Introduction to Cellular Geosynthetics (Geofoams and Geocombs)

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01 INTRODUCTION AND BASICS

Overview of Geomaterials

02 In recent decades, civil engineering practice worldwide has been impacted significantly by the fact that construction materials are undergoing significant changes with:

- improvements to existing, traditional materials such as steel and portland-cement concrete (PCC),
- development of new functions (roles) and applications for materials such as various types of plastics that already existed but were not traditionally used in engineered construction,
- development of new materials such as various concretes, fibers and composites, and
- use of recycled waste materials.

Geotechnical engineering practice has certainly been influenced significantly by these developments, primarily by the growth of geosynthetics technology (most geosynthetics represent new products and applications for existing materials) as well as the use of recycled waste materials.

Cellular Geosynthetics

Traditionally, geosynthetics were considered to be limited to relatively thin, planar product families such as geogrids, geomembranes and geotextiles. Although some definitions still hold to this, it is now widely recognized and accepted that any synthetic material or product used in a geotechnical application is, by definition, a geosynthetic. This has led to the recognition of a group of non-planar, three-dimensional materials that are referred to collectively as *cellular geosynthetics*. The focus here is on two cellular geosynthetic product families:

- *geofoams* and
- *geocombs*.

It should be noted that there is a geosynthetic product family called *geocells*. However, these products are more closely related to traditional planar products. In addition, they only function when their cells are filled with soil or other material whereas geofoams and geocombs are self sufficient materials and products. For these reasons, geocells are excluded from this discussion.

03 Within the context of the above-described changes occurring in civil engineering materials, all geocombs and most geofoams represent new uses for materials that have existed for many years but not heretofore used in engineered construction. However, some geofoams are entirely new materials and others consist of recycled waste materials.

Geofoam

04 Definition

The word "geofoam" when it appears alone is now used solely as the generic term for any closed-cell foam material or product that is used in a geotechnical application. Thus it is important to note that geofoam is not limited to a single, particular material or product as is sometimes erroneously stated in practice. As a result, it is important to clearly identify a specific type of geofoam material and product in any communication. This is consistent with what is done for other types of geosynthetics.

Most closed-cell foams are created by softening or melting a solid material then introducing a gas called a *blowing agent* into the material. Alternatively, the process may involve introducing a blowing agent into a liquid mixture. Depending on the particular material, geofoam manufacture may be done in a fixed plant dedicated to this purpose or in-situ at a project site. When the material or mixture subsequently cools or solidifies, it has a texture that consists primarily of cells (voids) formed by the blowing agent. The remaining solid material forms the walls of the cells. When measured on a volume basis, the relative proportion of solid material in the final foam material is generally very small. Some foams used as geofoam have a porosity (ratio of void volume to total volume) as high as 99%. As a result, the most commonly used geofoam materials have a density that is of the order of 20 kg/m^3 (1.25 lb/ft^3) which is only about 1% of the density of soil and rock.

Although recent research has revealed that the word geofoam was used on a limited basis as far back as the 1970s, it is important to note that its current definition and global, generic use are relatively new (since the early 1990s). However, most geofoam materials were actually developed circa 1950 and have been used worldwide in geotechnical applications since at least the 1960s. Thus there is actually a record of proven use and success for most geofoams that is longer than for most other geosynthetics.

Materials

Overview

Geofoam materials fall into two broad categories:

- polymeric (plastic) and
- inorganic.

Polymeric materials include:

- *polyethylene* (PE),
- *polystyrene* (PS, called *polystyrol* in some countries),
- *polyurethane* (PUR) and
- other (e.g. PS/PE copolymer blends).

It is of interest to note that other common polymeric foams such as *polyisocyanurate* have been tried in geofoam applications in the past but have not performed satisfactorily so are not included in this list.

Inorganic materials include:

- cellular glass and
- cementitious materials (e.g. foamed PCC).

It should be noted that the above are the correct generic terms that should always be used unless a particular product tradename is intended. In civil engineering practice it is important to avoid use of incorrect colloquial terminology which could lead to technical errors or contractual problems. For example, in the U.S.A. the word "styrofoam" is often used, incorrectly, to mean any type of plastic foam. In reality, Styrofoam® is the tradename of a particular brand of a particular type of polystyrene foam.

Polystyrene Foams

There are two distinctly different manufacturing processes for polystyrene foam. The different processes result in materials with radically different textures and, more importantly, significantly different geotechnically relevant properties even though each originated from basically the same raw material (solid polystyrene).

The two types of polystyrene foam are generally referred to worldwide as:

- *expanded polystyrene* (EPS) and
- *extruded polystyrene* (XPS).

Each is manufactured only in fixed plants and was invented circa 1950 so the basic materials and products are generic and generally available worldwide. However, it is common for both geofoam and non-geofoam products manufactured from EPS and XPS to be marketed using tradenames. In addition, certain geofoam products manufactured in whole or in part from EPS and XPS are proprietary because of various unique aspects of their manufacture or use.

It is easy to distinguish visually between EPS and XPS as the former consists of individual sand-size beads of cellular polystyrene that are permanently fused together. This is the reason that EPS is sometimes referred to colloquially as "beadboard" although this term should not be used in any technical or contractual context. On the other hand, XPS has a uniform cellular texture. Color can also be a useful distinguishing feature between EPS and XPS although care is required with this because of regional differences. EPS is inherently white in color and is typically sold as such in most countries whereas XPS is generally colored for product identification and marketing purposes. However, exceptions abound, especially when viewing things globally. In some countries (Canada and the United Kingdom are noteworthy examples), EPS is sometimes colored for geofoam marketing purposes. However, the colors used can conflict with practice in other countries. For example, pink is used in the U.K. for a particular EPS product that is sold exclusively for geofoam applications whereas in the U.S.A. the same color is used for a brand of XPS products used for both non-geofoam and geofoam purposes. Therefore, texture, not color, should always be used as the primary distinguishing feature between EPS and XPS.

Products

As noted previously, some geofoam materials can be foamed in place by either spraying or pumping in the open atmosphere (PUR and foamed PCC are the prime examples) or pumping under confined conditions as a grout (also PUR). However, the most commonly used geofoam materials, EPS and XPS, require a fixed plant for their manufacture similar to other geosynthetics. The preformed products are then brought to a project site and placed in the desired location and configuration, although limited on-site cutting is possible if required to fit local conditions.

Because both EPS and XPS are manufactured in fixed plants, it is possible to mold and/or cut the materials into different shapes. EPS is particularly versatile in this regard. There are two basic ways to mold EPS for geofoam applications:

- 05 into *blocks* (the term *billet* was used in older literature) that are typically of the order of 600 mm (2 ft) thick, 1200 mm (4 ft) wide and 2 to 5 metres (8 to 16 ft) long. It is important to note that there is no such thing as a "standard" EPS block size, even in a given country. This is because molds come in a variety of sizes. Blocks can either be used full size or pieces, generally panel shaped, can be cut from a block (generally at the factory). In either case, this is referred to as *EPS-block geofoam*.

- as individual pieces with a specific shape. Such products are referred to as *EPS-shape geofoam*. There has been innovative product development of shape-molded EPS specifically for the geofoam market in recent years, mostly in Europe, the United Kingdom (U.K.) in particular. Several examples are shown in the applications section of this presentation. One of the newest of these products is the *anti-buoyancy block* developed in Japan. It is molded to be 50 to 60% void inside yet has the same load-bearing capacity as a
  06 20 kg/m^3 (1.25 lb/ft^3) density solid EPS block (the de facto standard for many geofoam applications). The benefit of the anti-buoyancy block is that it has significantly less buoyancy than a normal EPS block.

XPS geofoam typically involves the use of plank- or panel-shaped pieces of the order of 1 metre (3 ft) wide and 2 to 3 metres (8 ft) long but no more than 50 to 100 mm (2 to 4 inches) thick. The XPS manufacturing process does not provide for thick, block-shaped pieces.

While each geofoam material and its products can have cost-effective applications, geofoam products consisting of or made from block-molded EPS have been and continue to be predominant in use worldwide for several reasons:

- The materials and technology for making it are generic, relatively modest and available worldwide.

- The geotechnically relevant material properties are variable, versatile and overall a good match for many geotechnical applications.

- The cost is generally lower than other geofoam materials.

Therefore, this presentation will focus on EPS materials and products simply because of their overwhelming, predominant use in practice. However, much of the discussion is sufficiently and intentionally generic so that the concepts can be applied to any geofoam material or product.

Geocombs

07 Definition

Geocomb is the generic term used since 1999 to define an open-cell material with a honeycomb-like cross-section (hence the name) created in an extrusion process. This can only be accomplished in a fixed plant, not in-situ. A geocomb is essentially a bundle of contiguous tubes.

Geocombs are one of the newer if not newest geosynthetic product families to be identified to date. However, the materials currently referred to as geocombs have actually been used in France and its territorial affiliates since at least the 1980s where they are called *structures alveolaires ultra légères* (SAUL) or *ultra light cellular structures* (ULCS) in English. Although geocombs have become more widely known in the last few years, they are still not readily available outside of France although this is changing.

Materials

Only polymeric (plastic) geocombs using the following materials are known to have been manufactured to date:

- a translucent polypropylene (PP) and
- black polyvinylchloride (PVC).

08 Only one manufacturer is known for each polymer which means that geocombs are proprietary products at the present time. The PP product line appears to be predominant in terms of product development and use at the present time.

In each case, the tubes that form the extruded honeycomb are each of the order of 1 inch (25 millimetres) across and the material has an overall porosity of approximately 96%. This compares to EPS-block geofoam which has porosities that are typically ~ 98% to 99%.

Products

The extruded honeycomb is typically factory cut into panel- or block-shaped pieces that are the basic final product. The blocks manufactured to date have dimensions that are close to those of EPS blocks as typically used for geofoam applications. This appears to be for handling convenience as opposed to some manufacturing requirement. In some cases, the geocomb product has a non-woven geotextile that is factory bonded to one face of the panel or block to prevent solid particles from filling the open tubes that form the honeycomb.

The panels or blocks are placed with the tubes oriented vertically as the overall product is significantly stiffer when loaded in a direction parallel to the longitudinal axes of the tubes as opposed to perpendicular to them. This is but one of the significant differences between geocombs and block-molded EPS which is inherently isotropic in all its mechanical (stress-strain-time) and thermal properties.

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DESIGNING WITH GEOFOAMS AND GEOCOMBS

09
Basic Concepts

The overall reason for, and benefit of, using any geosynthetic product is to provide a design alternative that is both technically acceptable as well as cost effective compared to traditional alternatives that do not use geosynthetics. Within this overall context, there are several features of geofoams and geocombs that make them unique both as civil engineering materials in general and geosynthetics in particular:

- Efficient use of material. On a volume basis, these materials are largely voids, in some cases up to 99% void. Thus a relatively small amount of solid material is used yet these materials are sufficiently strong and stiff for many geotechnical applications.

- Novel and innovative method of use. Problem solving with cellular geosynthetics is approached differently compared to the way most civil engineering materials, including other geosynthetics and various ground improvement strategies, are used. In virtually all geotechnical problems, there must be a balance between:

    - the loads that produce driving forces and moments, and

    - material strength and/or stiffness that produces resisting forces and moments.

  Depending on the particular design methodology used, service loads and safety factors may be employed or service loads may be factored upward and/or material strength factored downward. In ether case, the goal is to provide a margin of safety against failure (the limit state). Both the *serviceability limit state* (SLS) and *ultimate limit state* (ULS) need to be considered. In traditional civil/geotechnical engineering practice, natural forces are accepted as a given and material strength and/or stiffness is added to counteract whatever forces are anticipated during the design life of the structure. However, the philosophy when designing with geofoams and geocombs is completely the opposite as they work with the forces of nature and do not oppose them. Their low density is used to significantly reduce forces, both gravity and seismic, to the extent that the natural strength/stiffness of the ground can often support the forces satisfactorily without any increase. Yet because of the load-carrying efficiency of their cellular structure, geofoams and geocombs can support a wide range of loads satisfactorily despite their low density.

- Versatility. The use of cellular geosynthetics can be cost effective for both new construction as well as for the repair, renovation or upgrading of existing structures. This is very important in many countries where there is a significant existing infrastructure that requires maintenance as well as upgrading to sustain loads not considered in the original design. Depending on the specific material and product used, geofoams and geocombs can prove useful for both permanent and temporary construction, in a wide variety of climates and weather conditions, and in both "good" and "poor" ground conditions.

- Functions and functionality. With few exceptions, geofoams and geocombs provide geosynthetic functions not available with any other type of geosynthetic or any other civil engineering material for that matter. As a result, geofoams provide the design professional with a range of technical capabilities and design alternatives that were heretofore not available. In many applications, several of these functions can be used to advantage simultaneously. This multifunctionality increases the cost effectiveness of using geofoams and geocombs.

- Relationship with other geosynthetics. Both geofoams and geocombs work well with other types of geosynthetics. There are few applications where at least one if not more additional types of geosynthetics are used to complement and enhance the performance of the geofoam or geocomb product. In addition, some geofoams can work synergistically with other geosynthetics, especially tensile reinforcements such as geogrids and geotextiles, to provide a design solution that neither geosynthetic could provide if used alone. This adds to the design alternatives available in practice.

In summary, cellular geosynthetics provide a whole range of new design alternatives that can be cost effective in myriad applications.

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Overview of Design Process

The preferred process to be employed when evaluating a design alternative incorporating geofoam or geocomb is broadly similar to that used for more traditional construction materials. However, there are some nuances as well as special issues and considerations that are worthwhile to note:

- The overall process follows the "design by function" approach recommended whenever any geosynthetic is used. This means that the functions desired from the geosynthetics are clearly identified before any work begins. This allows the desired properties of the geosynthetics to be identified so that appropriate material and product selection can be made.

- As with any geosynthetic, the geofoam or geocomb material and product will have geotechnically relevant properties that are unique to that material and product. The necessary technical data will have to be obtained prior to performing any analyses for design. The most up-to-date source for this information is generally the manufacturer or local supplier (distributor) of the product.

- Although geofoams and geocombs have properties that are distinctly different from soil or rock, experience indicates that the geofoam or geocomb product can usually be treated as an equivalent earth material for analysis purposes. This means that traditional stress-strain concepts and geotechnical methodologies for settlement analysis, slope stability, pavement design, etc. can be employed in most cases.

- To the extent possible, cost estimates should consider not only the capital construction costs but the life-cycle operation and maintenance costs for the projected life of the structure. While this is a desirable goal under any circumstances, it can be particularly important when cellular geosynthetics are involved as in most cases they result in a drastic reduction in maintenance costs. Therefore this should be considered when comparing the cost of a geofoam or geocomb alternative to other, more-traditional solutions.

- Material and construction standards for most geofoam and geocomb materials and products are still in the developmental stage in many countries. In addition, for some geofoam materials such as EPS there is no, and never could be a, "universal" standard given the numerous applications for this material, each with its own unique needs. This makes the development of appropriate project-specific contract specifications somewhat more difficult than for traditional, well-established geotechnical technologies. Therefore, designers should take particular care to seek out the latest standards for a particular material and product that are appropriate for the intended functions and application. A specification that meets the unique needs of a project should then be developed from these standards. A designer should avoid the temptation to simply reuse another specification without verifying that it is both up-to-date as well as appropriate to the project at hand.

Additional discussion of these topics can be found in the following sections.

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Geosynthetic Functions

Introduction

Design by function requires knowledge of the geosynthetic functions that cellular geosynthetics can provide. Listed below in order of approximate chronological evolution are all the geofoam and geocomb functions that have been identified to date. There are some key facts to keep in mind while reviewing this list:

- As noted previously, with few exceptions these functions are not provided by any other type of geosynthetic or civil engineering material.
- In general, geofoams offer more functions than geocombs.
- EPS is the only known geofoam material that can provide all of the functions listed. This fact together with its relatively low cost explains why it is the material of choice worldwide in most applications where a cellular geosynthetic is called for.

Thermal Insulation

This function dates back to at least the early 1960s and is one that only geofoams have been used for to date. Experience indicates that all polymeric foams as well as cellular glass are effective materials for this function although EPS and XPS dominate and are often competitive in practice. The large relative volume (~ 98%) of gas enclosed in the cells of EPS and XPS provides a significant thermal-insulative value and is the reason these materials were developed in the first place circa 1950.

Lightweight Fill

The use of geofoams as lightweight fill dates back to circa 1970 when both block-molded EPS and XPS panels were tried more or less contemporaneously for this function. In retrospect, this was a logical outgrowth of their concurrent use as thermal insulation in the prior decade. The use of other geofoam materials such as foamed PCC came somewhat later followed by geocomb blocks in the 1980s. Thus there are many choices for lightweight fill among geofoams and geocombs. *Matériaux* (1997) is an excellent contemporary reference that covers most of these choices.

Although all geofoams and geocombs have a significantly smaller density compared to traditional earth materials (soil and rock) and are therefore considered "lightweight", just how much lighter can vary by more than an order of magnitude depending on the particular material and product. Therefore caution must be exercised as the various types of geofoams and geocombs are not, in general, interchangeable as lightweight fills. For this reason, EPS-block geofoam tends to be the lightweight fill material of choice unless an irregular volume has to be filled or there are other considerations (in which case foamed PCC is typically used). The reason is simple: EPS can have a density as low as ~10 kg/m^3 (0.6 lb/ft^3) which is unique among lightweight fills (foamed PCC is typically ~ 50 or more times denser) and less than 1% of that of normal earth materials. For this reason, EPS-block geofoam is sometimes referred to as *ultralightweight fill*. Despite its low density, the stiffness and strength of EPS can be sufficient to support motor vehicles, airplanes, trains and even small bridges and lightly loaded buildings.

It is important to point out the niche advantage that geocombs offer compared to all geofoams. Because of their significant porosity (~ 96%), all of which is easily accessed because of their inherent open-cell structure, geocomb blocks have almost no buoyancy when submerged in water. This can be a significant benefit that can render geocomb blocks the lightweight fill material of choice in some applications.

Drainage

Introduction

Drainage per se is generally not considered a geosynthetic function because it involves at least two distinct components:

- *transmission* of the fluid (gas or liquid) through a relatively high permeability material and
- *filtration* of soil particles to prevent their entry into the high permeability material.

In practice, it is transmission and filtration that are considered the geosynthetic functions because each is typically provided by a different geosynthetic that are combined into a single drainage geocomposite.

It is herein proposed to add a third drainage-related function to this list, that of fluid *storage*. Although storage is related to transmission, a separate functional identification seems appropriate as there are many geosynthetics that are quite adequate for transmission but do not provide any significant storage. Therefore, for the purposes of this presentation storage will be considered a separate geosynthetic function.

Discussion

The use of geofoams for fluid transmission was first identified circa 1970s. It is important to note that this is the one geofoam function that duplicates a function that can be provided by other types of geosynthetics such as sheet-drains and geonets. Compared to these materials, experience indicates that geofoams are only cost effective for fluid transmission when other geofoam functions (thermal insulation and/or compressible inclusion (the latter is discussed subsequently) are the ones used most often), are utilized in a given application.

Most geofoam materials have relatively low primary (intrinsic or inherent) permeability. Therefore, most geofoam products intended for drainage applications (EPS and XPS are typically used) must provide fluid transmission through secondary permeability by being factory shaped or cut so as to contain channels for the fluid to flow through. There are exceptions to this with geofoam materials developed specifically to have relatively high primary permeability:

- *glued polystyrene porous block*, which is related to EPS, and
- an assemblage of pieces of recycled PE.

Geocombs were developed in the 1980s and, because of their open-cell structure, have a very high primary permeability. However, more important than the fluid transmission this provides is the above-defined function of fluid storage. Because geocombs are typically ~ 96% voids and have an open-cell structure, they provide 96% efficiency in terms of volume of fluid (primarily water) that they are able to store indefinitely for every unit volume the geocomb panel or block occupies.

Noise and Vibration Damping

This function dates back to at least the 1980s and is one that only geofoams, primarily EPS blocks, have been used for to date. Although this is one of the lesser-developed geofoam functions, there is sufficient experience in both Europe and Japan to demonstrate that the relatively high stiffness to density ratio of EPS makes it relatively efficient at damping the small-amplitude ground vibrations and even air-borne noise from motor vehicles and trains.

Compressible Inclusion

This function dates back to at least the 1980s and is one that only geofoams, primarily EPS and related materials such as *resilient* (*elasticized*) EPS and glued polystyrene porous block, have been used for to date. This function is somewhat unique in that it works in a way that is typically not taught as part of traditional geotechnical engineering education. Therefore, in many cases even experienced geotechnical engineers have to be educated to its conceptual existence before specific applications and analytical methodologies can be addressed.

On the other side of the coin, the novelty inherent in compressible inclusions makes it difficult for the EPS industry and their salespersons to grasp compared to, say, lightweight fill which is quite intuitive even to a non-technical person. Collectively, these issues explain why this geofoam function has been relatively little heard of and utilized to date worldwide despite the fact it is potentially cost effective to use in a vast number of both routine and exotic earth retaining structure and foundation applications.

Although there are several application variations, the basic concept of a compressible inclusion is to place the geofoam layer between a relatively rigid and/or non-yielding (non-displacing) structure and the adjacent ground. The geofoam layer essentially acts as a sacrificial, crushable layer. In its most basic form, this allows *controlled yielding* (displacement) of the adjacent soil or rock which in turn reduces the load on the structure as the inherent shear strength of the soil is mobilized. Alternatively, it may be the structure that is displacing and the compressible inclusion used to absorb this displacement.

Structural/Miscellaneous

This category contains a range of geofoam applications that emerged largely in the 1990s and do not readily fit into any of the other functional categories.

Overall Analytical Approach

Introduction

One of the factors that often inhibits the use of geosynthetics by those unfamiliar with them is uncertainty over how to analytically deal with the geosynthetic. In this context it is useful to point out that designing with geofoams and geocombs is best approached by considering them to be equivalent earth materials with engineering properties and parameters such as density (unit weight), Young's modulus, Poisson's ratio, California Bearing ratio (CBR) and coefficient of thermal conductivity that are conceptually identical, although numerically different, than earth materials with which the design professional is presumably more familiar. As a result, normal geotechnical engineering analytical methodologies for settlement, slope stability, pavement design and heat flow (to name but a few) can generally be applied with little or no modification to problems that incorporate cellular geosynthetics. In fact, because geofoam and geocomb materials and products are manufactured, they are usually both more predictable as well as simpler in their behavior compared to normal earth materials. Consequently, designing with cellular geosynthetics is, overall, often easier than designing with soil and rock.

Although geofoams and geocombs can be easy to design with, the key element is to make sure that all relevant material and product properties are obtained from the manufacturer or supplier. The following sections discuss in generic terms what information must be obtained.

12 Important Aspects of Material Behavior and Other Technical Issues for Design

Index Properties

As with soil, index properties in and of themselves are not sufficient for design but they do provide important basic information. Index properties that are important for cellular geosynthetics include:

- material density or potential range in densities if applicable to the material or product,
- the effect of long-term water absorption both on material density and dimensional stability (shrink/swell) of the overall product, and
- the effect of temperature on the dimensional stability (expansion/contraction) of the overall product.

Mechanical (Stress-Strain-Time) Behavior

All geofoam and geocomb applications are load bearing to some extent. Therefore, detailed knowledge of the stress-strain behavior of a geofoam or geocomb product is always necessary. Because most geofoam and all geocomb materials are polymeric, this means that stress-strain behavior can be significantly influenced by:

- time (primarily the phenomenon of creep but also relaxation) and
- temperature.

Depending on the specific material and product, the stress-strain behavior of all geofoams and geocombs may also be influenced by:

- material density,
- product configuration,
- water absorption and
- material anisotropy that is the result of the manufacturing or application process unique to that material and/or product.

Thermal Properties

Most geofoam applications involve the function of thermal insulation whether this is sought explicitly or not so the appropriate thermal properties (primarily the coefficient of thermal conductivity) are required. The coefficient of thermal conductivity is affected by:

- long-term water absorption which tends to be not only material/product specific but application specific as well and
- temperature.

Constructability and On-Site Safety

Because geofoams and geocombs are still somewhat novel construction materials, many construction contractors may not be familiar with their use. Thus the designer needs to include in the contract document (plans and specifications) all details relevant to the proper handing and placement of the product. This includes issues such as:

- handling damage and on-site storage for products manufactured in a plant,
- site preparation and
- restrictions, if any, on weather conditions in which materials/products can be placed or applied.

In addition, although geofoams and geocombs are not inherently dangerous or hazardous materials, they can have certain behavioral nuances that can affect personal safety during construction. Again, because construction personnel may not be familiar with these materials/products it is important to call relevant issues to the contractor's attention in contract documents. This includes issues such as:

- minimum seasoning periods for factory manufactured geofoams to allow for outgassing of blowing-agent gases which can be combustible,
- personal-safety precautions for geofoams that are manufactured and applied on-site,
- heat-and-flame safety around polymeric geofoams and geocombs, and
- trafficability related to slip hazards on exposed geofoam surfaces in cold and/or wet weather.

Durability (Survivability)

Durability in this context means the ability of a geosynthetic to maintain the physical and material properties assumed in design both during construction as well as for the design life of the application once it is in the ground. The latter can be particularly important because most geosynthetics are polymeric and the ground and ground water can have long-term effects on polymer chemistries.

Durability is now recognized as an important design consideration for all geosynthetics and geofoams and geocombs are no exception. A thorough discussion of the durability of EPS-block geofoam can be found in Horvath (1999). Information for other materials or products would have to be obtained from the manufacturer or supplier.

Environmental Impact

Related to, but separate from, durability is the issue of the effect, if any, of the geofoam or geocomb material on the environment (air, soil/rock, water). This includes not only after the geofoam or geocomb is placed on or in the ground but, in the case of geofoams, during manufacturing as well. Because all geofoams whether manufactured in a fixed plant or in-situ require a blowing agent, the gas used for this can have an impact on the environment that may need to be considered.

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Economics

Economics are always an important consideration in engineering practice. A viable design alternative must be both technically acceptable in its anticipated performance as well as cost effective.

When developing a cost estimate for an alternative incorporating a cellular geosynthetic, there are a number of important factors to keep in mind so that an assessment of true life-cycle costs is obtained. Although geofoam and geocomb products typically cost more on a unit-volume basis (e.g. per cubic metre) compared to soil, the overall construction cost of a geofoam or geocomb alternative is often less when the following areas of cost are properly considered:

- design aspects of initial construction,
- constructability aspects of initial construction and
- post-construction operation and maintenance.

Application of this concept is outlined here using the common example of EPS-block geofoam used as lightweight fill for a road embankment on soft soil. Other alternatives for this would typically involve a soil embankment with some type of ground improvement and staged construction or a structure supported on deep foundations.

Considering first the design aspects of initial construction:

- Although block-molded EPS is typically more expensive than soil in a unit-volume basis, the geofoam alternative often requires a smaller total volume of material compared to soil. This is because an EPS-block geofoam fill can be constructed with vertical side/edge slopes (this is often referred to as a *geofoam wall*) if desired which minimizes the volume of geofoam material required compared to soil which must be sloped or structurally supported. Unlike soil, EPS blocks are self supporting on a vertical slope and do not require a retaining structure.

- Because the geofoam alternative can be constructed with a vertical side slope, such a fill requires less "footprint" area and right-of-way acquisition. This reduces the cost as well as the social/political and environmental impact of land acquisition for a project.

- The extremely low mass of the geofoam alternative minimizes if not eliminates the potential for causing settlement to adjacent roads, railways, utility lines and structures.

- The geofoam alternative usually allows other parts or components of the overall structure such as bridge abutments and bridge foundations to be reduced in cost or even eliminated. This is because the EPS blocks impose much smaller loads on adjacent structural components.

- The geofoam alternative generally does not require ancillary ground improvement strategies (e.g. wick drains and preloading). This eliminates not only the direct construction costs but related costs such for geotechnical instrumentation and data assessment and time for preloading.

Considering constructability next, the geofoam alternative achieves additional cost reductions because it:

- proceeds faster due to the very low density of the EPS blocks and concomitant ease of placement,

- does not require highly skilled and expensive labor for construction,

- generally requires minimal heavy equipment and

- is significantly less affected by weather compared to traditional earthwork.

Finally, when post-construction operation and maintenance costs are considered as they should always be, the geofoam alternative further reduces costs because of:

- typically reduced maintenance requirements due to less need to overlay or replace the road pavement due to differential settlement,

- lower energy consumption for operation (where relevant) and

- generally superior overall performance of the final structure.

The need to consider all costs of a design alternative is very important. An excellent example and model of how this concept was applied to a problem involving insulated road pavements can be found in the paper by Doré et al. (1995).

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Standards and Specifications

Standards

To begin with, it is important to note that standards and specifications are different although there is an important relationship between the two. Standards are the fundamental documentation and foundation of any successful technology, especially geosynthetics. This is because standards define basic, generic parameters and parameter values that are necessary for successful use of a technology. Material/product standards are required as a minimum. In addition, construction standards are often desirable, especially for technologies that may be in the relatively early stages of their evolutionary development and use when end users need the most guidance and assistance.

In most countries, standards development is undertaken by an organization or part of an organization that is permanently devoted to standards activities. This is to ensure a consistency and uniformity between standards that are under the jurisdiction of that organization. However, in some countries, and the U.S.A. is a prime example, there can be multiple standards organizations, each with a different emphasis or purpose to its existence. For example, the American Society for Testing and Materials (ASTM) is a general-purpose standards organization whereas the American Association of State Highway and Transportation Officials (AASHTO) focuses solely on transportation-related applications. It is important to recognize that whenever multiple standards organizations exist, it is possible that multiple, sometimes conflicting, standards for the same material/product can exist.

Because of the variety of cellular geosynthetics materials and products that can be made from them, one standard for cellular geosynthetics would not suffice. Multiple standards are necessary, sometimes more than one for a material like EPS that can be either block or shape molded into different products. Unfortunately, the current state of practice regarding standards for cellular geosynthetics is far from ideal and still in the early stages of development. Appropriate standards exist only in some countries and even at that only for a few combinations of materials/products and applications. Thus there is still much work that needs to be done globally for cellular geosynthetics standards development.

Specifications

Specifications are one component of the legal documents required for a construction project. They are used to verbally state the material, product and construction requirements for that specific project. By reference, specifications draw on information in one or more standards. For example, a standard for EPS-block geofoam would include several different material "types", i.e. molding densities. A specification for a specific project would reference that standard and state the particular material type to be used on that project.

APPLICATION EXAMPLES

Introduction

One of the best ways to learn about cellular geosynthetics is to look at a variety of application examples for each of the geosynthetic functions that geofoams and geocombs can provide. These examples illustrate both what can be accomplished reliably and routinely with the various materials and products as well the broader concept of a given function. Experience indicates that understanding the concept of how a function works stimulates innovation and development of new applications by both end users and material manufacturers alike.

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Thermal Insulation

Thermal insulation is useful in any application where it is desired to restrict the flow of heat. This may be for one or more desired outcomes:

- life-cycle cost savings from conservation of energy consumption during the entire design life of the structure,
- construction-cost savings and/or
- improved geotechnical and structural performance of the structure.

16 Contrary to many perceptions, geofoam thermal insulation can be used cost effectively in any climate and not just those subjected to seasonal or permanent cold weather. This is especially true if the geofoam product used is designed to be multifunctional and simultaneously provide other functions such as drainage and compressible inclusion. Examples of types of structures where geofoam thermal insulation has been used as the primary function include:

- below-ground portions (exterior face of exterior walls and underside of slabs-on-grade) of buildings that have conditioned (cooled and/or heated) interior space. This is done in all climates for life-cycle energy savings. For exterior walls, this can be combined with the compressible inclusion and drainage functions for additional construction-cost savings;
- beneath refrigerated buildings and storage tanks in all climates for both life-cycle energy savings and to prevent subgrade freezing and heaving. The latter can cause both serviceability problems for the structure as well as structural distress;

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- landfill liners in all climates to protect the permeability of clay liners which can be compromised by both solar heating as well as seasonal freeze/thaw;
- the exterior face of roofs of shallow buried structures such as cut-and-cover tunnels and parking garages in all climates to limit seasonal thermal changes to the structure roof. This can cause expansion and contraction of the roof and result in structural distress;

18

- a wide variety of earth retaining structures including bridge abutments, gravity and cantilever retaining walls and soil-nailed walls in cold climates to prevent seasonal freezing of the wall drainage systems and retained soil. Either or both of these could result in increased lateral pressures acting on the retaining structure. Note that if the wall is rigid and non-yielding, the geofoam can also be designed to act as a compressible inclusion for additional, construction-cost savings;

- 19 pavements (roads, airfields, etc.) and railway tracks in cold climates to prevent or at least limit seasonal subgrade freezing and heaving. When applied to roads this is sometimes called the *Insulated Pavement* concept. As an extension of this concept, in areas with
  20 permafrost the use of pavement or railway insulation can retard the permanent ground thawing that will inevitably occur beneath the pavement or railway. This can extend the time between required maintenance cycles to repave or relevel railway tracks;

- 21 liquid-bearing underground conduits (utility lines and pipelines) in cold climates to allow shallower embedment without freezing or increasing the viscosity of the contents of the conduit. This can be particularly useful when normal embedment depths would require excavation into bedrock. This application is sometimes called the *Frost Shielding* concept when it is applied to water supply lines and sewerage; and

- 22 shallow foundations (typically continuous wall footings) of heated buildings without below-ground space in cold climates to allow shallower foundation embedment without frost penetration beneath the foundation. There are additional savings in life-cycle energy costs for the structure. This is sometimes called the *Frost Protected Shallow Foundation* concept.

Most thermal insulation applications require only relatively thin (50 to 100 mm (2 to 4 inch) thick) panels of geofoam. The products used tend to be either panels of EPS of desired thickness that are factory cut from full-size blocks or XPS panels manufactured directly to the desired thickness. An important design detail is that drainage around the geofoam layer should be provided to the greatest extent practicable to keep moisture from accumulating in the geofoam. This will help preserve the thermal efficiency of the geofoam material.

23 Lightweight Fill

Both geofoams and geocombs can be useful as a lightweight fill material in any application where their relatively low density compared to soil and rock can be used advantageously to reduce vertical and/or horizontal stresses. This includes not only under normal gravity conditions but also under dynamic loading such as from earthquakes.

Typical applications to date include:

24 to 32

- embankments and fills for:
  - transportation structures (roads, airfields, railways),
  - water-resources structures (flood levees),
  - direct foundation support of structures (small buildings and bridges) and
  - architecture and landscaping; and
- earth retaining structure backfills and fills (bridge abutments, gravity and cantilever retaining walls, basement walls, anchored bulkheads).

Lightweight fill applications typically use the following materials and products:

- more or less full-size blocks of EPS-block geofoam,
- foamed-PCC geofoam or
- geocomb blocks (typically only where buoyancy is a problem).

Note that the new EPS-shape anti-buoyancy blocks developed in Japan are a potential alternative in applications where geocomb blocks might be considered.

Where seismic loading is a design consideration, research and experience conclusively indicate
33 that some sort of mechanical inter-block connector is necessary with EPS blocks to ensure adequate inter-block shear resistance during the seismic event. Various designs, each involving a
34 barbed plate, have been used to date although recent research suggests that an alternative shape such as a ring may be a more-efficient design style.

35 Drainage

As noted previously, both geofoams and geocombs can be used to provide fluid transmission with geocombs also capable of providing significant fluid storage. Because fluid transmission is a geofoam/geocomb function that duplicates one available with other types of geosynthetics such as sheet drains and geonets, applications where geofoam/geocomb can be cost effective as a drainage product are generally limited to where one or more additional functions such as thermal insulation and/or compressible inclusion (for geofoams) or fluid storage (for geocombs) can be used beneficially.

Examples of where geofoam, used either alone or together with geotextiles as part of a drainage geocomposite, have proven to be cost effective include as part of a system for the collection and disposal of:

- ground water around:
  - building basements and
  - earth retaining structures;
- leachate collection systems in landfills; and
- ground-borne gases (methane, radon) around basements of buildings.

36 Geofoam products used to date include EPS that has been shape-molded for specific applications as well as panels of block-molded EPS and XPS factory cut with grooves or
37 channels. There is also a material generically called glued polystyrene porous block (also known colloquially as "brown board") that is made using the same raw material as EPS. It was developed
38 specifically for drainage applications because of its unique (for a geofoam material) inherent permeability. More recently, a product has been developed that consists of pieces of recycled PE that are bonded into flexible mats.

39 Geocomb panels and blocks, typically with a geotextile between the geocomb product and adjacent soil, have proven to be useful in a wide variety of applications where it is desirable to temporarily store surface runoff water and discharge it into the ground water system in a controlled recharge manner over time.

40 Noise and Vibration Damping

Examples where geofoam has been used to provide this function include:

- 41 attenuation of small-amplitude, ground-borne vibrations from:
    - motor vehicles and
    - trains, and
- 42 attenuation of wheel-rail noise from trains, especially surface light rail (trams, trolleys) in urban environments.

Geofoam products used typically consist either of full-size blocks of EPS or panels cut from a block of EPS. PUR panels have also seen use.

43 Compressible Inclusion

Applications involving the use of geofoam as a compressible inclusion have shown significant diversity even in just the relatively few years and limited extent that this function has been exploited in practice. To date, applications have been in three broad categories:

1. with any type of rigid/non-yielding earth retaining structure to:
    - reduce lateral earth pressures acting on the structure by:
        - 44 allowing displacement and shear-strength mobilization within the retained soil (significant additional lateral earth pressure reduction is possible if geosynthetic tensile reinforcement is also placed within the retained soil),
        - accommodating volume change of earth materials (expansive or freezing soil/rock) and
        - 45 accommodating structure movement (usually thermally induced) such as that which occurs with integral-abutment bridges; and
    - reduce surface settlements behind the structure if geosynthetic tensile reinforcement is also placed within the retained soil;
2. 46 to 49 beneath and adjacent to foundation elements to reduce stresses from expansive soil or rock; and
3. 50 above or below underground conduits to reduce vertical stresses acting on the conduit by inducing vertical arching within the overlying soil. This is the modern, evolutionary variant of an innovative concept developed originally by Marston and later Spangler in the State of Iowa, U.S.A. in the early 20^{th} Century.

Geofoam products used in compressible inclusion applications are typically either low-density (~10 kg/m^3 (0.6 lb/ft^3)) EPS or, more recently, resilient (elasticized) EPS. The latter material is normal EPS that has been subjected to an additional manufacturing step to permanently modify the shape of the molded beads. This permanently changes the stress-strain characteristics of the EPS to enhance its compressibility under stress magnitudes encountered is most geotechnical applications.

Experience also indicates that compressible inclusion applications are ones where the inherent
51 multifunctionality of geofoams can be used to both technical and economic advantage. Thus the
use of a geofoam-based geocomposite to act as a compressible inclusion as well as provide
drainage and thermal insulation is increasingly common.

52 Structural/Miscellaneous

Applications involving the structural function are still evolving. Some that have been identified and used to date include:

- 53 wall forms for cast-in-place PCC construction. Note that these forms are designed to be left in place after construction to provide permanent thermal insulation and life-cycle energy cost savings for the structure. Other functions such as drainage and compressible inclusion could be incorporated into such products to make them even more cost effective to use for all types of below-grade walls;

- 54 ultralightweight facing panels for mechanically stabilized earth walls (MSEW). Widely
55 available generic *exterior insulation finishing system* (EIFS) technology can be used to
create a wide variety of durable architectural finishes;

- 56 lightweight void formers for cast-in-place PCC construction;

- 57 crash barriers for motor vehicles and aircraft;

- 58 impact cushioning for PCC rock sheds in mountainous regions; and

- void filling and foundation remediation using foam grouts.

The geofoam products used for these applications are primarily based on block- or shape-molded EPS, with XPS used to a limited extent as well. Other geofoam materials are used for certain specific applications, e.g. PUR grout and a proprietary cementitious foam for airfield runway "overrun" areas.

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FURTHER STUDY

Those interested in further study are directed to Horvath (1995) and *Matériaux* (1997) for information related to geofoams and Perrier (1997) and *Matériaux* (1997) for information related to geocombs. More-advanced information on selected topics can also be found via the Internet on the World Wide Web at the Manhattan College Center for Geotechnology website:

www.engineering.manhattan.edu/civil/CGT.html.

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