Geofoam and Geocomb: Lessons from the Second Millennium A.D. as Insight for the Future

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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

On the eve of what is colloquially (but incorrectly) taken to be the dawn of the third millennium A.D., the Geosynthetic Institute (GSI) held its 13th annual conference (*GSI-13*) titled "Geosynthetics in the Future: Year 2000 and Beyond". The GSI, which is affiliated with Drexel University in Philadelphia, Pennsylvania, U.S.A., is currently headquartered in Folsom, Pennsylvania. The conference was held December 14-15, 1999 at the Philadelphia Hilton Airport Hotel.

It is believed that *GSI-13* was the first time there was a presentation related solely to geofoam at a GSI annual conference. To make things even more significant, the geofoam presentation, and accompanying paper, at *GSI-13* was invited personally by Prof. Robert M. Koerner, Ph.D., P.E., the director of GSI. The presentation on geofoam (the newly (1999) coined "geo" product category of geocomb was subsequently included given the complementary and synergistic relationship between geofoam and geocomb) was given on the first day of the conference by Prof. John S. Horvath, Ph.D., P.E. of Manhattan College. His presentation was titled "Geofoam and Geocomb: Lessons from the Second Millennium A.D. as Insight for the Future". Because of severe time restraints, Prof. Horvath’s actual presentation covered only a small portion of his conference paper of the same title. The presentation focused on the future of geofoam and geocomb and was, per explicit direction from Prod. Koerner for this "millennium" event, more lighthearted than would normally be considered appropriate for a professional/technical presentation although serious and significant messages were conveyed. The accompanying paper was, however, traditional in its professional and technical content and presentation.

A special proceedings volume containing all the papers of *GSI-13* will eventually be published (information on the exact venue and timing was unavailable at this time). However, to make the contents of Prof. Horvath’s paper available immediately to those interested in geofoam and geocomb this report has been prepared. It contains the complete, final, peer-reviewed version of Prof. Horvath’s paper with some technical corrections to the material on geocomb. This was to take advantage of new technical material that was received from a French manufacturer only one week prior to *GSI-13*. In addition, minor publication changes in font style and size as well as page layout were made to the camera-ready manuscript that was submitted for *GSI-13*.

ABSTRACT

Cellular materials, whether open- or closed-cell, are very efficient in load-bearing because of their ability to support relatively large loads with relatively small amounts of material. There are now two geosynthetic families of non-planar (three- dimensional) cellular materials and products, geofoams (closed cell) and geocombs (open cell), that bring the technical attributes and cost effectiveness of cellular materials to geotechnical applications.

This paper provides a summary of geofoam and geocomb usage to date as a background for the focus of this paper which is future trends and developments of these technologies. Overall, geofoams are much more versatile than geocombs in terms of actual and potential applications. In addition, geofoams are a relatively mature geosynthetic technology with global usage dating back to at least the 1960s. Consequently future geofoam developments are expected to consist primarily of developing incremental improvements and fine tuning of the technology in several broad areas:

- Additional laboratory testing and constitutive-model development to increase the existing knowledge base in these areas and expand the capabilities of numerical modeling.
- Development of proper generic standards and specifications covering all geofoam materials, products and functional applications.
- New applications for existing geofoam materials and products. Examples include using EPS-block geofoam as lightweight fill in flood levees and crash barriers along roadways.
- New geofoam products based on existing geofoam materials, targeted to specific geotechnical applications and markets. Examples include several EPS products developed in the U.K. for specific applications such as MSEW facing panels and ground-borne gas drainage.
- New geofoam materials and products based on existing foam materials, targeted to specific geotechnical applications and markets. An example is the use of elasticized (resilient) EPS as a compressible inclusion behind earth retaining structures. Prior to its first geofoam use in the mid 1990s, elasticized EPS had been used for decades in non-geofoam applications.
- New geofoam materials and products based on new foam materials, targeted to specific geotechnical applications and markets. An example is the geosynthetic sheet drain developed circa the 1970s based on glued polystyrene spheres, a foam material apparently developed solely for this geotechnical application as it has no other known application, geotechnical or otherwise.

With regard to geocombs, this technology appears to have much more limited application and room for technological growth. In addition, it is far less advanced compared to geofoams as geocombs have been used only since the 1980s and in a much more limited geographical area (France and its affiliated territories). Consequently, future geocomb developments will likely consist primarily of a wider geographical spread of existing technology as well as research into optimization of material selection. Material testing and development of standards and specifications is also anticipated to bring geocomb technology up to the level of geofoam.

INTRODUCTION

Background

The upcoming change in millennia is causing worldwide reflection on the past and future. The theme of the Geosynthetic Institute's (GSI's) 13th annual conference (*GRI-13*), "Geosynthetics in the Future: Year 2000 and Beyond", is certainly consistent with this ongoing global introspection. Because history can be such an excellent teacher, it is perhaps best to base our thoughts of the future on persons and events in the past.

This paper and its summary presentation at *GRI-13* draw on two disparate persons from the second millennium anno domini (A.D.): Christopher Columbus (1451-1506) and Richard Buckminster "Bucky" Fuller (1895-1983). Columbus sought, among other things, to disprove the then widely held perception that the Earth is flat. Fuller is recognized for his intellectual genius in many areas. Of particular interest here was his broad conceptual appreciation for, and inventive devotion to, making less material do more work. As a corollary to this was his interest in working with, rather than fighting, the forces of nature. This is well summarized in the following quote attributed to him:

"Don't oppose forces; use them."

And so the geosynthetic subjects of this paper, geofoam and geocomb, make the points taken from Columbus and Fuller that:

- Not all geosynthetics are planar (two-dimensional) as has traditionally been defined. Geosynthetics technology and society as a whole can only benefit from all those involved with geosynthetics accepting and promoting three-dimensional geosynthetic materials such as geofoam and geocomb.
- Sometimes it is more effective technically and more efficient cost wise to reduce forces on a structure (something geofoams and geocombs excel at) rather than to increase the strength of the structure as has been the traditional approach using planar geosynthetics and, in fact, civil engineering materials in general.

It is certainly not the premise of this paper that geofoams and geocombs are unilaterally superior to traditional planar geosynthetics or traditional materials used in engineered construction (steel, portland cement concrete, etc.). Rather the premise is that geosynthetics of all types should and can coexist in a complementary and synergistic manner to achieve the optimum solutions to geotechnical problems.

Geofoam and Geocomb

Because the term geofoam, which was coined by the author, has been used in publicly published documents only since 1992, there is still some confusion as to its definition. Quite simply, geofoam is the generic family name for any closed-cell foam material or product used in a geotechnical application. Geofoam is now recognized worldwide as a geosynthetic product type or category.

As in any family with multiple members, because the term geofoam encompasses a wide range of materials and products it is always necessary to clearly identify the specific geofoam material and product being discussed. Again, this is similar to what is done with other types of geosynthetics. For example, it is necessary to specify a specific polymer, product thickness, surface texture and other properties to completely describe a geomembrane.

The term geocomb, also coined by the author, is of more recent (1999) vintage and is used to define open-cell extruded materials that, in cross-section, have a honeycomb appearance. Such products were formerly called "ultra light cellular structures" (ULCS).

Purpose and Scope of Paper

The materials used in engineered construction are undergoing significant changes. Traditional materials such as structural steel and portland cement concrete are now routinely of significantly greater strength than used even just a few years ago. New, more durable mixtures for asphaltic concrete have been heavily researched in recent years and are now entering routine use. Simultaneously, recycled materials as well as innovative manufactured materials such as plastics, inorganic fibers and composites are seeing increasing use in construction.

As part of this ongoing materials revolution in engineered construction, the 1990s has seen a rapid increase in the global recognition and use of geofoam after decades of underutilization in many countries, including the U.S.A. At the very close of the 1990s, there are indications of a similar growing interest in geocombs.

In keeping with this theme of changing trends in construction materials as well as the theme of *GRI-13*, the primary purpose of this paper is to explore the future research and development (R&D) directions and needs of geofoam and geocomb technologies. Such R&D efforts are necessary to sustain and grow any technology in an orderly, rational fashion.

In addition to the forward-looking focus of this paper, the past and present of geofoam and geocomb technologies are reviewed briefly as this information provides the necessary basis for planning for the future. As such, this paper also serves as a brief primer for those not already familiar with geofoam and geocomb.

The majority of this paper is devoted to geofoam. This simply reflects the much wider diversity of materials, products, applications and historical usage of this family of materials compared to geocombs.

Organization of Paper

The specific sections and contents of this paper are as follows:

- Primer. Although geofoams have been used worldwide since at least the 1960s, they are still relatively unknown to end users (civil/geotechnical engineers, architects, etc.) in many countries including the U.S.A. Furthermore, even many people in the foam industry are unaware of the full range of geofoam applications of their products. With regard to geocombs, they are relatively unknown outside of France and its affiliated territories where they have been used since at least the 1980s. Therefore, a brief primer on geofoam and geocomb materials is given for the benefit of those just learning about them.
- Past. Geofoam and geocomb product and application evolution, and past usage are summarized to provide an understanding of current practice.
- Present. A summary of the current state of geofoam and geocomb usage is presented to provide a basis for suggested future research and development.
- Future. This is the primary focus of this paper. Specific suggestions for developing the various aspects and applications of geofoam and geocomb technology are given.

The portions of this paper that present background information on geofoam represent a heavily abridged version of material discussed in much greater detail in the comprehensive monograph on geofoam published previously by the author (Horvath 1995). Therefore, interested readers are directed to that reference for additional information on these topics. Some updated information developed since the publication of this monograph is also provided where relevant.

The portions of this paper dealing with the future of geofoam technology represent an updated version of material presented previously in Horvath (1995). Because geofoam technology in particular is an ever-changing topic, interested readers can keep track of future developments for both geofoam and geocomb via the Internet by visiting *The Geofoam WWW Site*™ (http://www.geofoam.org).

The portions of this paper that deal with geocomb reflect material found in greater detail in *Matériaux* (1997) and Perrier (1997). These two references are the primary English-language state-of-art references available on the geocombs.

A BRIEF PRIMER

Functions

Because they are geosynthetics, the correct way to design with both geofoam and geocomb is to *design by function*, a process that has proven effective with other types of geosynthetics (Koerner 1998). Design by function is a design philosophy rather than a particular methodology. It simply means that the geosynthetics end user (civil/geotechnical engineer, architect, landscape architect, specifier, builder, etc.) first decides which one or several of the many available geosynthetic functions is (are) required to be provided in a particular project application, then selects the geosynthetic product(s) that will satisfy these needs most cost effectively.

The specific functions offered by geofoams and geocombs are itemized and discussed in the next section of this paper. However, there are several broad aspects regarding the functions provided by geofoam that are particularly noteworthy at this point:

- <u>Unique functions</u>. With the exception of fluid transmission (drainage) where there are several competing types of geosynthetics and lightweight fill (only geocomb), geofoam functions do not duplicate those of any other geosynthetic material, product or geocomposite. Therefore, geofoam provides the end user with several unique functional tools for solving geotechnical problems. In general, geofoams work best when used to reduce naturally occurring forces such as from gravity and earthquakes rather than to strengthen or stiffen a structure to resist these forces.
- <u>Multi-functionality</u>. Depending on the specific material and product used, geofoam can be inherently multi-functional. This increases its cost effectiveness in many applications because several technical and financial benefits can be derived from using only one geofoam product.
- <u>Complementary</u>. Geofoam products are rarely used alone. In most geofoam applications, one or more other type of geosynthetic is (are) used. In some cases, the other geosynthetic (e.g. a geotextile) is actually part of a geofoam-based geocomposite. Therefore, geofoams complement the use of other geosynthetic products.
- <u>Synergy</u>. Geofoam products allow the use of other types of geosynthetics (especially geogrids and other tensile-reinforcement products) in applications where these other geosynthetics were heretofore of little or no use. Therefore, there are applications where geofoam and other types of geosynthetics can be combined synergistically to produce new, unique results that would not be possible otherwise.

Overall, because of geofoam usage there is increased collateral usage of other types of geosynthetics of all types (geocells, geogrids, geomembranes, geotextiles) that would not occur had geofoam not been used.

Although geocombs are much more limited than geofoams in their functional applications, their niche is to complement and work synergistically with geofoams in certain applications where a lightweight fill material is desired. Among geosynthetics, only geocomb and geofoam can provide the function of lightweight fill.

It is important to recognize that two important aspects of geofoam and geocomb usage apply regardless of the specific geofoam material, product, function or application:

- Both geofoam and geocomb can be used as part of a cost effective design alternative not only in new construction but also in the rehabilitation or renovation of existing structures. With particular regard to existing structures, it is often more cost effective to use geofoam and/or geocomb to reduce forces acting on a structure, for example, than to increase the strength of the structure to resist the forces that would exist without geofoam. This is particularly true when structures are being upgraded to resist forces such as from seismic loading that may not have been considered when the structure was originally designed and built. This philosophy of load reduction as opposed to strength increase is the opposite of what is usually emphasized in civil engineering education and practice so a certain amount of change in thinking and habit is required among end users to be able to visualize and utilize the full spectrum of geofoam benefits.
- Contrary to a common perception, geofoam and geocomb are not just useful in "poor" soil conditions or on "big" projects. They can be a cost-effective alternative in any type of soil or rock condition and for projects of any size.

In summary, the overall success of both geofoams and geocombs derives from the fact that they work with the forces of nature rather than resisting natural forces as construction materials are traditionally designed to do.

Materials

Geofoam

Definition. The current definition of geofoam was developed by the author in the early 1990s and formally stated in Horvath (1995). It is repeated here for the sake of completeness and to dispel misinformation currently being promulgated on this issue.

Geofoam is any manufactured material created by some internal expansion process that results in a material with a texture of numerous, closed, gas-filled cells. The cell walls are solid although generally relatively thin and permeable to gases. Manufacturing can be in a fixed plant or in situ at a project site. Most geofoam materials are polymeric (plastic) but glass (cellular glass) and cementitious foams have been and are used. Although gases (called blowing agents) other than air are typically used in manufacturing geofoams, with time (which can vary widely depending on the geofoam material, a fact that many fail to consider properly when designing) the cells of a geofoam material usually become filled with air. Note that the definition of geofoam is intentionally broad to allow inclusion of materials such as foamed portland cement concrete (e.g. *Elastizell*®) as well as foam grouts.

It is worth noting that there is a relatively recent and ongoing effort within ASTM Committee D-35 (Geosynthetics) to alter this universally accepted definition of geofoam but in a regressive, restrictive way. Specifically, this ASTM effort is seeking to significantly restrict the definition of geofoam to polystyrene foams. There are even some who believe that the term geofoam should apply to one specific type of polystyrene foam, expanded polystyrene (EPS, which happens to be the most commonly used geofoam material). This current ASTM effort is, in the author's opinion, biased and misguided in its goals and potentially a future source of significant and needless confusion should standards development continue in this vein.

Polystyrene Foams. One of the reasons for the current ASTM effort to restrict the definition of geofoam is believed to have its origins in the fact that polymeric materials have always dominated the geofoam market. Although several different polymers have been tried in geofoam applications the one used most often by far is polystyrene. There are two ways to manufacture polystyrene foam:

- By a two-stage, molded-bead process that produces "molded expanded polystyrene" or, as it is more simply and commonly called, "expanded polystyrene" (EPS). EPS is the white foam familiar for its numerous non-geofoam consumer applications such as beverage cups and cushion packaging. Because the individual beads (produced during the first stage of manufacturing) can generally been seen in the final product, EPS is sometimes referred to colloquially as *beadboard* although the EPS industry generally deprecates the use of this term. Pentane, a naturally occurring hydrocarbon gas, is typically the blowing agent used to manufacture EPS although different blowing agents have been and are used in some countries (e.g. butane in Japan).
- By a continuous extrusion process that produces "extruded expanded polystyrene" or, as it is more commonly called, "extruded polystyrene" (XPS). A simple way to identify XPS geofoam is that in most countries it is colored for proprietary marketing purposes. For example, in the U.S.A. XPS geofoam is always colored either blue, green, pink or yellow depending on the manufacturer. On the other hand, EPS geofoam is generally (at least in the U.S.A.) left in its natural white color. It is of interest to note that fluorocarbon gases have been and still are used in the manufacturing of XPS. Chlorofluorocarbon (CFC) was used for many years but now that it is banned internationally for environmental purposes gases such as hydrochlorofluorocarbon (HCFC), hydrofluorocarbon (HFC) and possibly others are used or under study. It is suggested that users of XPS ask the supplier or manufacturer what blowing-agent gas is being used as this has potential environmental as well as engineering property implications (the thermal conductivity of XPS can be affected by the blowing agent used).

Collectively, EPS and XPS are referred to generically by ASTM as "rigid cellular polystyrene" (RCPS). As a matter of historical interest, both EPS and XPS were invented circa 1950.

It is important to note that polymeric foams should never be referred to generically as "styrofoam", a practice that, unfortunately, appears to be almost universal in the U.S.A. and possibly elsewhere. *Styrofoam®* is actually the registered trademark of a particular brand of blue-colored XPS products manufactured by The Dow Chemical Company that are available in the U.S.A. and elsewhere. As always, correct generic terms such as EPS and XPS should be used unless a particular product is indeed intended.

Because RCPS has always and still does dominate the geofoam market (which explains why many mistakenly equate geofoam with RCPS), the remaining portions of this paper that are devoted to geofoam will focus on EPS and XPS.

Geocomb

The term *geocomb* was coined to have a concise "geo" name to replace the unwieldy term ultra light cellular structures that has been used to date. Concurrent with this change in terminology the author defined geocomb as any manufactured material created by an extrusion process that results in a final product that consists of numerous open-ended tubes that are glued, bonded, fused or otherwise bundled together. The cross-sectional geometry of an individual tube typically has a simple geometric shape (circle, ellipse, hexagon, octagon, etc.) and is of the order of 25 mm across. The overall cross-section of the assemblage of bundled tubes resembles a honeycomb which gives rise to the name geocomb. Only rigid polymers (polypropylene and PVC) have been used to date as geocomb material.

Products

Geofoam

Expanded Polystyrene (EPS). There are two primary way to mold EPS into a final product:

- "Block molding" which produces prismatic blocks (sometimes referred to in the past as "billets") with finished dimensions that, in the U.S.A., were until recently typically 600 mm thick, 1200 mm wide and 2400 mm long. Blocks that are up to 1 m thick and/or 5 m long are increasingly common with newer molding equipment and can offer economies in some geofoam applications. Block sizes in other countries often vary somewhat from these dimensions depending on locally available molding equipment as well as other factors but are generally not smaller than 500 x 1000 x 2000 mm. Block size per se is generally irrelevant in geofoam applications although it does affect design details such as block layout in a lightweight fill for example. Blocks can be cut into panels or pieces of various shapes for specific applications where full-size blocks are neither required nor desired. Factory cutting using a special hot-wire cutter is generally preferred for economy and precision, but field cutting using a mechanical saw (chain or wire) or portable hot-wire cutter is also possible. Geofoam products that result from using either an entire or partial block are generically called "EPS-block geofoam". This has been and still is the predominant type of EPS geofoam and the predominant geofoam product overall worldwide. Because EPS-block geofoam is the most commonly used geofoam product worldwide, it has become increasingly common for manufacturers (molders) to tradename and even color this generic product for marketing purposes. One of the very useful aspects of EPS-block geofoam is that it can be manufactured over a range in densities. This is relevant because if the EPS block is manufactured to certain minimum quality standards, then (and only then) can density be a useful index property for material compressibility, etc. in the same way that particle-size distribution of coarse-grained soils or Atterberg Limits and water content of fine-grained soils are useful index properties of soils.
- "Custom shape molding" which produces pieces with specific shapes. In non-geofoam applications, common examples of shape-molded EPS products include the ubiquitous white foam coffee cup and the cushion packaging used around consumer electronics and appliances. Shape-molded EPS products for geofoam applications (called "EPS-shape geofoam") were rare until the last few years. This appears to be changing rapidly, especially in some countries such as the United Kingdom (U.K.).

There is a variation on block molding that the author calls "slab molding" in which relatively thin (of the order of 100 mm maximum) panel-shaped pieces are produced directly (as opposed to cutting a panel from a thicker block), sometimes with a custom shape on one face of the panel so that it is actually a slab-shape hybrid. Such products for geofoam applications are globally relatively rare (although regionally common, with Canada and the State of Alaska in the U.S.A. being two examples) because of the highly specialized molding equipment required and relatively limited geofoam applications where such products are necessary or cost effective. There are other niche geofoam materials derived from or related to EPS such as elasticized (resilient) EPS block and glued or molded polystyrene porous block that are described in Horvath (1995).

Geocomposite products that utilize EPS or EPS-related materials as a component are becoming increasingly common. One example that has been available for many years throughout the world is a panel-shaped piece of glued polystyrene porous block (a geofoam material related to EPS) with a geotextile attached to one face of the panel. This product is available in several countries including the U.S.A. where it is called *GeoTech Insulated Drainage Panel®*. Another geofoam-based geocomposite is the *GeoTech Geoinclusion®* which is available only in Canada and U.S.A. at the present time. This product uses a panel-shaped piece of either elasticized or normal EPS-block geofoam as its primary component plus a drainage geocomposite (which itself may use geofoam) that is attached to one face of the panel.

Extruded Polystyrene (XPS). XPS is produced primarily in relatively thin (typically up to 100 mm maximum) plank- or panel-shaped pieces. It is possible to custom-extrude a particular shape but the distinction between planks and shapes in geofoam terminology is not done (at least to date) as it is for EPS. Consequently, the term "XPS geofoam" is used collectively to refer to any XPS product used in a geofoam application.

Geocomb

Geocomb products manufactured to date consist of a family of block- and panel-shaped products targeted for different applications but each with the similar characteristic that the axes of the bundled tubes are oriented parallel to the thickness (minimum) dimension of the block or panel. The block-product dimensions produced to date appear to be of the same order of magnitude as full-size blocks of EPS geofoam (500 x 1000 x 2000 mm). The panel-shaped products have a range of thicknesses with the minimum of the order of 50 mm. Geocomb blocks and panels are typically placed in the ground with the bundled tubes oriented vertically.

In most cases, the open ends of the geocomb blocks and panels are covered with a geotextile. The purpose of this is to prevent soil particles from entering the open ends of the tubes once the product is buried in the ground.

Durability

Geofoam

Durability of geosynthetics in general has been a subject of great interest in recent years. Overall, the durability of EPS and XPS geofoams is excellent, with no problems involving polymer breakdown or other chemical changes as can affect other types of geosynthetics. There is in-ground experience dating back to the 1960s to support this. A complete discussion of the topic can be found in a recent state-of-art discussion of geofoam failures (Horvath 1999a, 1999b). The former reference can be viewed and downloaded via the Internet at *The Geofoam WWW Site*.

Typically, the only concern with EPS and XPS geofoams is that they might need to be protected from liquid petroleum hydrocarbons such as gasoline and diesel oil with a geomembrane or other barrier in some applications. When selecting a geomembrane, there is some experience from non-geotechnical (roofing) applications which suggests that EPS and XPS should not be placed in direct contact with PVC geomembranes. Reportedly the plasticizer in the PVC can migrate with time into the EPS/XPS causing the foam to soften and the PVC to become brittle.

There are also a very few applications (thermal insulation around the below-ground space of wood-frame residential buildings is the one in particular) where there have been problems with damage by certain burrowing insects such as termites ("white ants") and carpenter ants ("black ants"). Although neither EPS nor XPS is a nutritive food source for any known living organism, insect burrowing for habitation and/or to access wood on the other side of the foam has been found to occur. A passive, inorganic, USEPA-approved treatment against potential insect infestation called *Timbor* has been developed for EPS block but not XPS. EPS block with this treatment is available throughout the U.S.A. as *R-Control Perform Guard*® as well as other tradenames regionally in the U.S.A. (e.g. Polyfoam Packers Corporation's *Bug Block-R*™ or *Teps*™).

Geocomb

Geocombs have been used to date significantly less and for much less time than either EPS or XPS geofoam. Therefore, their durability should be considered somewhat unknown at this time although the limited published literature (*Matériaux* 1997, Perrier 1997) suggests satisfactory durability for all typical geotechnical exposure parameters except ultraviolet (UV) radiation. As a first-order assessment of durability, it appears reasonable to assume that the durability of geocomb of a certain polymer would be similar to the same polymer used for another type of geosynthetic. Thus the knowledge gained for polypropylene and PVC in general might be of use in assessing geocomb durability.

THE PAST

Geofoam

Overview

As noted previously, foams have been used successfully in geotechnical applications since at least the mid 1960s. However, most engineers are unaware of this history of usage that is longer than for almost all other geosynthetic products so a brief review of geofoam history is presented in this section. This section is also used to introduce and describe each of the geosynthetic functions that geofoam can provide.

Functions and Their Applications

Thermal Insulation. EPS and XPS were both used initially to provide thermal insulation, first above ground (1950s) and then below (1960s). Foams in general are very efficient thermal insulators because they are approximately 98% to 99% gas by volume (as noted previously, the gas trapped in the cells of most foams is air, at least in the long term) and gases are typically very efficient thermal insulators. Therefore, it is perhaps not surprising that the first known application of what we now call geofoam was as thermal insulation of:

- road and airfield pavements, and railway track systems to prevent or at least reduce seasonal frost heaving and thawing or retard thawing in permafrost areas;
- the below-ground portions of buildings to reduce seasonal heating and/or cooling requirements;
- beneath refrigerated storage buildings and sports arenas to prevent freezing and heaving of the underlying ground and
- beneath on-grade storage tanks containing cold liquids, also to prevent freezing and heaving of the underlying ground (one of the relatively few applications where glass foam was and is used almost exclusively).

Known examples of these applications date back to the mid 1960s.

Each of these applications was successful overall with respect to the original primary goal(s). Unfortunately, unexpected problems developed with pavement insulation because of a phenomenon called "differential icing" (see Horvath (1999a, 1999b) for a detailed discussion of this phenomenon). This led many early users of insulated pavements, especially government agencies (typically state departments of transportation in the U.S.A.), to limit or ban outright the future use of insulated pavements. This is unfortunate as insulated pavements can be quite effective in reducing pavement damage such as potholing (which can also be a safety hazard) due to frost heaving and concomitant thawing. Extensive research into the causes of differential icing was subsequently conducted in Scandinavia, especially at the Norwegian Road Research Laboratory (NRRL). This led to the development of design strategies that eliminate or at least minimize differential icing. However, despite the availability of knowledge to design against differential icing, the use of insulated pavements has never achieved its potential for use, especially in some countries such as the U.S.A.

(Ultra)Lightweight Fill. Geofoams, especially polymeric ones such as EPS block, are unique materials in that they have a density that is only about 1% to 2% of the density of soil and rock yet because of the structural efficiency of their cellular structure are sufficiently strong to support many types of loads encountered in geotechnical applications, especially transportation facilities (e.g. road and rail embankments). Thus one of the earliest functions of geofoam that was developed was its use as a lightweight fill material (some have used the term "ultralightweight" which is arguably a better term, at least for EPS-block geofoam, but one not widely used) in a wide variety of earthworks. The general benefit of using geofoam as opposed to other materials in earthworks is the significantly reduced stresses on the underlying subgrade. This can have multiple benefits in terms of reduced settlements, increased stability against bearing and slope failures, etc.

The exact origins of using geofoam as lightweight fill are contentious and, unfortunately, even up to the present often acrimonious. However, what can be stated without dispute is that the use of geofoams as lightweight fill began in several countries, including the U.S.A., more or less simultaneously circa 1970. While both EPS block and XPS were tried initially in this function, the economics have always been, and still are, clearly in favor of EPS block. Equally clear is that the credit for the systematic development of the use of EPS-block geofoam as lightweight fill belongs solely to the Norwegian Road Research Laboratory (NRRL). The NRRL has also been very generous in sharing their knowledge with others without seeking any patent royalties or similar compensation. In addition, the first international symposium on using EPS-block geofoam as lightweight fill (organized by the NRRL in 1985) was the catalyst for its use in other countries, especially Japan where significant additional research and development (especially with regard to creating the entire state-of-knowledge for seismic loading) has been conducted since 1985.

It is interesting to note that the use of EPS-block geofoam as lightweight fill has tended to flourish in those countries such as Norway and Japan where a government (Norway) or industry (Japan) organization either already existed (Norway) or was established (Japan) to promote its use. On the other hand, in countries such as the U.S.A. where there was (and still is to a significant extent) chronic indifference by both industry and government to geofoam technology and its promotion to end users the use of geofoam in general as lightweight fill has languished. This is pointed out because many engineers in countries such as the U.S.A. have an initial distrust of geofoams in general from the viewpoint of "how come it has been around so long but used so little?" Clearly, the lack of meaningful promotion and technology transfer by the geofoam industry and government agencies is the root cause, not some hidden technical shortcoming.

Compressible Inclusion. Beginning in the mid to late 1980s (as with so many things, the exact origin is difficult to pin point), it was noted that some geofoam products (glued polystyrene porous block and EPS block in particular) could be used in applications where significant compressibility and relatively large deformations were desired. Examples of such applications are above underground conduits (pipes, culverts, small-diameter tunnels) to induce vertical arching or behind non-yielding (non-moving) earth retaining structures to induce lateral arching and the active earth pressure state (or lower). In each of these applications, the benefit of using geofoam for what is called the "compressible inclusion" function is a significantly reduced load on a structure (conduit, wall, etc.).

Fluid Transmission (Drainage). Typically, geofoam materials are like most solid materials in that they possess very low primary (inherent) permeability for liquids and only a modest permeability at best for gases. However, both EPS and XPS geofoam products can be manufactured to have a geometry (typically grooves or channels) such that they readily transmit both gases and liquids (especially ground water) along one face or side of the product. In some cases, the product is sold as a geocomposite with a geotextile (which provides separation and filtration functions to prevent clogging of the geofoam core) covering one side of the foam.

In addition, there are geofoam materials that are purposely manufactured to have a significant inherent permeability throughout their entire thickness. The most common example is referred to generically as "glued polystyrene porous block". This material dates back to perhaps the 1970s and may have been the first foam material developed specifically for a geofoam application. This material, which is typically manufactured as a panel-shaped product, uses expanded spheres of polystyrene from the first stage of EPS manufacturing that are glued using a bitumen emulsion into an open matrix (instead of being molded into solid EPS block). In the U.S.A., this product is called *GeoTech Insulated Drainage Board®*. In practice, it is generally desirable to cover one face of the panel with a geotextile (again, to provide separation and filtration to prevent clogging of the geofoam core) so the final product is actually a geocomposite. In the U.S.A., this product is called *GeoTech Insulated Drainage Panel*.

Regardless of the actual geofoam material and product used, the function of the geofoam in drainage applications is to act as the high-permeability core to provide fluid transmission. It is also worthwhile to note that drainage is the primary functional application where geofoam competes with several other types of geosynthetics such as sheet drains and geonets. As a rule geofoam is cost effective as a drainage material only when one or more of its other functions (typically thermal insulation) is (are) utilized.

Damping. The inherent very low density yet significant stiffness of some geofoams can be beneficial in reducing ground-borne, small-amplitude waves that produce noise and/or ground motions disturbing to people and/or harmful to sensitive equipment. Typical sources of such vibrations are motor vehicles and trains. It should be noted that for vibrations of large amplitude, e.g. from earthquakes where relatively large displacements of the ground are involved, the benefit of using geofoam appears to derive more from the compressible-inclusion function (allowing the ground to yield allows it to mobilize its inherent strength) rather than the damping function.

The first use of geofoam to reduce small-amplitude vibrations is unclear but papers and magazine articles on the subject (all involving EPS-block geofoam) have been found as far back as the 1980s. Regardless of its origin, this is perhaps the least studied and utilized geofoam function to date.

Structural. This is the newest geofoam function and its exact definition is, consequently, still in the process of evolution. Included in this category are those applications where the geofoam is either serving as a structural element or some application that does not clearly fit into another functional category.

Geocomb

Available information suggests that geocomb usage originated in France in the 1980s. The geocomb functions identified and used to date include:

- lightweight fill (geocomb blocks have densities in the range of 40 to 50 kg/m^3),
- drainage (primarily as underground stormwater storage chambers) and
- structural (providing cellular confinement of coarse-grained soils).

It is of interest to note that, unlike geofoam, geocomb competes with other geosynthetic products in each of its functional areas (lightweight fill with EPS-block geofoam; drainage with various types of geopipes; cellular confinement with geocells).

THE PRESENT

Overview

In this section, the status of current geofoam usage is summarized. This is to provide a basis for future R&D activities that are suggested in the following section. Again, a functional organization is useful for this purpose.

Geofoam

General

A significant activity that benefits geofoam technology in general is a two-day continuing education seminar (short course) titled *Designing with Geofoam Geosynthetic*. This seminar, begun in January 1999 and currently planned into early 2000, is being taught by the author under the auspices of the American Society of Civil Engineers. This seminar is believed to be the first in the world to target teaching generic geofoam design for numerous functional applications to post-graduate engineers as well as other interested persons.

Thermal Insulation

There have not been any radical developments in applications involving this function in recent years. Rather, there have been evolutionary improvements (including new product development) and extensions of applications involving thermal insulation of the below-ground space of buildings. Examples include:

- The use of products, especially made of EPS block or shape, to act as both concrete formwork for below-ground walls during construction and permanent thermal insulation afterward.
- The globally wider use, especially in the U.S.A., of the "frost protected shallow foundation" (FPSF) concept that was developed in Scandinavia circa the 1960s to allow significantly shallower footing embedment depths for structures without below-ground space in areas where seasonal ground freezing is a foundation-design consideration.
- Increasing interest in the U.S.A. in insulated utility applications (sometimes referred to as "frost shielding"), a concept used successfully for years in Alaska and Canada among other places.

With regard to insulated pavements, unfortunately it appears that many organizations (especially government agencies in the U.S.A.) that might use or approve use of insulated pavements have retained a permanent bias against this technology because of the initial problems with differential icing in the late 1960s/early 1970s. In addition, it appears that the benefits of using insulated railway track systems has not been utilized at all in many countries (such as the U.S.A.) where it might prove cost effective. By comparison, every kilometre of mainline railway track in Norway is thermally insulated with geofoam (primarily block-molded EPS).

Lightweight Fill

The use of EPS-block geofoam as lightweight fill represents a fairly mature application that, at long last, is spreading rapidly in countries such as the U.S.A. where the technology has languished for decades. However, further research and refinements into this application have been made in recent years. Among the more noteworthy are:

- Ongoing research (conducted primarily in Japan) to better understand the behavior of EPS-block geofoam fills under seismic loading.
- The increasing use of "geofoam walls". These are applications, most commonly in what are called side-hill fills, in which the exposed (downslope) face of the geofoam mass is made vertical or near vertical as opposed to being sloped at a fairly flat angle (such as would be used for a traditional soil embankment). This allows use of a considerably reduced volume of geofoam material (a cost reduction) as well as requires significantly less right of way, an important consideration in hilly or mountainous terrain as well as environmentally sensitive areas such as wetlands.
- A recently (July 1999) inaugurated two-year research project based at the University of Illinois at Urbana-Champaign in the U.S.A. to develop a design manual, computer software and generic specification to facilitate the use of EPS-block geofoam as lightweight fill in certain types of road embankments.

Compressible Inclusion

This is the geofoam function that has seen the greatest research interest in recent years because of the diversity of potential applications. Rather than repeat the many activities in this area that are literally papers in themselves interested readers are directed to the following current publications:

- An overview of this function, its numerous applications and products used can be found in Horvath (1996). This paper was republished in Horvath (1998a), a document that can be viewed and downloaded via the Internet at *The Geofoam WWW Site*.
- A detailed discussion of analytical methods for various applications can be found in Horvath (1997). This paper was republished in Horvath (1998b), a document that can also be viewed and downloaded via the Internet at *The Geofoam WWW Site*.

As an indication of the ongoing and growing research interest in this function, there are known current research activities in such diverse institutions as Manhattan College and Virginia Tech in the U.S.A.; Queen's University and the Royal Military College in Canada; Karadeniz (Black Sea) Technical University in Turkey; and the Transport Research Laboratory in the U.K. Topics being research include gravity loading on integral-abutment bridges and underground conduits, and seismic loading on and expansive soils behind earth retaining structures.

Drainage

The most significant activity in this functional area in recent years has been:

- The development of EPS-shape geofoam products in the U.K. specifically for ground-borne gas (primarily methane) drainage.
- The use of existing geofoam-based drainage products (specifically glued polystyrene porous block) as part of the new *GeoTech Geoinclusion* geocomposite product.

Damping

Little has been done in recent years to further develop analytical methodologies, etc. for this function although there is increasing interest in its use. Documented case-history applications, especially in English language, remain few in number.

Structural

This function has seen the greatest relative growth in recent years because it is the newest geofoam function. The primary product developed to date is the use of panels of EPS block as facing panels in what is essentially a mechanically stabilized earth wall (MSEW). This is the *Tipform®* system that was developed in the U.K. Other products include the use of pieces of EPS as void formers in structural slab and drilled-shaft construction, the latter application most exploited to date in the U.K.

Geocomb

It appears that at the time this paper was written (late 1999) geocomb usage is still limited to France and its affiliated territories. Although geocomb blocks as lightweight fill are reportedly more expensive than EPS-block geofoam on a cubic-metre basis, geocomb blocks offer what can be a significant advantage in some applications in that they will not float if submerged in water. This is because the open tubes readily fill with water.

THE FUTURE

Overview

Successful development and implementation into practice of any technology requires that a trilogy of related and coordinated activities occur more or less simultaneously. This trilogy can be likened to a three-legged stool. If any one leg is significantly "shorter" (i.e. technically weaker or less developed) than the rest or even missing entirely then the stool is inherently unstable and unusable.

The components of this trilogy are:

- Technology transfer. This is the education of both end users as well as the geofoam and geocomb industry through continuing-education short courses and seminars, as well as design manuals and technical papers and articles in magazines, journals and conferences. Experience indicates that education not only aids technology growth but often actually leads it. It is interesting to note that with many new technologies (not just geofoam, geocomb or geosynthetics in general), it is the end user who, by their demands for a product and concomitant product support, forces otherwise reluctant manufacturers into product research and development. A relatively recent magazine article by Pooley (1996) illustrated how this process of end-user-driven interest is what finally turned a structural engineering product (reinforced, glued-laminated timber in Pooley’s article) into an "overnight" success that really involved more than twelve years of effort.
- Technology documentation. Development of relevant (this aspect cannot be emphasized too strongly) generic standards to provide a bridge between end users and industry so that there is a predictable consistency of product as assumed in design and manufactured and delivered to a project site. In the absence of proper standards, the potential for delivering and using inferior products increases dramatically. This can lead to an unsuccessful, perhaps even catastrophic, application of a technology. Experience indicates that only one bad project or experience, especially if significant property damage or human injury or loss of life is involved, can hinder a technology for a long time. Consider, for example, the lasting negative effect that problems and concerns arising out of differential icing (and reportedly fatal motor-vehicle accidents attributed to same) of insulated pavements going back 30 years ago now has had on use of this technology in many areas such as the U.S.A. Again, experience indicates that standards development in many countries is driven by end-user demand and critical need rather than manufacturer foresight and initiative. It is the author's opinion that inappropriate or irrelevant standards are in many ways worse than no standards at all because they can convey a sense of knowledge and security that is simply not there.
- Technology advancement. This includes research and development jointly by end users and industry into materials and products as well as applications of these products.

Note that this trilogy is never static or completed, but just assumes a constant, repetitive cycle of growth for a technology. In the following sections, a detailed discussion of the needs of each component of this trilogy as it applies to geofoam (EPS and XPS in particular) and geocomb is presented.

Geofoam

Technology Transfer (Education)

The basic, critical need to synthesize almost 30 years of geofoam usage worldwide was provided by the publication of the author's monograph *Geofoam Geosynthetic* (Horvath 1995). This monograph, the first and still the only independent, objective documentation of all aspects of geofoam technology, effectively summarizes the state of geofoam knowledge, including an extensive bibliography, up to the time of the publication of this monograph (mid 1995).

As noted previously, since January 1999 the American Society of Civil Engineers has been sponsoring the continuing-education seminar *Designing with Geofoam Geosynthetic*. This seminar is an evolutionary continuation and extension of the author’s monograph as it not only provides a summary of basic background information on geofoam from the monograph but instructs attendees on how to design with geofoam for typical applications involving a wide variety of lightweight fill, compressible inclusion and thermal insulation applications. This numerical, text-book type of information was intentionally omitted from the author's 1995 monograph which was never intended to be a textbook.

There are also very focused initiatives that should benefit certain applications and end users of geofoam technology in the relatively near future. One of these is the ongoing U.S. Federal Highway Administration (FHwA) instructional seminar on ground improvement related to road construction that includes a section on lightweight fill materials, including EPS-block geofoam.

Another more-recent example with greater potential effect on practice is the ongoing research project at the University of Illinois that was also mentioned previously. Although the deliverables for this project will focus on the use of EPS-block geofoam as lightweight fill for certain road applications, the concepts used are sufficiently broad so as to be useful in outlining the conceptual design approach for other lightweight-fill applications and even with other materials (both geofoam and geocomb).

In keeping with the forward-looking goal of this paper, it is appropriate to think in a similarly progressive manner as to how future developments in geofoam technology will be communicated to both end users and manufacturers in the future. Overall, the author’s vision of this is that the primary medium for distributing information will be via the Internet or some successor type of real-time communication venue in which an interested party can access information essentially instantaneously on demand. Print and CD-ROM media will likely play less and less of a role as time goes on although their total demise is unlikely any time in the foreseeable future (recall predictions of the "paperless office" made decades ago).

With specific application to geofoam, there will be two components to this real-time communication:

- Day-to-day types of developments, including links to catalog-type information sites maintained by the geofoam industry, will be through some central type of Internet site. The current geofoam website developed and maintained independently by the author since July 1996 can be viewed a precursor of this. In the future it is hoped that such a central site will be created and maintained by some sort of industry organization.
- Detailed technical information, including both textbook and design-guide types of documents, will be available at separate sites but also on line. This is already occurring at an increasing pace just in the last year or so, primarily through files posted on the Internet in Adobe’s PDF format that can be read by *Adobe Acrobat Reader®* software that is available from the Internet and elsewhere.

Predictions of the future are notoriously short on specifics and prone to error, and the ones made here by the author are no exceptions to this. However, perhaps the most important fact to keep in mind is the trend that has already developed on the Internet that users expect free information after they have paid for or otherwise have their basic Internet access. While many have tried to date to make money from the Internet, it is the author's opinion that it is difficult to do so directly, e.g. by charging to access a site. Therefore, it is proposed that rather than try to charge an access fee to read a design guide, for example, on the Internet access should be free with development and support cost borne by industry who would recoup their investment through sales.

The author is fully aware of the practical problems associated with securing funding for widespread industry support of these proposed efforts, especially in the highly and often contentiously fragmented geofoam industry (there are currently more than 100 EPS block molders in the U.S.A. for example). However, the Internet was founded on the premise of free access to information. The author's perception is that to turn the Internet into a for-pay operation at this relatively late time will be difficult. This is supported by the author's observation, as unscientific as it may be, that attempts to charge for Internet services directly are generally unsuccessful. Therefore, it is the author's opinion that education in the geofoam industry should be supported by the relatively few raw material suppliers worldwide (this would be resin suppliers in the EPS industry) as the fewer the parties involved the relatively easier it should be to develop consensus support. For example, in the U.S.A. at the present time there are only three major suppliers of the raw material used to manufacture EPS.

Another trend of the future will likely be the greater use of on-demand distance learning, especially for continuing education of engineers and other end users in practice. It is likely that such activity will also occur via the Internet, especially once higher-speed and voice communication capabilities become more widespread and at a lower cost than at present.

In summary, the ways in which knowledge is transmitted and accessed are likely to change dramatically even in the relatively near future. Those organizations who control information (industry, professional societies, academia) will need to anticipate and be responsive to these changes.

Technology Documentation (Standards)

This is arguably the weakest leg of the current technological trilogy of geofoam. It is especially true in countries such as the U.S.A. where geofoam-specific standards are essentially non-existent which requires the interim use of existing ASTM standards (most notably C 578 which is strictly applicable only to thermal-insulation applications) that are not totally applicable (although still very useful) to geofoam needs. This deficiency in standards is not unlike the situation that existed early in the technology for other types of geosynthetics.

While some geofoam standards development has occurred in a few countries, the fact that most geofoams, especially EPS block, are generic and available worldwide suggests that geofoam standards activities overall might be best served by coordination through an international geosynthetics organization such as the well-established GSI that is capable of relatively rapid, focused and responsive geosynthetics standards development. This would allow for development of globally based geofoam standards, an important benefit recognized for polymeric materials in general (Watson 1996). As has happened with other geosynthetics, such GSI standards would eventually transition into ASTM or ISO standards as well as standards for application-specific needs (e.g. AASHTO).

Unfortunately, the greatest single obstacle to standards development in the U.S.A. remains the lack of a meaningful commitment by the geofoam (EPS in particular) industry. Unless and until this industry recognizes that a broad commitment to meaningful generic geofoam standards development is in its best interest of all concerned, it will suffer from needless confusion and the possibility of problems arising out of the lack of appropriate standards. If left alone, end users will wind up writing their own standards (this has and is already occurring to some extent) that the geofoam industry may find needlessly restrictive.

Particular areas where geofoam-specific standards are required include:

- The inclusion of serviceability based parameters (initial tangent Young's modulus, elastic-limit stress) in standards in addition to the traditional parameter of compressive strength which has little relevance in modern analytical methodologies.
- Locations and protocols for sampling geofoam materials, especially EPS block.
- Parameters for EPS test specimen shape and size as well as loading rates, especially for EPS block.
- Standardized densities for EPS-block products in the commonly used 12 kg/m^3 to 32 kg/m^3 range.
- Standardized densities for EPS-block up to approximately 100 kg/m^3.

Standards are required for many other issues involving geofoam materials but these are the ones judged most critical for current practice. The author again urges that at all stages of geofoam standards development care be taken to avoid irrelevant or inappropriate standards.

Technology Advancement (Research and Development)

Introduction and Overview. In general, developments in geofoam technology both past and future can be categorized as follows:

- New applications for existing geofoam materials and products. Examples include using the well-known and -established EPS-block geofoam as lightweight fill in flood levees and crash barriers along roadways.
- New geofoam products based on existing geofoam materials, targeted in many cases to specific geotechnical applications and markets. Examples include several block- and shape-molded EPS products developed in the U.K. for specific geotechnical applications such as MSEW facing panels and drainage.
- New geofoam materials and products based on existing foam materials, targeted in many cases to specific geotechnical applications and markets. An example is the use of elasticized (resilient) block-molded EPS as a compressible inclusion behind earth retaining structures. Prior to its first geofoam use in this function and application in the late 1990s, elasticized EPS had been available and used for decades in non-geofoam applications.
- New geofoam materials and products based on new foam materials, targeted in many cases to specific geotechnical applications and markets. An example is the geofoam sheet-drain product developed circa the 1970s based on glued polystyrene spheres, a foam material apparently developed solely for this geotechnical application as it has no known other product application, geofoam or non-geofoam.

The remainder of this section will focus on needs for EPS block. Not only is it the most commonly used geofoam material but it is inherently generic. Research and development needs for proprietary materials and products are considered beyond the interest and scope of this paper.

Material Testing and Constitutive Models. Although the basic behavior of EPS block is well established after almost 50 years of testing and use, additional testing in selected areas of interest for geofoam applications is still required. This is driven by the overall need to design load-bearing aspects of geofoam based on deformations and serviceability rather than compressive strength as has been done historically.

Specific areas requiring research attention include:

- A study of the interface friction angles between various geofoam materials and other geosynthetics, especially geotextiles and geomembranes.
- Development of an accurate creep model for both small- and large-strain applications. Current creep models such as the "LCPC power-law model" developed in France for small-strain applications such as lightweight fills have proven to be inaccurate (Horvath 1998c). Other, more-accurate polymer creep models such as the Findley equation are unwieldy to use (Horvath 1998c).
- A study of stress-strain behavior, especially under creep conditions, for temperatures greater than those typically encountered in a laboratory environment (approximately +23°C). The elevated temperatures selected for testing should reflect the upper range of average annual air temperatures found in the warmest climates of the Earth. This is particularly relevant because it is in such areas such as Southeast Asia and the equatorial regions of Africa, Asia and South America where much of the growth of geofoam usage, particularly for lightweight-fill applications, is likely to occur in the future. It is the author's opinion that the current body of laboratory test data and case history experience (overwhelmingly in relatively cool Northern Hemisphere climates) may not be wholly appropriate because the creep of polymeric geofoams is known to increase with increasing temperature.
- A fundamental evaluation of the behavior under relaxation (defined as stress decrease with time under constant strain) is required. To date, relaxation behavior has been inferred from mathematical manipulation of creep-test data but this needs verification using the results of explicit relaxation testing before it can be used with confidence in practice.
- Guidelines for post-molding "seasoning" times required to eliminate the potential for post-delivery fires due to outgassing blowing agent (see Horvath (1999a, 1999b) for a detailed discussion of this issue).
- Fundamental study of block-molded EPS containing a relatively large proportion (say of the order of 50%) of recycled EPS (most likely limited to in-plant scrap for quality control purposes). Such products could prove both cost effective as well as environmentally beneficial (reduced waste) in certain applications where load bearing is not critical.

It is worth noting that several of these issues are being addressed, at least in a preliminary fashion, in the current (as of late 1999) research project at the University of Illinois. It is anticipated that this project will at least clearly define the issues involved and provide preliminary design guidance although additional research will undoubtedly be required.

It is strongly suggested that atmospheric (barometric) pressure be recorded during all future laboratory tests, especially those under extended duration such as creep and relaxation. This suggestion applies to long-term field instrumentation as well. The results from unpublished relaxation tests performed several years ago by the author suggest that the gas pressure inside the cells of EPS lags atmospheric pressure changes. Thus depending on the relative pressure change the EPS can appear to be temporarily stiffer or softer than some average value because of differential pressures across the cell walls. This phenomenon, which was encountered unexpectedly by the author, requires further study.

To make the best use of the extensive material testing performed to date and planned for the future, there needs to be a consistent program for developing constitutive (mathematical) models, first for EPS block and eventually for other geofoam materials such as elasticized EPS block, glued polystyrene porous block and XPS. Such models should incorporate (as a minimum) stress, strain, time and material density as variables, with temperature to be added as a variable at a later date when sufficient data are available. This need is driven by the increased sophistication in geofoam analyses that has occurred in recent years, especially using the finite-element and, more recently, distinct-element methods. While sporadic attempts have been made at geofoam constitutive modeling, it would be arguably better if work were coordinated within a single framework.

Thermal Insulation Applications. The efficacy of EPS and XPS geofoam as thermal insulation is well established. What is needed are efforts in two broad areas:

- A reassessment of applications that have never developed their full potential. As part of this revival effort, the opportunity to develop more comprehensive yet user-friendly analytical methods for these applications can be implemented.
- Development of practical analytical methods, charts, etc. for new applications.

With regard to underutilized applications, the classic example is insulated pavements. It is clear that a new assessment of the cost-effectiveness of insulated pavements is long overdue, led by the current generation of geotechnical engineers who are presumably not biased by early problems with his technology. After all, pavements that develop potholes as a result of frost heaving and subsequent thawing create their own type of safety hazard as well create costs for localized pavement repair (which is generally unsuccessful in the long term) as well as for vehicle damage. As noted previously, design strategies exist that will largely overcome differential icing which was the primary reason for abandoning pavement insulation originally.

There is no doubt that evaluation of insulated pavement systems would be greatly assisted by development of simplified but comprehensive models that allowed for cost optimization of systems while considering:

- Pavement construction cost as reflected in the protection offered against subgrade freezing. When insulated pavements were first used, they were designed to provide full protection against frost penetration into the subgrade beneath the geofoam and concomitant frost heaving. Some later designs allowed partial frost penetration of the subgrade, primarily as an economy measure (thinner panels of geofoam were required) as well as to ease transitions to non-insulated pavement sections.
- Differential icing which is largely affected by how deep in the pavement section the geofoam is placed and the nature of the soil and pavement materials overlying the geofoam.
- Cost per thermal resistivity ("R-value" in U.S. terminology) per unit thickness. This is because the most thermally efficient geofoam material may not be the most cost effective. It is often more economical to use a thicker piece of less thermally efficient geofoam depending on relative material costs. This cost calculation should include a realistic allowance for long term water-absorption. All geofoam materials absorb ground water with time and this reduces their thermal resistivity so should be accounted for in design. As part of this, there should be a consideration of the cost effectiveness of using geomembranes above and/or geonets below the geofoam insulation layer to reduce water absorption. Studies with residential geofoam thermal insulation in Scandinavia have indicated that water absorption, at least for EPS, can be reduced to almost zero with the use of other geosynthetics which simply did not exist when insulated pavements were first tried.

- Pavement life-cycle costs as reflected in the number of load cycles before pavement repair or replacement is required due to pavement rutting or fatigue cracking. This depends on both the deflection per load cycle as well as any heave/thaw damage if the design is for only partial insulation.

An excellent example of the framework for such a cost-based technical model (although certain requisite parameters such as differential icing were not included) is the study reported in Dore et al. (1995).

With regard to research and development for new applications, one that seems to be in some demand from engineers, at least in the U.S.A., is a relatively simple and practical method for designing insulation (frost shielding) for buried water and sewerage utility lines in climates subjected to seasonal ground freezing. Using insulated utility lines allows a reduced burial depth for the utility line which reduces construction cost. The geofoam could also be designed to provide the compressible-inclusion function which would reduce the vertical stress on the utility pipe, reducing construction costs even further.

Regardless of the specific application, perhaps the most significant issue for geofoam in thermal applications is the effect of water absorption by the geofoam on reducing the coefficient of thermal conductivity of the geofoam. There needs to be more effort devoted to understanding the many variables that influence the relative amount of absorbed water so that improvements in future designs can be developed.

Lightweight Fill Applications. The efficacy of using EPS-block geofoam for this function is well established. What is needed are efforts to develop procedures to make selection of cost-effective designs simpler in routine practice. This includes established applications such as road fills as well as emerging applications such as for flood levees.

Several areas where such efforts would be useful for established applications such as road fills include:

- Fundamental study into the need for a separation layer (geotextile, geomembrane, etc.) between the top of an EPS fill and overlying soil, pavement, etc.
- Fundamental study into when mechanical connectors (e.g. barbed plates) are required between EPS blocks, as well as a rational methodology for selecting the number and placement of blocks.
- Development of standardized, generic design details for facing systems (shotcrete, precast panels or blocks, EIFS coating, etc.) for geofoam walls.
- A fundamental study of the efficacy of using geogrid or geocell reinforcement within the unbound layer(s) of a pavement or railway track system above a geofoam fill.
- A cost-based technical optimization procedure similar to that recommended for insulated pavements but to determine the optimum pavement system to be placed over the EPS blocks. This should include consideration of:

    - whether or not a reinforced concrete slab or soil- or portland-cement concrete filled geocell layer is used on top of the EPS, or geogrid reinforcement is placed within the unbound pavement layer(s),
    - pavement capital construction cost,
    - pavement life-cycle maintenance costs based on number of load cycles before repair or replacement is required due to rutting or fatigue cracking,
    - vertical stresses and strains within the EPS as influenced by EPS density,

- global total and differential settlement of the EPS fill and overlying pavement due to stresses on the underlying subgrade and
- differential icing (if appropriate).

It is worth noting that several of these issues are being addressed, at least in a preliminary fashion, in the current (as of late 1999) research project at the University of Illinois. It is anticipated that this project will at least clearly define the issues involved and provide preliminary design guidance although additional research will undoubtedly be required.

For emerging applications such as flood levees, there is a fundamental need to observe the performance of such applications to verify that it equals or exceeds expectations. There should then be research into developing analysis and design procedures that result in designs that optimize both technical performance and cost in a user-friendly manner. These are similar to initiatives either done in the past or planned for the future (as outlined above) for more established applications such as road fills.

Practice should also reflect recent trends in the U.S.A. requiring EPS-block geofoam suppliers to provide shop drawings for block layout (as opposed to past and current practice where designers plan block layout) as well as use of third-party manufacturing quality assurance (MQA) to replace or at least significantly reduce need for on-site sampling and follow-up testing of the EPS. The development of a generic product certification program under the auspices of the GSI, as has been done for other geosynthetics, is another possibility.

Compressible Inclusion Applications. This is the function requiring the greatest research because of the greatest diversity of potential applications. Applications fall into two broad categories:

- Earth retaining structures where horizontal arching is involved.
- Underground conduits where vertical arching is involved.

With regard to earth retaining structures, there are numerous combinations of variables that require evaluation and the development of analytical techniques suitable for routine practice. Key variables are:

- soil type (traditional coarse-grained soils as well as fine-grained soils);
- loading (static, including compaction effects and surface surcharges, as well as dynamic and seismic);
- without geosynthetic tensile reinforcement in the retained soil (called the "Reduced Earth Pressure (REP) Wall" concept) versus with tensile reinforcement (called the "Zero Earth Pressure (ZEP) Wall" concept) and
- for reinforced fine-grained backfills, the effect of providing drainage with the reinforcements.

Research efforts should take advantage of the full spectrum of state-of-the-art physical testing (geotechnical centrifuge, large-scale-model shake table and instrumented full-scale retaining wall test facilities) that are available worldwide as well as a parallel effort of numerical modeling using the finite-element and distinct-element methods.

It is worth noting with regard to compressible-inclusion applications in general that only a relatively small volume of geofoam (compared to say a lightweight fill) is required in most applications to achieve significant benefits. Thus this geofoam function and it myriad applications are unlikely to attract much interest from the geofoam industry because:

- The potential sales volume is small compared to other geofoam and non-geofoam markets. Other application markets such as lightweight fill tend to be high volume and obvious interest to industry.
- The applications tend to be rather esoteric, theoretical and complex to solve (in the author's 10-plus years of experience with this geofoam function even many geotechnical engineers have difficulty grasping the concept at first). This makes compressible-inclusion applications inherently difficult for non-geotechnical engineers to even begin to comprehend no less sell. By comparison, the concept of a lightweight fill material is very straightforward and intuitive to most everyone.

Therefore, it is likely that most developments in compressible-inclusion product development and application will be driven by geotechnical engineers. In fact, the very reason this geofoam function was even formally identified and exists today is largely a result of research, including product investigation and development, begun independently by the author in 1988.

Drainage Applications. There is significant potential for using geofoam for this function if the geofoam can be used for one or more other functions. As noted previously, geofoam products are rarely cost effective compared to other drainage geocomposites (sheet drains and geonets) when only drainage is required. If the drainage function of geofoam products is pursued in the future, it will be necessary to develop appropriate standard laboratory test methods to evaluate their transmissivity/permeability, especially under long-term loading. Geofoam drainage products tend to compress significantly under sustained loads in particular due to inherent material creep. This, in turn, has a significant effect on their transmissivity/permeability that must be taken into effect during hydraulic design of the drain.

Damping Applications. There is significant potential growth for using this function, especially when the geofoam is being used for other functions. What is needed to make greater use of this function are analytical methods that are amenable for use in routine practice so that the benefit if using geofoam to dampen noise and small-amplitude ground vibrations can be estimated beforehand.

Structural Applications. There appears to be significant potential for using geofoam panels as facing for MSEW (in the way that precast concrete panels are used now) and as blocks in segmental retaining walls (SRWs, in that way that concrete blocks are used now). The benefit of this may be particularly useful under seismic loading where the very low density of EPS geofoam can be beneficial.

There also appears to be a significant potential application for using EPS blocks as relatively inexpensive and easily replaced crash protection along roads. This is already being done at some automobile racing tracks in the U.S.A.

Geocomb

The use of geosynthetic products for stormwater storage or cellular confinement is well established with several types of geosynthetics competing with geocomb in these functional applications. Thus the use of geocomb for these applications is largely a matter of economics between competitive products.

The most significant growth potential for geocombs is likely to be its use as lightweight fill. The author's experience is that there are many projects where a lightweight fill is desired but an EPS-block geofoam alternative is ultimately ruled out as it was impossible to develop a design that provided minimal gravity loads (the reason a lightweight fill was wanted in the first place) under normal conditions yet would not float if subjected to flooding in some extreme design event (e.g. a 100-year flood). It appears that geocomb blocks, although apparently inherently more expensive than EPS-block geofoam, could be cost effective in such applications because they possess a relatively low density (approximately 2% of that of soil) yet will not float. Note that it would not necessarily be required to construct the entire fill cross-section of geocomb blocks. It might be necessary to use the geocomb blocks only for the lower layers of the fill with EPS-block geofoam above. Thus geocomb blocks are actually complementary and synergistic, not competitive, with EPS-block geofoam and could actually lead to increased EPS-block geofoam sales in the long term.

Although it appears that some testing has been performed for geocomb block products available in France (*Matériaux* 1997, Perrier 1997), a broad program of generic research and standard and specification development is still required, especially for geocomb products manufactured in countries other than France. The program of testing and document development should be similar to that for EPS-block geofoam.

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