the absolute thickness of the unbound material between the insulation and pavement surface. Assuming that the proper<sup>f</sup> material is used, the required minimum depth of the insulation layer below the pavement surface for Norwegian climate and traffic conditions varies from 400 to 800 mm (16 to 24 in) (*Expanded* 1992).

## APPLICATION OF LESSONS LEARNED TO NON-EARTH MATERIALS IN GENERAL

### Introduction

The geothermal lessons learned from insulated pavements are:

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<sup>e</sup> AC and portland cement concrete (PCC) are essentially devoid of water so are ineffective as a heat sink.

<sup>f</sup> Unfortunately, a detailed specification such as particle-size-distribution-curve ranges for what constitutes acceptable material does not appear to have ever been published. Thus "proper" is left to the judgment of the engineer.

- Even a relatively thin layer of non-earth material used close to the Earth's surface can significantly affect the surface thermal balance. To what extent depends on several variables which include:
  - the thermal properties (thermal conductivity, heat capacity and latent heat) of the non-earth material compared to soil,
  - the thickness of the non-earth material used and
  - its depth below the surface.
- A modified surface-heat balance may result in significant safety and/or maintenance problems for pavements underlain by non-earth materials.

Therefore, it is of interest to investigate the extent to which various non-earth materials that are used in transportation applications affect the Earth's surface thermal regime. Where potential problems exist, it is also of interest to develop designs that minimize any problems. In general, non-earth materials offer too many advantages to simply discontinue using them.

### **Design Considerations**

Each non-earth material has unique thermal material properties that must be evaluated and compared to the thermal material properties of earth materials encountered at a given project site. Consideration of how these various material properties can be determined is discussed briefly in the Appendix of this report.

Once the appropriate thermal material properties have been determined, the project-specific geometry of the earthwork, etc. that will utilize the non-earth material needs to be considered. While much can be learned from the decades of experience with insulated pavements, there are important differences between most applications using non-earth materials and insulated pavements. For example, for insulated pavements the thickness of the insulation material is relatively small (a few tens of millimetres (inches)) and only the coefficient of thermal conductivity of the material is important. Also, the latent heat of EPS- and XPS-geofoams are essentially zero. However, most applications using non-earth materials involve considerably thicker material layers that are measured in metres (tens of feet). Therefore, the heat capacity and latent heat (if water is present) of the material may also be important. Also, the overall geometry of many applications may be significantly different than for a typical insulated pavement.

Given the current state of knowledge, it may be desirable on major projects to perform a rigorous geothermal analysis to evaluate the effect of using non-earth material. This will generally require a two-dimensional numerical analysis of a continuum using the finite-element method (Horvath 1993). However, for smaller projects or preliminary design of large projects based on the current state of knowledge it appears that differential icing of the pavement surface overlying a non-earth material is the primary design concern. Issues related to accelerated failure of the pavement itself due to heating, etc. may also be important but do not have the immediate safety related implications of differential icing. However, in climates where differential icing is a physical impossibility the issue of pavement heating would be relatively more significant.

### **Research Needs**

While much has been learned from insulated pavements about the geothermal impact of non-earth materials, this knowledge is relatively narrow in terms of the materials, applications and climates considered to date. There is still much to learn about the geothermal implications of using a wider variety of non-earth materials in many different types of applications and climates. Therefore, it is recommended that explicit consideration of geothermal issues be included as part

of the design process whenever non-earth materials are used beneath paved areas. To assist engineers with this, it is recommended that research be performed in the following areas:

- There should be standardized American Association of State Highway and Transportation Officials (AASHTO) tests for the coefficient of thermal conductivity, heat capacity and, where appropriate, latent heat of non-earth materials. Where these materials are recycled waste products that are inherently variable in composition, project-specific testing should be required although it may be possible to develop typical ranges of values that can be applied to any project, at least during the preliminary design phase. Because manufactured materials are more consistent in their composition, it should be possible to develop parameter values that can be used from project to project. This is certainly the case with EPS- and XPS-geofoams which are possibly the most extensively used non-earth materials to date.
- A design procedure should be developed for evaluating the effect of non-earth materials on the surface temperatures of pavements. This procedure should, as a minimum, allow for consideration of different materials, material thickness, the thickness and composition of the pavement system overlying the non-earth material, problem geometry and climate. This procedure should also include more-explicit guidance on how to choose particle-size gradations of unbound pavement system materials so that the potential for differential icing is minimized.
- An analysis procedure should be developed for quantifying the thermal and mechanical (stress-strain) effects of non-earth material on pavement life, especially for AC.
- A design manual, possibly incorporating microcomputer software, should be developed that incorporates the analysis and design procedures developed in the preceding steps. This design manual should be developed specifically for use by designers of transportation earthworks and earth retaining structures using non-earth materials.
- The use of thermal instrumentation on projects incorporating non-earth fills should be increased and the information obtained shared publicly in a timely fashion. Such instrumentation should be placed not only within the pavement system overlying the non-earth material as has typically been done to date but within and below the non-earth material as well. One unverified concern of the author's is that a relatively thick layer of non-earth material, such as typically used for lightweight fills, might trap the upward geothermal flux coming from within the Earth. The end result could be a progressive build up over time of heat underneath and eventually within the non-earth fill material. The temperatures resulting from this heat buildup could rise above the normal average ground temperature (which is approximately the average annual near-surface air temperature in a given area) and create problems either for the non-earth fill material itself or surrounding materials. Although this has not been found to be a problem in the almost 30 years that EPS-block geofoam has been used for lightweight fills in thicknesses now exceeding of 15 metres (50 feet), this may be because almost all of the projects to date have been in relatively cool temperate zones with relatively shallow ground water. Not only does water act as a very efficient heat sink, it is always flowing so that any heat buildup underneath a non-earth fill is continuously carried away. Such conditions would possibly not exist in an arid or semi-arid climate.
- It is suggested that the Federal Highway Administration (FHWA) take the lead role in initiating and coordinating this research because of its longstanding policy of promoting the engineered use of non-earth materials in transportation applications. The FHWA should act

in collaboration with industry as well as other Federal agencies such as the Federal Aviation Administration and Department of Defense that have an interest and/or experience with non-earth materials used beneath pavements for transportation applications.

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## REFERENCES

Coutermarsh, B. A. (1997). "*Frost shielding protection of a water line, Berlin, New Hampshire*", Special Report 97-1, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., U.S.A., 25 pp.

Coutermarsh, B. A. and Carbee, D. L. (1998). "*Frost-shielding methodology and demonstration for shallow burial of water and sewer utility lines*", CRREL Report 98-4, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., U.S.A., 23 pp.

Coutermarsh, B. A. and Phetteplace, G. E. (1991a). "Analysis of frost shields using the finite element method", *Proceedings of the Seventh International Conference on Numerical Methods in Thermal Problems*, R. W. Lewis, H. Chin and G. M. Homsy (eds.), Pineridge Press, Swansea, U.K., Vol. 7, pp. 122-132.

Coutermarsh, B. and Phetteplace, G. (1991b). "Numerical analysis of frost shields", *Proceedings of the Cold Regions Sixth International Specialty Conference*, D. S. Sodhi (ed.), American Society of Civil Engineers, New York, N.Y., U.S.A., pp. 178-190.

Doré, G., Konrad, J. M., Roy, M. and Rioux, N. (1995). "Use of alternative materials in pavement frost protection: material characteristics and performance modeling", *Transportation Research Record No. 1481*, Transportation Research Board, Washington, D.C., U.S.A., pp. 63-74.

Elias, V., Welsh, J., Warren, J. and Lukas, R. (1999). "*Ground improvement technical summaries*", Publication No. FHWA-SA-98-086, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., U.S.A.

Esch, D. C. (1988). "Embankment case histories on permafrost", in *Embankment Design and Construction in Cold Regions*, American Society of Civil Engineers, New York, N.Y., U.S.A., pp. 127-159.

"*Expanded polystyrene used in road embankments - design, construction and quality assurance*" (1992). Form 482E, Road Research Laboratory, Oslo, Norway, 4 pp.

Horvath, J. S. (1993). "Computer software for load-deformation and geothermal analyses in problems involving geosynthetics", *Geotextiles and Geomembranes*, Elsevier Science Ltd., London, U.K., Vol. 12, No. 5, pp. 425-433.

Horvath, J. S. (1995a). "Non-earth subgrade materials and their thermal effects on pavements: an overview", preprint paper No. 95-0069, Transportation Research Board 74<sup>th</sup> Annual Meeting, Washington, D.C., U.S.A.

Horvath, J. S. (1995b). "*Geofoam geosynthetic*", Horvath Engineering, P.C., Scarsdale, N.Y., U.S.A., 229 pp.

Horvath, J. S. (1999). "*Lessons learned from failures involving geofoam in roads and embankments*", Research Report No. CE/GE-99-1, Manhattan College, Civil Engineering Department, Bronx, N.Y., U.S.A.

Jutkofsky, W. S. (1998). "*Geofoam stabilization of an embankment slope; a case study of Route 23A in the Town of Jewett, Greene County*", report, New York State Department of Transportation, Geotechnical Engineering Bureau, Albany, N. Y., U. S. A., 42 pp.

Kersten, M. S. (1949), "*Thermal properties of soils*", Bulletin No. 28, University of Minnesota, Institute of Technology, Engineering Experiment Station, U.S.A., 225 pp.

Kestler, M. A. and Berg, R. L. (1992). "*Performance of insulated pavements at Newton Field, Jackman, Maine*", CRREL Report 92-9, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., U.S.A., 24 pp.

Kestler, M. A. and Berg, R. L. (1995). "Case study of insulated pavement in Jackman, Maine", *Transportation Research Record No. 1481*, Transportation Research Board, Washington, D.C., U.S.A., pp. 47-55.

Leonards, G. A. (1966). "*Pavement construction*", U.S. Patent No. 3,250,188.

Lunardini, V. J. (1985). "Analytical methods for ground thermal regime calculations", in *Thermal Design Considerations in Frozen Ground Engineering*, American Society of Civil Engineers, New York, N.Y., U.S.A., pp. 204-257.

"*Matériaux légers pour remblais/lightweight filling materials*" (1997). Document No. 12.02.B, PIARC - World Road Association, La Defense, France (in English and French).

Refsdal, G. (1987). "Frost protection of road pavements", in *Frost Action in Soils No. 26*, Committee on Permafrost, Oslo, Norway, pp. 3-19.

Sanger, F. J. (1969). "*Foundations of structures in cold regions*", Cold Regions Science and Engineering Monograph III.C4, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., U.S.A., 92 pp.

"*Sikring mot teleskader*" (1976). Frost i Jord No. 17, Norges Teknisk-Naturvitenskapelige Forskningsråd og Statens Vegvesens Utvalg For Frost i Jord, Oslo, Norway, 400 pp.

Zarling, J. P. and Braley, W. A. (1988). "Geotechnical thermal analysis", in *Embankment Design and Construction in Cold Regions*, American Society of Civil Engineers, New York, N.Y., U.S.A., pp. 35-92.

### **SELECTED BIBLIOGRAPHY**

Andersland, O. B. and Anderson, D. M. (eds.), "*Geotechnical engineering for cold regions*", McGraw-Hill, New York, N.Y., U.S.A., 1978, 566 pp.

Freitag, D. R. and McFadden, T. (eds.), "*Introduction to cold regions engineering*", ASCE Press, New York, N.Y., U.S.A., 1997, 738 pp.

Jumikis, A. R., "*Thermal geotechnics*", Rutgers University Press, New Brunswick, N.J., U.S.A., 1977, 375 pp.

Phukan, A., "*Frozen ground engineering*", Prentice-Hall, Englewood Cliffs, N.J., U.S.A., 1985, 336 pp.

Sanger, F. J., "*Foundations of structures in cold regions*", Cold Regions Science and Engineering Monograph III.C4, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., U.S.A., 1969, 92 pp.

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## APPENDIX - EMPIRICAL FORMULAE FOR THERMAL PROPERTIES OF SOIL

### Introduction

Experience indicates that the thermal properties of soil can be calculated with accuracy sufficient for routine geotechnical projects using empirical or derived relationships. This is fortuitous as the alternative to using these relationships is to physically sample and test the project-specific soil(s) which requires special testing apparatus and is beyond the capability of many commercial laboratories. However, the author's experience dealing with geothermal problems since 1980 is that the necessary empirical and theoretical relationships tend to be scattered throughout references that are not easily found by the typical geotechnical engineering practitioner. Therefore, the primary purpose of this appendix is to present all the necessary relationships in a single, concise source.

The thermal properties of rock appear to have been relatively less studied to date, at least for geotechnical engineering applications. In addition to consulting generalized, tabulated values in the various sources listed in the Selected Bibliography section of this report, practical guidance can be found in Coutermarsh and Phetteplace (1991a, 1991b), Coutermarsh (1997) and Coutermarsh and Carbee (1998). The last two references are probably the best to start with and at the time this report was finalized were available digitally in PDF format and at no cost via the Internet at <[www.crrel.usace.army.mil/techpub/CRREL\\_Reports/](http://www.crrel.usace.army.mil/techpub/CRREL_Reports/)>.

It is important to note that the information in this appendix should not be used with non-earth materials. Unless the necessary thermal-property data are already available from manufacturer's literature or other published literature, it will be necessary to determine the relevant property values experimentally in the laboratory.

### Coefficient of Thermal Conductivity, $k$

The classic reference work used for this is Kersten (1949) who developed empirical relationships in specific imperial units based on a comprehensive laboratory testing program. He found it necessary to distinguish between predominantly coarse- versus fine-grain soil as well as the unfrozen versus frozen states of each as follows:

- fine-grain/unfrozen:  $k = \left\{ [0.9(\log_{10} w_n) - 0.2] \times 10^{0.01\gamma_d} \right\}$  (A-1a)

- fine-grain/frozen:  $k = \left[ (0.01 \times 10^{0.022\gamma_d}) + (0.085 \times 10^{0.008\gamma_d} \times w_n) \right]$  (A-1b)

- coarse-grain/unfrozen:  $k = \left\{ [0.7(\log_{10} w_n) + 0.4] \times 10^{0.01\gamma_d} \right\}$  (A-1c)

- coarse-grain/frozen:  $k = \left[ (0.076 \times 10^{0.013\gamma_d}) + (0.032 \times 10^{0.0146\gamma_d} \times w_n) \right]$  (A-1d)

where  $k$  always has units of BTU-in/ft<sup>2</sup>-hr-°F;  $w_n$  = natural water content of the soil in percent and determined in the conventional manner relative to the dry weight of the soil<sup>g</sup>; and  $\gamma_d$  = dry unit weight of the soil in lb/ft<sup>3</sup>. When working with SI units, it is useful to note that 1 BTU-in/ft<sup>2</sup>-hr-°F = 0.144314 W/m-K.

<sup>g</sup> This is emphasized here because the water content of many synthetic thermal insulation materials such as EPS and XPS geofoams is traditionally calculated and expressed on a relative volume basis, i.e. volume of water in the material divided by the total volume of the material and expressed as a percent.

### Volumetric Heat Capacity, $c_v^h$

Theoretical relationships for this are given in many texts on the subject. Several that were consulted by the author when preparing this section of the report are listed in the Selected Bibliography section of this report. The only variation found between references is in the assumed specific heat of soil particles which varies between 0.17 and 0.20, with 0.18 reportedly an average (the different references variously use 0.17, 0.18 or 0.20). The average value of 0.18 is used here. Because this is a theoretical equation, any consistent set of imperial or metric units can be used.

It is necessary to distinguish between the unfrozen and frozen states:

- unfrozen: 
$$c_v = \left\{ c_{mw} \gamma_d \left[ 0.18 + \left( \frac{w_n}{100} \right) \right] \right\} \quad (\text{A-2a})$$

- frozen: 
$$c_v = \left\{ c_{mw} \gamma_d \left[ 0.18 + \left( \frac{w_n}{200} \right) \right] \right\} \quad (\text{A-2b})$$

where  $c_v$  has appropriate imperial or metric units (1 BTU/ft<sup>3</sup>-°F = 67066 J/m<sup>3</sup>-K in SI);  $c_{mw}$  is the mass heat capacity of water with appropriate imperial or metric units ( $c_{mw} = 1$  BTU/lb-°F = 4187 J/kg-K in SI);  $w_n$  = natural water content of the soil in percent and determined in the conventional manner relative to the dry weight of the soil; and  $\gamma_d$  = dry unit weight (when imperial units of lb/ft<sup>3</sup> are used) or density (when SI units of kg/m<sup>3</sup> are used).

### Volumetric Latent Heat of Fusion, $L_v$

A theoretical relationship is given by Sanger (1969). Again, any consistent set of imperial or metric units can be used:

$$L_v = \left[ (L_{mw} \gamma_d) \left( \frac{w_n}{100} \right) \right] \quad (\text{A-3})$$

where  $L_v$  has appropriate imperial or metric units (1 BTU/ft<sup>3</sup> = 37259 J/m<sup>3</sup> in SI);  $L_{mw}$  is the mass latent heat of fusion of water with appropriate imperial or metric units ( $L_{mw} = 144$  BTU/lb  $\cong$  333000 J/kg in SI); and the remaining terms were defined previously.

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<sup>h</sup> This notation should not to be confused with the *coefficient of consolidation* in soil mechanics.