

# ***Lessons Learned from Failures Involving Geofoam in Roads and Embankments***

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**by**

**John S. Horvath, Ph.D., P.E.  
Professor of Civil Engineering**

**Manhattan College  
School of Engineering  
Civil Engineering Department  
Bronx, New York 10471-4098  
U.S.A.**

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## PREFACE

A special book containing both invited and contributed papers documenting and discussing failures involving all types of geosynthetics in all types of applications is currently in preparation. The editors are a pre-eminent group of international experts led by Dr. Jean-Pierre Giroud, the founder of modern geosynthetics.

One of the invited papers that will appear in this book is titled “Lessons Learned from Failures Involving Geofabric in Roads and Embankments” and was authored by me. The original manuscript of this paper was prepared in mid 1998. By early 1999 it had been peer reviewed, edited and accepted for publication. Unfortunately, neither the publisher nor publication date of the book in which this paper will eventually appear is finalized as of this date. Therefore, to make the contents of this paper available to those interested in geofabric at the earliest possible opportunity I prepared this report. It contains the final, edited version of my paper.

John S. Horvath, Ph.D., P.E.  
Bronx, New York, U.S.A.  
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Subsequent to writing the original report, I was provided with technical information that was hitherto unknown to me in over 10 years of researching geofabrics. As a result of this information, I realized that there was a small factual error in one of the case histories (No. L2). This error does not change my assessment of the issues involved and suggested lessons learned from this case history.

Normally, once a research report is prepared it remains unchanged in time. Nevertheless, I decided it was appropriate to make this minor factual correction in this report in the same way that minor errors are corrected in multiple printings of books. Thus this revised report contains corrections to Case History L2.

As information, as of the date that this revised report was prepared there is still no indication as to when the book on geosynthetics failures will be published or by whom.

John S. Horvath, Ph.D., P.E.  
Bronx, New York, U.S.A.  
July 1999

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## EXECUTIVE SUMMARY

*Geofoam* is the generic term used to describe the family of geosynthetic products made of closed-cell foam materials. Geofoams have been used in a wide variety of applications since at least the 1960s, but primarily in roads and embankments to date (1998). Thus there is considerable experience on which to base an evaluation of geofoam failures, at least for the most commonly used geofoam materials, expanded polystyrene (EPS) and extruded polystyrene (XPS), in roads and embankments. Overall, there have been relatively few failures involving geofoam. Nevertheless, there have been some problems and lessons learned from them that have an impact on practice not only for roads and embankments but other applications as well. These lessons are primarily in the areas of material specification and lightweight fill and insulated pavement applications.

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## 1 INTRODUCTION

### 1.1 Purpose and Scope of Paper

The geosynthetic materials and their products that we now refer to generically as *geofoam* have been used in geotechnical applications since at least the 1960s. Thus only the term *geofoam* is relatively new (in use since the early 1990s) and there is actually more than 30 years of experience with various *geofoam* materials and products in actual applications. This allows meaningful conclusions to be drawn from both failures and non-failures of *geofoam* applications, and an assessment of lessons learned from *geofoam* failures is the primary subject of this paper. Although most *geofoam* applications and failure experiences to date (1998) involve roads and embankments, the lessons learned from *geofoam* failures are useful in the broad and growing range of *geofoam* applications.

Because of the perhaps surprisingly extensive experience to date with *geofoam*, the overall structure of this paper is to present broad lessons learned from *geofoam* failures rather than to focus on one or two failure case histories in great detail. Thus in each of the failure categories presented subsequently in Sections 3 and 4 of this paper, details are given only to the extent necessary to explain the observed failure mechanism and its cause(s). For most of the failures, additional details, sometimes voluminous, are contained in the cited reference for that failure mechanism. In the interest of brevity and focusing on the essential elements of the failure mechanism, these additional details have been omitted from this paper.

### 1.2 Definition of Failure

Because the focus of this paper is failure, it is useful to restate the civil-engineering definition of the term which is *loss of function*. Every structure (used here in the broadest sense and not limited to buildings) is built for some intended function or purpose. If that structure cannot perform its intended function or if it prematurely ceases to perform that function, the structure has failed from the perspective of its owner or user. Thus failure may involve what is called *serviceability*, e.g. excessive settlement of a building so that doors do not close properly, in addition to the traditional perception of failure as a *total loss*, e.g. collapse of building. Thus in assessing *geofoam* failures both *serviceability* as well as *total loss* are considered.

## 2 GEOFOAM: BACKGROUND INFORMATION

### 2.1 Introduction

Because many engineers are still (in 1998) unfamiliar with *geofoams* to varying degrees, a brief overview of those aspects of *geofoam* relevant to this paper is presented in this section. Additional details are provided by Horvath (1995b).

### 2.2 Materials and Products

*Geofoam* is a generic term that refers to any closed-cell foam material used in a geotechnical (on- or in-ground) application. *Geofoams* may be polymeric (plastic) or inorganic in composition. Thus in addition to the many different plastic *geofoams* available (polyethylene, polyisocyanurate, polystyrene, polyurethane) there is glass foam (cellular glass) as well as cementitious materials. Also, a *geofoam* material can be manufactured in a fixed plant or foamed in place which thus includes several types of foam grouts among *geofoam* materials. Finally, it is

possible to shape most geof foam materials (particularly those manufactured in a fixed plant) into a variety of products including geocomposites composed of different types of geof foam and/or other geosynthetics. Therefore, as with other types of geosynthetics, it is important to clearly identify the geof foam material and product when discussing any aspect of geof foam behavior including failures. This point is emphasized because a portion of the recent (up to 1998) literature on the subject of geof foam has not clearly identified the material and product involved.

Because most of the geof foam materials and products available today have been in use since the 1960s, there is considerable experience worldwide as to which geof foam materials and products are technically feasible and cost effective in the many geof foam applications tried to date (1998). This experience has revealed that the vast majority of geof foam applications are best satisfied using a polymeric foam made of polystyrene. There are two distinct types of polystyrene foam and collectively they are referred to as *rigid cellular polystyrene (RCPS)*, a term commonly found in American Society for Testing and Materials (ASTM) standards. However, for geotechnical engineering purposes it is both more common and useful to identify them individually as *expanded polystyrene (EPS)* and *extruded polystyrene (XPS)*.

EPS is formed in a unique two-stage, in-plant manufacturing process so that it has the texture of individual expanded beads that are permanently fused together thermally. This explains why in some countries EPS is referred to colloquially as *beadboard* although this term is deprecated in technical conversation and literature. EPS is naturally white in color (a useful distinguishing feature in practice) although certain EPS-geof foam products in some countries (e.g. Canada, United Kingdom) are colored solely for product marketing purposes. In addition, it has become increasingly common in certain countries (e.g. Canada, UK, USA) to sell otherwise generic EPS-geof foam products, regardless of color, under a tradename also for marketing purposes.

XPS is formed in a single, continuous, in-plant process that results in a material with a uniform cellular structure. XPS is almost always colored and tradenamed for marketing purposes, e.g. The Dow Chemical Company's blue-colored *Styrofoam*® line of XPS products. Note that the term *styrofoam* is a manufacturer's tradename of a particular type of plastic foam and thus must never be used generically to refer to plastic foam.

Because EPS and, to a much lesser extent, XPS have always dominated the geof foam market, it is not surprising that the relatively few geof foam failures have been documented in the literature involve only EPS and XPS. Therefore, the remainder of this paper focuses on these two geof foam materials and products composed of them. However, it should not be assumed that other geof foam materials are problem free in their use. There is simply no sufficiently documented published information to permit a discussion of failures involving these other materials. Similarly, the majority of geof foam applications to date (1998) involve roads and embankments so the geof foam case histories presented in Sections 3 and 4 reflect this. However, the lack of documented failures in other geof foam applications does not imply that failures in these applications could not occur.

### 2.3 Functions

Depending on the particular geof foam material and product used, geof foam can provide a wide variety of geosynthetic functions. With one exception, geof foam functions do not duplicate those provided by traditional planar geosynthetics.

The functions provided by geof foam are (arranged in chronological order of their first use in practice):

- *Thermal Insulation.* The large relative volume (approximately 98%) of gas enclosed in the cells of geof foam materials provides a significant thermal-insulative value and is, in fact, the

reason that most materials eventually used as geof foam were developed in the first place. As a matter of historical interest, the most-commonly used geof foam materials (EPS and XPS) were both invented circa 1950 although their first documented use as geof foam did not occur until the 1960s.

- *Lightweight Fill.* Geof foam materials, EPS in particular, can have a density as low as  $\sim 10 \text{ kg/m}^3$  which is less than 1% of that of normal earth materials (soil and rock). Nevertheless, the stiffness and strength of geof foam can be sufficient to support motor vehicles, trains, airplanes and even lightly loaded buildings. Thus geof foam is useful as a lightweight fill material.
- *Fluid Transmission.* This is the one geof foam function that duplicates a common function of other types of geosynthetics. The geof foam material can either be inherently highly permeable (most geof foam materials are not) or, more commonly, the final geof foam product can be shaped or cut so as to contain voids or channels for the fluid to flow through.
- *Vibration Damping.* The relatively high stiffness to density ratio of most geof foam materials makes them relatively efficient at damping the small-amplitude ground vibrations and even air-borne noise from motor vehicles and trains.
- *Compressible Inclusion.* Geof foam can be formulated to be highly compressible and thus efficient for use behind or above rigid/non-yielding structures. This allows what is called *controlled yielding* (movement) of the adjacent soil or rock which in turn reduces the load on the structure. The classical soil mechanics phenomenon of arching is one type of yielding that can be induced using a compressible inclusion as is the development of the active earth pressure state behind an otherwise non-yielding wall. trains.
- *Structural.* This function relates to some of the newest and still emerging (as of 1998) uses of geof foam such as panels of EPS as facing for mechanically stabilized earth walls (MSEW) and a variety of EPS and XPS products used as formwork for poured-in-place reinforced concrete foundations and walls.

It is important to reiterate that not all geof foams can provide each of these functions. In fact, only one geof foam material (EPS) can cost effectively provide each of these functions which accounts for its worldwide dominance as a geof foam material. Also, there are miscellaneous applications that do not fit into any of the functional categories mentioned above.

### 3 OBSERVED FAILURES: LIGHTWEIGHT-FILL APPLICATIONS

#### 3.1 Introduction

“Lightweight fill” is the most widely used geof foam function worldwide. The first documented use of geof foam as a lightweight fill material occurred circa 1970. Several different geof foam materials and products (EPS, XPS, polyurethane) were tried initially but by 1972 block-molded EPS (*EPS-block geof foam*) was established as the geof foam material and product of choice for this function. This has continued to the present (1998) and is expected to continue for the foreseeable future. Therefore, the only geof foam material and product considered explicitly in this section is EPS-block geof foam. However, XPS is mentioned where information relevant to it as well is discussed.

## 3.2 Case L1: Fires During Construction

### 3.2.1 Background Information

Polymeric materials are inherently flammable. Combustibility is often measured or expressed by the *oxygen index (OI)* of a material. The OI is the minimum relative proportion (expressed as a percent) of oxygen in some mixture of gases that is required to support combustion. Air is approximately 21% oxygen so if a material has an OI less than 21% it will burn freely in air. If the OI of the material is greater than 21%, it will not.

Polystyrene has an OI of 18% which means that EPS and XPS are inherently flammable. However, it is possible to incorporate an inorganic, bromine-based chemical into the raw material used to manufacture EPS and XPS so that final products are flame retardant and will not support combustion (they can still melt however). In the USA, ASTM specifications for flame-retardant EPS and XPS call for a minimum OI of 24% which is 3% greater than the OI of air. It is of interest to note that flame-retardant EPS or XPS cannot be identified visually nor are other engineering properties affected by the bromine additive.

### 3.2.2 Case History Details

Despite the worldwide availability of flame-retardant EPS-block geofoam, its use is neither universal nor guaranteed. Reportedly, flame-retardant EPS-block geofoam costs up to 10% more than non-flame-retardant EPS-block geofoam due solely to slightly higher raw material cost so it has been the practice in some countries not to specify flame-retardant EPS-block geofoam for economic reasons. This means that non-flame-retardant EPS-block geofoam is vulnerable to ignition during construction when the geofoam is exposed and there are potential sources of ignition from both construction operations (e.g. flame-cutting and welding of steel) as well as vandalism. Once the geofoam is covered, flammability is neither an issue nor a concern.

Frydenlund and Aabøe (1996) reported that two fires involving EPS-block geofoam have occurred in Norway during the period 1972-1995 (standard practice in Norway is, or at least was until recently (1998), not to specify flame-retardant EPS-block geofoam). Both fires occurred during construction and were due to welding steel members (not related to the geofoam blocks) too close to uncovered geofoam and thus considered to be contractor error. Total loss of the geofoam occurred within minutes in each case. Figure 1 shows one such fire. As dramatic as this photograph is, it should be kept in mind that these were the only reported fires during a 25-year period when hundreds of lightweight fill projects using non-flame-retardant EPS-block geofoam were constructed in Norway.

If fires have occurred in other countries where non-flame-retardant EPS-block geofoam is or has been used they have not been reported in the published literature.

### 3.2.3 Lessons Learned

***In general, when a polymeric geofoam product is used, consider the potential for fire whenever the geofoam will be exposed to the atmosphere during construction.***

As part of this evaluation, consider if it is possible to make the geofoam flame retardant and what cost premium is associated with this.

***For EPS-block geofoam in particular, do not assume that flame-retardant material will be supplied. Flame-retardant EPS-block geofoam should be specified explicitly if deemed desirable on a project.***



**Figure 1. Fire causing total loss of non-flame-retardant EPS-block geofoam being used as lightweight fill on a road project (Euroroad E6 in Vestby, Norway). This is one of only two known projects in the world where there was a total loss of EPS-block geofoam due to fire. The loss in each case was due to contractor error (courtesy of Mr. Tor Erik Frydenlund of the Norwegian Road Research Laboratory).**

Although the historical record for lightweight fill applications suggests that the probability of fire during construction appears to be low, many engineers prefer to accept the additional cost of flame-retardant EPS-block geofoam and specify it exclusively. In addition, in some countries (e.g. USA) commonly used geofoam materials such as EPS and XPS are routinely manufactured with flame-retardant raw material. However, it should not be assumed that flame-retardant EPS or XPS will be automatically supplied. Material specifications must include the appropriate language or reference specification if a flame-retardant material is desired.

### **3.3 Case L2: Fires Due to Outgassing from Insufficiently Seasoned Blocks**

#### **3.3.1 Background Information**

As part of their manufacture, all geofoam materials require the use of a gas referred to generically as a *blowing agent* to create the closed-cell texture shared by all geofoam materials. Different geofoam materials use different blowing agents. For EPS, pentane is almost always used (butane is used sometimes in Japan). Most other geofoam materials use a fluorocarbon (FC) family gas such as chlorofluorocarbon (CFC, now banned in most countries), hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) as the blowing agent.

After an EPS block is released from its mold during the final stage of manufacturing, thermal cooling of the heated block occurs rapidly. In addition, over time the blowing agent remaining in the cells of the EPS is passively replaced by air in a process known as *outgassing*. For EPS, outgassing occurs over a period of days to weeks which is relatively rapid compared to some other geofoam materials such as XPS which may take years to outgas all of their blowing agent. Slight material shrinkage accompanies the cooling and outgassing process for EPS. A plot of shrinkage versus time is provided by BASF AG (1992).

### 3.3.2 Case History Details

Miki (1996) summarized work published originally by Hashimoto (1994) that involved EPS-block geofoam used for construction of Kiba Park in Tokyo, Japan, in 1991. Toward the end of the placement of the geofoam, small fires were discovered burning simultaneously in approximately 40 to 60 separate locations despite the use of flame-retardant EPS-block geofoam. However, only about 500 m<sup>3</sup> of the 11000 m<sup>3</sup> of geofoam was lost due to melting.

A forensic investigation indicated that each fire occurred at a joint between blocks of EPS and what burned was not the EPS but the remnants of the butane blowing agent which outgassed after the geofoam was placed on site (the gas collected in the joints between blocks). The ignition source was believed to be sparks from a grinder used as part of construction. As often happens on relatively large EPS-block geofoam lightweight fill projects, the local manufacturer (called a *block molder*) on this project shipped EPS blocks relatively soon after molding to keep up with construction demand. On this project, the time between block molding and placement on site was reportedly as low as three days toward the end of the project when the fires occurred (the author is aware of one project in the USA where the time was reportedly less than 24 hours). Research in Japan after this fire incident indicated that even after three days of outgassing sufficient butane was still being generated to have caused this fire.

### 3.3.3 Lessons Learned

***Be careful of open flames or other heat sources on construction sites when any polymeric geofoam material is used.***

Even if the geofoam is flame retardant, it can still melt.

***Specify adequate seasoning of any geofoam product that uses a flammable blowing agent such as pentane or butane before placement.***

After the fire incident in Japan, specifications there for EPS-block geofoam now require a least a seven-day seasoning period between molding and block placement at a site to allow for adequate outgassing of the blowing agent. However, this seven-day period should not be taken as a universal standard. The reasons are twofold. First, the blowing-agent content in the raw material for EPS varies from country to country due to air quality regulations (pentane and butane are a type of *volatile organic carbon* or *VOC* and regulated in some countries). Second, the dimensions of blocks also varies even within a country depending on the mold size used. EPS blocks in Japan tend to be among the smallest in the world, typically 500 by 1000 by 2000 mm. By comparison, on a recent (1998) project in the USA (the innovative Gateway Centre in Chicago, Illinois, where the slab-on-grade and spread footing foundation for a building were both supported on EPS-block geofoam) blocks 1016 by 1219 by 4877 mm were used. The larger the block the longer is the distance the residual blowing agent must travel to outgas. Thus the minimum required seasoning time for large blocks may be more than seven days. Therefore, minimum seasoning period for EPS-block geofoam is something that should be determined separately for each country to reflect local practices.

## 3.4 Case L3: Premature Pavement Failure Due to Block Shifting Under Traffic

### 3.4.1 Background Information

Lightweight fills of EPS-block geofoam are constructed by placing individual blocks. However, load-deformation analytical methods used in routine practice for designing EPS-block

geofoam fills for both static and dynamic/cyclic loads assume that the geofoam behaves as a homogeneous mass. More than 26 years experience to date (1998) suggests that this assumption is usually reasonable provided certain guidelines are followed.

### 3.4.2 Case History Details

Duškov (1994, 1997a, 1997b) discussed a project in Rotterdam, The Netherlands, that involved the reconstruction of a street named Matlingeweg. The existing soil subgrade was partially replaced with EPS-block geofoam as a key part of the reconstruction to permanently reduce overburden stresses on underlying soft soils. A portion of the reconstructed street used only a single layer of EPS blocks 500 mm thick. The remaining portion used two layers of blocks. Within one month after the reconstructed road was opened to traffic in late 1990, cracking sufficient to be considered failure was observed in the asphaltic concrete wearing surface of the pavement system. All cracking occurred in a portion of the road with only a single layer of EPS blocks. A subsequent forensic investigation revealed that the EPS blocks had shifted at their joints. Relative movements between blocks both vertically (up to 5 mm as shown in Figure 2) and horizontally (resulting in gaps as much as 20 mm wide as shown in Figure 3) were found. The movements were attributed to failure to ensure intimate block contact during placement which would have maximized inter-block friction. No type of mechanical (barbed-plate) inter-block connector was used for any of the vertical joints but, in fairness, such connectors are rarely if ever used in this way. In addition, a line of vertical joints between blocks happened to coincide with one of the vehicle tire paths on the overlying asphaltic concrete which tended to concentrate vertical live loads at this particular joint location. This street was subjected to heavy traffic, including trucks, which certainly exacerbated the situation.



**Figure 2. Relative vertical movement of approximately 5 mm between blocks of EPS geofoam used as lightweight fill in the Matlingeweg street reconstruction project in Rotterdam, The Netherlands. This movement occurred within an portion of the street with a single layer of geofoam blocks and contributed to premature failure of the overlying asphaltic concrete pavement after one month of service (courtesy of Dr.-Ir. Milan Duškov of Oranjewoud International).**



**Figure 3. Relative horizontal movement and a resulting gap of approximately 20 mm between blocks of EPS geofoam used as lightweight fill in the Matlingeweg street reconstruction project in Rotterdam, The Netherlands. This movement occurred within an portion of the street with a single layer of geofoam blocks and contributed to premature failure of the overlying asphaltic concrete pavement after one month of service (courtesy of Dr.-Ir. Milan Duškov of Oranjewoud International).**



**Figure 4. New bridge approach fill under construction utilizing EPS-block geofoam as lightweight fill on Highway 7 at the Stave River in British Columbia, Canada. Important design details such as multiple layers of geofoam blocks and alternating block orientation, both of which contribute to the individual geofoam blocks acting as a single homogeneous mass, are illustrated (courtesy of Mr. Michael Tobin of AFM<sup>®</sup> Corporation).**

### 3.4.3 Lessons Learned

*Use at least two layers of EPS-block geof foam in lightweight fills where possible, especially for fills that will be subjected to dynamic and cyclic loads such as traffic by motor vehicles.*

The ability of an assemblage of EPS blocks to act as a homogeneous mass depends on a combination of inter-block interlocking due to judicious layout of the blocks as well as inter-block sliding friction, particularly along horizontal surfaces. Experience indicates that to achieve this requires at least two layers of blocks with attention paid in particular to laying out the blocks so that continuity of vertical joints is minimized.

Figure 4 illustrates typical good practice in the layout of an EPS-block geof foam lightweight fill. Note in particular how the length dimension of each block within a given layer is oriented perpendicular to the length dimension of blocks of the underlying layer. On this particular project, the sides of the fill are vertical and form what is called a *geof foam wall*. EPS-block geof foam is self-stable in this configuration and only requires a non-structural surface covering for long-term UV protection and architectural finish (the latter usually governs the specific type of covering used). Use of a geof foam wall as opposed to the more-traditional sloped arrangement of geof foam blocks with soil covering is increasingly common worldwide because of its cost effectiveness (less geof foam as well as less right-of-way acquisition is required).

## 3.5 Case L4: Unexpected Block Flotation

### 3.5.1 Background Information

The extremely low density of EPS and its closed-cell texture makes the material extremely buoyant in liquids such as ground water. Experience indicates that even when EPS blocks have been submerged for many years the relatively small volume of absorbed water does not significantly reduce their buoyancy. Therefore, for any EPS-block geof foam fill that may be subjected to submergence, there must be a dead-load stress on the geof foam or other physical restraint sufficient to counteract uplift forces due to water.

### 3.5.2 Case History Details

Frydenlund and Aabøe (1996) noted two cases, one in Norway in 1987 and the other in Thailand, where completed fills incorporating EPS-block geof foam floated during floods that occurred some time after construction. As a result, the overlying pavement systems were damaged to the point of failure and the fills had to be reconstructed. In the case in Norway, two separate fills in the Oslo area were affected by the same storm event. One of the fills had been in place 15 years at the time of the flood-induced failure. It is important to note that the 1987 flood event was unusually severe and produced a water level 850 mm higher than that assumed during design of the older (1972) fill.

### 3.5.3 Lessons Learned

*In areas where flooding of a lightweight fill is possible, choose the flood frequency assumed for design with care.*

In the author's experience, engineers generally recognize that they have to consider submergence and flooding where appropriate in the design of geof foam fills. However, the biggest problem is generally selecting an appropriate flood return period (frequency) and concomitant flood elevation. Choosing an overly conservative high flood elevation can make the

use of geofoam unfeasible because so much dead load has to be placed over the geofoam to counteract potential buoyancy that the fill settles excessively under normal (non-flood) conditions. In essence, the large dead load is working against the reason that geofoam was considered necessary in the first place. Therefore, it is sometimes necessary to allow some risk of buoyancy in extreme flood events in order to be able to use geofoam.

In a few cases, mechanical tie down of the geofoam using vertical passive ground anchors has been done to provide the desired uplift resistance for flooding. However, this has not been widespread to date (1998) and increases construction costs. Also, there is a relatively new (as of 1998) extruded open-cell polymeric product that has been developed for lightweight fill applications that eliminates the flotation issue because its cells can easily fill with water during flood events (Perrier 1997). While this product does not fit within the current (1998) definition of geofoam, the definition may be broadened in the future to accommodate such products that complement the existing suite of geofoam materials and products.

## **4 OBSERVED FAILURES: THERMAL-INSULATION APPLICATIONS**

### **4.1 Introduction**

The first documented use of foam as a thermal insulation material placed in the ground occurred in the 1960s. Several different geofoam materials were tried initially but within a few years EPS and XPS were established as the geofoam materials of choice for this function. This has continued to the present (1998) and is expected to continue for the foreseeable future. Therefore, EPS and XPS are the only geofoam materials considered in this section. Typically, relatively thin (25 to 100 mm thick) panels of EPS or XPS are used for this application.

### **4.2 Case T1: Water Absorption**

#### **4.2.1 Background Information**

Any water absorbed into a geofoam product will, as a minimum, increase the coefficient of thermal conductivity of the geofoam and thus reduce its thermal efficiency. This should be considered during the thermal design of geofoam used as thermal insulation. In addition, some geofoam materials (but not EPS or XPS) can have their mechanical (stress-strain) behavior negatively affected by absorbed water. Volume change (increase or decrease) of some geofoam materials (but not EPS or XPS) can also result from water absorption.

Geotechnical engineers should be aware of the fact that absorbed water in foam materials is always reported as percent on an absolute volume basis, i.e. volume of water as a percent of the total volume of the geofoam product. This is fundamentally and significantly different from how water content of earth materials is expressed which is on a relative weight basis (weight of water divided by weight of dry soil or rock). It appears that the reason water content of foams is expressed this way is because water is on the order of 50 times denser than most foam materials so a water content expressed on a weight basis would be a relatively large number (several hundred percent). While there is nothing inherently wrong with this, it does present a nuisance (writing large numbers) as well as has psychological and marketing impacts (large numbers imply large problems, which is not necessarily the case).

### 4.2.2 Case History Details

Experience indicates that both EPS and XPS will always absorb some water once installed in a geofoam application. Despite this fact, many engineers still do not consider water absorption in their thermal designs which can lead to underdesign and eventual potential underperformance of the insulation system. Therefore, current (1998) practice can be considered a failure in the broad sense although the specific effect on individual projects is difficult to quantify. This is exacerbated by the fact that water absorption often increases with time meaning that failure may take decades to develop.

Designing for water absorption is complicated by the fact that there are many variables affecting how much water will be absorbed in a given application. A review of the published literature provided by Horvath (1995b) indicates that the reported range in observed water absorption is relatively large.

### 4.2.3 Lessons Learned

*Geofoam materials will absorb water with time once placed in the ground. The long-term effect on geofoam material properties needs to be considered during design.*

Despite more than 30-years experience with using geofoam as thermal insulation, there are still no definitive design guidelines concerning absorbed water. At the present time (1998), the summary of observed ranges in practice as published by Horvath (1995b) remains the best guidance.

## 4.3 Case T2: Failure of Insulated Pavement Systems

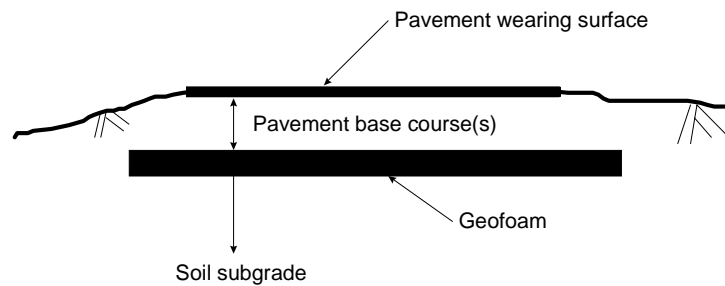
### 4.3.1 Background Information

The first widespread use of geofoam was for insulated road pavements. This began in the early 1960s more or less simultaneously in several countries in the northern hemisphere that experience significant seasonal freezing and thawing of the ground. The concept was later extended to airfield pavements and railway tracks.

Figure 5 illustrates a cross section through a typical insulated road pavement. The original goal was to use a sufficiently thick layer of geofoam (typically 50 to 100 mm) so that the soil subgrade beneath the geofoam would not freeze. One benefit of this is that there would be no frost heaving for subgrades composed of soil with heave potential. Another benefit is that there would also be no subgrade thawing in the spring so that thaw-weakening of the soil subgrade, the leading cause of potholes in pavements, would not occur either. It was common in early designs to place the top of the geofoam layer as close to the pavement surface as practical (of the order of 300 mm or less) based on calculated stresses from wheel loads compared to the strength of the geofoam material used.

In later years, designs were modified to allow some freezing of the subgrade beneath the geofoam. This was for economic reasons (a thinner panel of geofoam could be used) as well as to create smoother transitions to adjacent paved sections without insulation. Regardless of whether full or partial subgrade freezing protection was desired, the use of insulated pavements was viewed as less expensive than excavation and replacement of heave-susceptible soils or frequent, periodic maintenance of potholes, etc.

A variation of this application is used in areas of permafrost. Construction of a paved surface such as for a road or airfield disrupts the natural heat balance at and just below the Earth's surface. Over time, this causes the permafrost to permanently thaw from the surface downward.



**Figure 5. Schematic cross section of key components of an insulated pavement system.**

The thawed permafrost has a low undrained shear strength initially and consolidates with time. The combination of these factors can result in shear failures of embankments as well as significant total and differential thaw-consolidation settlement that affects both the trafficability and life of the paved surface. In this case, the use of geofoam thermal insulation serves to retard the inevitable permanent thawing of the permafrost and thus extend the life of the road or airfield.

#### **4.3.2 Case History Details**

Norway was one of the countries to pioneer the use of insulated pavements in areas of seasonal freezing. Refsdal (1987) summarized more than two decades (1964-1985) of insulated pavement use there, in part to examine why insulated pavements had never achieved (by the mid 1980s) the extent of potential use in Norway that was apparently envisaged by some when the technology was first developed. He found that one-third of insulated road pavements had suffered what was considered to be premature failure, typically shorter-than-expected pavement life due to excessive surface cracking. The primary cause of failure was judged to be a pavement base course with insufficient capacity due to low material strength and/or insufficient thickness. Other factors were (in the order given by Refsdal):

- thermal underdesign of the geofoam;
- low subgrade bearing capacity;
- geofoam panels placed on an uneven subgrade;
- overstressing (and resulting compression) of the geofoam panels during construction;
- road shoulders too narrow (insufficient lateral support for geofoam panels)

- difficulty adequately compacting pavement base course material above geof foam;
- effect of dynamic (vehicle wheel impact) loads on geof foam; and
- open joints between panels of geof foam.

In a more-recent case history involving both insulated road and airfield pavements in Jackman, Maine, USA, Kestler and Berg (1995) reported the unsatisfactory performance of the insulated airfield pavement. An extensive forensic investigation indicated that there were several contributing factors, all from the above list given by Refsdal. In addition, the author's personal experience with municipal road pavements in Anchorage, Alaska, USA, is that damage of the geof foam panels due to overstressing by vehicle wheel loads during construction was a significant factor contributing to failure of insulated pavements on some recent (1997) projects there. Part of this is due to the continued historical focus on compressive strength of geof foam materials even though it is now well known that compressive strength is not a relevant design parameter. Rather, an explicit deformation analysis that takes into account the elastic stress range and creep properties of the geof foam material is required. This issue is discussed in detail by Horvath (1995b).

### 4.3.3 Lessons Learned

#### *Insulated pavements require particular care in both design and construction.*

Insulated pavements and railway tracks remain (as of 1998) an underutilized geof foam application. In the author's opinion, this is largely due to lingering negative impressions formed during the late 1960s/early 1970s when the technology was new and somewhat problematic (an additional problem contributing to this is discussed separately in Section 4.4). More than 26 years of successful construction of geof foam lightweight fills proves that it is possible to design a pavement system above geof foam that will perform satisfactorily and to construct that pavement system without damaging the geof foam. However, care must be exercised during construction to ensure this. Road construction cannot proceed as if the geof foam were not there. This is quite similar to lessons learned with other types of geosynthetics, particularly those used in reinforcement applications.

The key guidelines for successful placement of geof foam whether as pavement insulation or lightweight fill are:

- The surface on which the geof foam panels or blocks are placed should be free of construction debris, reasonably dry, smooth (leveled to  $\pm 10$  mm over a 3 metre distance) and without large (gravel-size or larger) soil or rock particles on the surface.
- Construction vehicles should never traffic directly on the surface of the geof foam. A layer of soil from 150 to 450 mm thick (depending on the size of the compaction equipment to be used) should be pushed over the geof foam and then compacted. The remainder of the pavement system can then be constructed in the usual way. If heavy construction vehicles are to traffic over the geof foam, e.g. as a temporary haul road, then it is generally desirable to construct the entire pavement system except for the asphaltic concrete surface layer and place a temporary crushed-stone surface layer before permitting heavy vehicle traffic on the road. Once construction hauling is completed, the temporary crushed-stone surface can be removed or leveled and the asphaltic concrete surface layer placed.

Additional suggestions that are specific to insulated pavement and lightweight fill applications are given by Horvath (1995b).

#### 4.4 Case T3: Differential Icing of Pavement Surface

##### 4.4.1 Background Information

As discussed by Horvath (1995a), the use of any non-earth material beneath a pavement will alter the thermal balance between air and ground near the Earth's surface. In some cases, e.g. the use of geofoam to create an insulated pavement, this alteration is intentional. However, in other cases, e.g. the use of geofoam as lightweight fill, this alteration is incidental or unintended, which can lead to problems unless considered appropriately during design.

##### 4.4.2 Case History Details

As discussed by Refsdal (1987) and Horvath (1995b), early in the use of insulated pavements an unanticipated problem was noted. This problem was observed relatively soon after construction and is thus separate from Case T2 discussed in Section 4.3 which reflects longer-term problems.

The problem discussed here is referred to as *differential icing* and is a condition wherein a section of insulated pavement develops surface ice when an adjacent section of uninsulated pavement does not. This icing produces a potentially serious safety problem as drivers of motor vehicles encounter unanticipated ice. This problem is sometimes referred to colloquially as the *bridge-deck problem* because the well known phenomenon of bridge decks freezing before adjacent road sections on the ground is symptomatically identical although different as to cause.

The most extensive forensic study of the differential-icing problem was performed in Norway. The physical cause of differential icing is related to a natural phenomenon called *hoarfrost*. The optimum conditions for formation of hoarfrost occur at night and with a clear sky. At night, any surface (including the ground) radiates heat into the atmosphere. Clear-sky conditions maximize the radiation transmission rate. As a surface radiates heat, the surface temperature can drop below the air temperature. If there is sufficient humidity in the air and the surface temperature drops below the dew point of the air, the water vapor in the air will condense on the surface. If the surface temperature has dropped below the freezing point, the condensed vapor will freeze. This frozen condensate is hoarfrost. Note that hoarfrost can form even if the air temperature is above freezing depending on weather conditions.

The problem of differential icing of pavements is thus defined as formation of hoarfrost (on pavements, hoarfrost is often called *black ice* because the ice is clear and only the usually dark asphaltic concrete pavement surface is visible) on the surface of a section of road with an insulated pavement when an adjacent non-insulated but otherwise identical section of road does not develop hoarfrost. The reason that an insulated pavement section develops hoarfrost first is related to the natural stored heat in the ground and its ability to escape into the atmosphere.

Differential icing of insulated pavements was found to occur most often in the autumn for the following reason. In the autumn, the natural soil or rock subgrade beneath the pavement is unfrozen and still retains heat from the summer. For a non-insulated pavement, as heat radiates from the pavement surface, the lost heat can be relatively easily replaced by this stored heat as well as additional heat from the Earth's geothermal gradient flowing upward. However, when the pavement is insulated, the presence of the geofoam insulation significantly retards and effectively prevents the Earth's heat from leaving the underlying subgrade, especially during the relatively short duration of night. As a result, the limited heat held within the pavement system

above the geofoam layer is rapidly lost and the temperature of the pavement surface drops below the surface temperature of the adjacent non-insulated pavement. Thus under the right conditions the surface of the insulated pavement section can develop hoarfrost when an adjacent non-insulated pavement does not. In the studies performed in Norway and summarized by Refsdal (1987), insulated pavements were found to develop hoarfrost under an unfavorable combination of conditions when the air temperature was as high as +4°C and, in an extreme case, +11°C.

The differential icing problem and the publicity and attention it received at the time (late 1960s/early 1970s) contributed to insulated pavements never achieving the use that was anticipated initially. This underutilization continues to this day (1998) worldwide. For example, there are states in the USA that still ban use of this technology.

There are two important corollaries from the experiences with differential icing. First, although the phenomenon was first noted with insulated pavements, it can occur anytime a pavement is underlain by material with a coefficient of thermal conductivity lower than that of natural earth materials such as soil or rock. This includes geofoam lightweight fills well as fills that may utilize waste materials such as shredded rubber tires. Thus the potential for differential icing is a significant design consideration in many geofoam as well as non-geofoam applications other than insulated pavements. This has not been widely recognized or discussed to date.

Second, a reverse phenomenon can develop during summer months. In this case, solar heat entering the ground is trapped within the pavement system because the geofoam (or other non-earth material) retards the propagation of the heat into the Earth. The relevant result is that the temperature of the asphaltic concrete wearing surface becomes greater than that of an otherwise identical pavement underlain only by earth materials. It is well known that the Young's modulus of asphaltic concrete decreases with increasing temperature. This means that the strains within asphaltic concrete increase with increasing temperature for a given applied stress. The relevance of this is that cracking and eventual failure of asphaltic concrete pavement systems are related to strains developed under applied load. Therefore, it is possible that an asphaltic concrete pavement system underlain by any non-earth material, including geofoam, will deteriorate faster due to fatigue cracking than an otherwise identical pavement underlain by soil. Unfortunately, this phenomenon has never been studied in sufficient detail to evaluate whether or not it has significant practical importance.

#### **4.4.3 Lessons Learned**

*In areas of seasonal freezing, consider differential icing of pavement surfaces in both insulated pavement and lightweight fill applications.*

The lessons learned from differential icing of insulated pavements are equally applicable to applications involving any paved surface over a lightweight fill composed of geofoam as well as many other non-earth fill materials. As summarized by Horvath (1995b), the results of extensive study in Norway indicate that the potential for differential icing can be minimized or even eliminated if two equally important factors are considered. First, the distance between the top of the geofoam and the pavement surface needs to be greater (500 mm or more) than that used in early designs of insulated pavements (300 mm or less). Second, the pavement base course material placed above the geofoam should have some fines content to enable it to hold some water. A modest water content is desirable because water has a relatively large heat capacity and thus helps the pavement system retain more solar heat energy. Of course the fines content should not be too large as to make the base course material heave-susceptible or otherwise unacceptable from a geotechnical load-carrying perspective.

There is insufficient evidence at this time (1998) to state with any certainty whether or not the seasonal increase in asphaltic concrete pavement temperature caused by heat trapped by a

geofoam layer has a significant effect on reducing pavement life. The current (as of 1998) state of practice ignores this issue.

## **4.5 Case T4: Geofoam Damage Due to Insect Infestation**

### **4.5.1 Background Information**

EPS and XPS are non-nutritive to any living organism. Therefore, there is no potential that EPS or XPS placed on or in the ground will be consumed as a food source.

### **4.5.2 Case History Details**

In several places in the USA where relatively thin (25 to 50 mm thick) panels of EPS or XPS geofoam have been used as thermal insulation adjacent to wood-framed residential structures, significant physical damage of the geofoam has been observed subsequent to installation. This has been the result of certain insect species such as termites and carpenter ants tunneling through and/or nesting within the geofoam as part of their attack on the wood within the structure.

On the other hand, there is no known evidence that insect damage to geofoam has occurred in more general types of geotechnical applications such as insulated pavements or lightweight fills for roads. There was an active discussion of this topic at Session 6 of the International Symposium on EPS Construction Method (EPS Tokyo '96) that was held in Tokyo, Japan, in 1996 and reported by EPS Development Organization (1996) for this symposium. Based on the exhumation of a number of EPS-block geofoam lightweight fills around the world, one of which had been in the ground for 25 years, there was no observed insect damage to the geofoam.

Perhaps for any number of reasons the observed damage to relatively thin panels of geofoam used for insulation of residential construction has not been widely documented in the published literature. Literature on the subject is generally limited to brochure material for a proprietary EPS-block product that claims insect resistance (AFM Corporation 1994). This product is normal EPS block with a proprietary inorganic chemical added during the manufacturing process. The chemical additive is claimed to deter insect infestation. As information, the process used to manufacture XPS precludes its being treated with this chemical.

### **4.5.3 Lessons Learned**

*Consider the potential for insect damage to or infestation of geofoam at least in thermal insulation of residential construction.*

This issue is highly contentious within the USA at the present time (1998) as EPS-block geofoam treated for insect infestation is currently (as of 1998) available only in the USA, Canada and Puerto Rico from certain block molders. The potential extent and severity of insect infestation and how best to deal with it is the subject of ongoing debate. Therefore, definitive suggestions are not available at the time this paper was written. However, engineers and others should at least be aware of the fact that this issue exists.

It is worth noting that some engineers have specified that insect-resistant EPS-block geofoam also be used for lightweight fill projects despite the fact that there is no known evidence that this is necessary. On the other hand, using EPS-block geofoam treated for insect infestation does not affect the visual appearance or geotechnically relevant mechanical (stress-strain-time) or thermal properties of the geofoam so cannot be considered to be an unacceptable practice. In addition, where insect-resistant EPS-block geofoam is available its cost is reportedly not much higher than

that of untreated EPS-block geofoam although the exact cost differential is difficult to quantify as it is subject to market competition issues.

## 5 OBSERVED FAILURES: OTHER FUNCTIONAL APPLICATIONS

The experiences with geofoam installed primarily for functions other than lightweight fill or thermal insulation, primarily in roads and embankments, have not produced any documented failures to date (1998). However, this should not be taken that there are no failures in other functions and applications.

## 6 LESSONS LEARNED: FINAL COMMENTS

Overall, there have been relatively few documented failures of geofoam structures to date (1998) despite the use of geofoam since at least the 1960s. This itself is an important lesson. The implication is that, overall, geofoam materials, products and design practices up to the time this paper was written have provided durable structures. Nevertheless, those failures that have been observed provide several important lessons that are useful in routine practice (see Sections 3.2.3, 3.3.3, 3.4.2, 3.5.3, 4.2.3, 4.3.3, 4.4.3 and 4.5.3). These lessons apply to all aspects of geofoam design including material specification, construction specification and monitoring and design details.

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