Manhattan College

Center for Geotechnology

Geomaterials Research Project
-
Concepts for Cellular Geosynthetics Standards with an Example for EPS-Block Geofoam as Lightweight Fill for Roads

Research Report No. CGT-2001-4

by

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October 2001

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

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

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

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

- Technology advancement through research and development that involves not only the engineering practitioner but also other end users of geotechnology such as construction contractors and material manufacturers to the greatest extent practicable.

- Technology transfer (T^2) through education of engineers, contractors and manufacturers in a multi-faceted, proactive way.

- Technology documentation through standards development so that all end users (practitioners, contractors and manufacturers) of a given technology work to a common set of guidelines.

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

The CGT receives no direct financial support on a regular basis from Manhattan College. Thus the success and growth of the CGT is totally a function of outside funding from individuals and organizations whose philanthropic philosophies are consistent with the stated goal of the CGT to treat technology growth in a more holistic fashion than is typically done in academia and considers the entire process from research to standards with end-user input at all stages. In addition, as part of its mission to promote technology transfer through education to the greatest extent practicable the CGT is willing to partner with industry and other academic institutions not only in research but also technology transfer and standards activities on any topic relevant to geotechnical or geoenvironmental engineering. The new Manhattan College School of Engineering William J. Scala Academy Room, which is located on the main floor of the Leo Engineering Building and available for CGT activities, offers modern facilities for hosting technology transfer activities. One benefit of Manhattan College's location on the northern edge of New York City adjacent to both Interstate I-87 and mass transit is that it is quite accessible (including free off-street parking adjacent to Leo Engineering Building) from both within and outside the City. When appropriate, the CGT will bring its technology transfer activities off campus to meet the needs of a particular activity.

Regardless of financial support, the ultimate success and growth of the CGT will depend on its being responsive to the needs of the engineering practitioner. Towards this end, the CGT welcomes input from practitioners on an ongoing, continual basis. Suggestions for future research and technology transfer activities based on perceived needs in practice are always welcome. There is no topic that is too modest or simple for consideration. In fact, much of the research conducted by Prof. Horvath since he came to Manhattan College in 1987 has been based on ideas, large and small, that he developed as a result of his years in engineering practice.

Additional information about the CGT as well as access to published documents and other resources can be found on the Internet at <www.engineering.manhattan.edu/civil/CGT.html>.

Preface

I can still clearly recall as an entry level engineer in practice that I had a dim view of contract specifications. Whenever I was tasked to develop or contribute to a "spec" for a particular project, I would hunt around for something that either I or someone else had used before. I viewed specs as just so much boilerplate that did not really matter and that no one really ever read, a necessary evil that was to be dispatched as quickly and painlessly as possible.

Almost 30 years of geotechnical engineering practice has taught me the short-sighted ignorance of my professional youth. From both personal experience in engineering practice as well as my research work since 1988 with what we now refer to generically as geofoams, I developed a whole new appreciation of the technical and legal power and importance of both specifications and the standards that they are based on. I have learned that a single word or omission of same in a specification can have a profound effect on the outcome of a construction project.

As a result of these lessons learned, I make it a point to emphasize the importance of standards and specifications to my students at Manhattan College in every course I teach. In addition, I have devoted increasing energy in recent years to trying to make some contribution to the "good of the order" when it comes to standards and specifications for cellular geosynthetics, especially the widely used EPS-block geofoam. Thus I hope that there are at least a few people out there who will find this report of some interest and use, if only to stimulate their own thinking and action in the area of cellular geosynthetics standards and specifications.

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Executive Summary

Standards development is one of the three essential components for developing, maintaining and advancing any technology. Experience with planar geosynthetics (geogrids, geomembranes, geotextiles, etc.) during the final decades of the 20th Century demonstrated conclusively that standards development is the component of the "trilogy of technology" that generally lags both research (always the leader) and education, sometimes significantly. This retarded development of standards has an negative effect on the quality of construction specifications as "specs" are dependent on standards for their own development and reference.

Although knowledge and use of geofoams and, to a lesser extent, geocombs has grown significantly worldwide during the 1990s, standards development for these two families of geosynthetics (which are collectively referred to as cellular geosynthetics) has, unfortunately, followed the pattern set by the traditional, planar geosynthetics and seriously lagged research and usage. Even in areas such as western Europe where significantly more attention has been paid to cellular-geosynthetics standards development than in other parts of the world these standards are typically quite narrow in scope. Given the myriad combinations of cellular geosynthetic materials and products and their geosynthetic functions and applications, these efforts, while important, are only a small beginning. Consequently, development of meaningful standards for cellular geosynthetics covering the entire spectrum of use should be a high priority worldwide.

This report is intended to be a contribution to furthering cellular-geosynthetics standards development in several complementary ways:

- Concepts and suggestions are presented to provide a generic framework that can be used for any cellular-geosynthetic material, product, geosynthetic function and application. It is intended that this information would be used by members of the various standards organizations who are responsible for actual standards development.

- The application of this framework to a specific combination of variables is illustrated in detail. The problem considered is the use of block-molded expanded polystyrene (EPS) geofoam as lightweight fill in road construction. Both design and material/product and construction standards are presented. Not only does this illustrate the proposed standards-development methodology but the standards themselves are sufficiently complete so as to be usable in practice.

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Section 1
Introduction

1.1 BACKGROUND

As noted in the Manhattan College Center for Geotechnology (CGT) mission statement that is included in the introductory pages of this report, technology documentation through standards development is one of the three essential components for developing, maintaining and advancing any technology. Experience with planar geosynthetics (geogrids, geomembranes, geotextiles, etc.) during the final decades of the 20th Century demonstrated conclusively that standards development is the one component of the "trilogy of technology" that generally lags both research (always the leader) and education, sometimes significantly. This retarded development of standards has an negative effect on the quality of construction specifications as "specs" are dependent on standards for their own development and reference.

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1.2 PURPOSE AND SCOPE OF REPORT

1.2.1 Background

Standards development is typically carried out under the overall jurisdiction of organizations dedicated in whole or part to that activity. Standards organizations in the U.S.A. that are active in the geosynthetics area include the:

- American Association of State Highway and Transportation Officials (AASHTO),
- American Society for Testing and Materials (ASTM) and
- Geosynthetics Institute (GSI).

There are similar groups elsewhere. For example, in western Europe there are both regional standards organizations (e.g. CEN in western Europe) as well as individual national efforts (e.g. CROW in The Netherlands).

However, the actual standards development within these groups is typically performed by committees consisting of a diverse assemblage of volunteers, each with a commercial, financial or professional interest in a particular standard. In general, these volunteers are not involved with standards making as a full-time vocation. In addition, they are typically not formally educated in standards development and learn "on the job" by trial and error. Therefore, there is a utility in providing guidance and assistance to those involved with standards development.

Because standards organizations typically operate on a consensus basis, the first step in developing a particular standard should always be to develop a logical framework or outline for that standard. This framework should be based on all of the key material/product parameters and other technical issues that the standard should address. Only after a consensus is reached as to what parameters and issues are relevant to that standard should the actual standards writing commence, with each committee member adding their input based on their particular expertise or knowledge.

1.2.2 Overview of Scope

Given the relative dearth of geofoam and geocomb standards at the present time, there is clearly much work to be done to advance the state of cellular geosynthetics standards. The primary purpose of this report is to present a conceptual or model framework that can be used for this purpose. There is no intent here to usurp the jurisdiction or function of the various standards organizations around the world. Rather, this report is intended to be an objective contribution in support of their efforts. As noted in the preceding section, the most important step in any standards development should be to agree on what topics need to be covered by a particular standard.

As a complement to presenting this conceptual framework, the secondary purpose of this report is to illustrate how it was used in a zero-based effort to develop a comprehensive suite of new design, material, product and construction standards for block-molded expanded polystyrene (EPS-block) geofoam used as lightweight fill in road embankments on soft ground. This particular standards development effort was one task of work begun in July 1999 as contract research for U.S. National Cooperative Highway Research Program (NCHRP) Project 24-11 for Federal Fiscal Year 1998[a]. These standards, which are officially considered interim or provisional in nature at this time, were developed in AASHTO format. A draft version was included as part of the preliminary (Phase I) report (Horvath et al. 2000) that was submitted in April 2000 to the Transportation Research Board (TRB), the private agency that administers NCHRP projects.

At one time, free copies of Horvath et al. (2000) were available to the general public for their review and comment[b]. However, the supply of these Phase I reports is exhausted and will not be replenished as a final (Phase II) project report is due out in 2002. It is currently planned that this final report will contain a final interim version of these standards. However, in the mean time it is hoped that access to the draft interim standards in this current report will serve a purpose in continuing to disseminate this knowledge for evaluation by industry and end users alike.

It is useful to note that although the NCHRP Project 24-11 standards presented herein are intentionally very narrow in their scope for contractual requirements, experience indicates that they are applicable to a much wider range of lightweight-fill applications. This includes not only other types of transportation-related "earthworks" for airfields and railways but lightweight-fills supporting structures such as small buildings and bridges and backfills/fills behind various types of earth retaining structures.

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[a] The official name of this project is "Guidelines for Geofoam Applications in Embankment Projects". However, the scope is limited to EPS-block geofoam.

[b] In addition to soliciting post-publication comment, in developing these draft interim standards in the first place all known, relevant existing EPS-block geofoam standards and specifications from around the world were researched, reviewed and considered by the Project team. Input was also solicited from both the EPS industry and end users throughout the U.S.A. via a public questionnaire developed specifically for this NCHRP project. Thus the draft interim standards as issued in April 2000 already contained significant input from a wide spectrum of outside sources.

1.3 REPORT ORGANIZATION

The remaining sections of this report are organized as follows:

- Section 2 presents the conceptual framework that is proposed for use in developing standards covering design and construction for any type of geofoam or geocomb material and product in any geosynthetic function and application.

- Sections 3 to 6 inclusive illustrate in detail how to implement this framework in practice to a particular material, product, geosynthetic function and application. As noted in the preceding section, the example used is EPS-block geofoam lightweight fill for road embankments on soft ground. This illustrated example is comprehensive as it presumes absolutely no prior knowledge of the material, product, function or application. The specific topics covered by each section are as follows:

    - Section 3 provides a primer on EPS. Primers are not normally found in standards documents as a basic knowledge of the material covered by the standard is presumed. However, when dealing with technologies such as cellular geosynthetics that are still considered emerging from the viewpoint of traditional geotechnical engineering textbooks, education and practice, the value of and need for such a primer should not be underappreciated. Unfortunately, most people involved in standards activities, by virtue of their own intimate knowledge of a subject, tend to forget the value of the basic knowledge inherently contained in a primer for the broader population, both engineers and non-engineers alike[c].

    - Section 4 is a commentary that details the rationale used as the basis for key technical decisions regarding contents of the standards. As such, it provides a detailed example of the conceptual framework presented in Section 2 that is the primary purpose of this report.

    - Section 5 contains the design standard for this specific material, product, geosynthetic function and application.

    - Section 6 contains the combined material/product and construction standard for this specific material, product, geosynthetic function and application.

- Section 7 contains a list of references cited throughout this report.

- Appendix A contains a brief primer on the use of recycled material called *regrind* in the manufacture of EPS. This information is included because the issue of whether or not explicitly specifying regrind percentage belongs in EPS geofoam standards and specifications has become of great interest and contention in just the last few years.

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[c] To support this argument, as noted in the CGT mission statement that is included in the introductory pages of this report in recent years it has been necessary to offer "educate the educator" events in several topical areas within geotechnical engineering as diverse as drilled-shaft foundations and geosynthetics in general. This underscores that fact that if even academicians are unfamiliar with new and emerging technologies then it is highly likely that the people they educate will be similarly unfamiliar.

- Appendix B contains a tabular summary of the manufacturing quality assurance (MQA) procedures that are detailed in Section 6. This appendix provides a concise, convenient overview of this important aspect of the material/product and construction standard. This tabular summary was prepared by Mr. David Arellano, P.E. of the University of Illinois at Urbana-Champaign who is one of the Principal Investigators for NCHRP Project 24-11. His assistance with preparing this summary is acknowledged with gratitude.

Section 2
A Conceptual Framework for Developing Cellular Geosynthetics Standards

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2.1 INTRODUCTION

As noted in Section 1, when taken as a whole cellular geosynthetics is still a relatively new technology to most civil engineers and other end users in many countries. This state of knowledge has two broad effects on cellular geosynthetics standards development. First and fundamentally, the topics and the level of detail that should be covered by standards for cellular geosynthetics at the present time should be much more extensive than would be required for standards covering more-traditional geotechnical subjects. This is because most users of cellular-geosynthetics standards have little or no prior education and knowledge of the subject. This overall unfamiliarity with cellular geosynthetics is reflected in the suggested framework for cellular geosynthetics standards presented in this section.

As a secondary effect of the unfamiliarity that many still have concerning cellular geosynthetics, there is a need to provide objective, basic knowledge on the subject of cellular geosynthetics in the form of primers. As noted in Section 1, such technical primers are normally not part of standards although there is no reason why this traditional practice could not or should not be changed. It is suggested that, as a minimum, standards should at least reference objective sources of basic knowledge so that standards users are at least directed to this information.

2.2 TOPICS FOR CONSIDERATION

2.2.1 Overview

As noted in Section 1, multiple standards for cellular geosynthetics are necessary because of the myriad combinations of variables involved. Therefore, the first step in standards development should be decide which combination of variables are to be covered by a particular standard or group of standards. The variables to consider are:

- material,
- product,
- geosynthetic function and
- application.

The interaction of these variables should be considered in two broad contexts:

- design and
- construction.

Each of these topics is discussed in detail in the following sections.

2.2.2 Material

"Material" is defined here as the basic composition (both the specific polymer as well as manufacturing method in the case of plastics) of the substance used as the basic component of the cellular geosynthetic. Note that in this context expanded polystyrene (EPS) and extruded polystyrene (XPS) are considered different materials even though they both derive from solid polystyrene (PS) and existing ASTM standards (e.g. the widely referenced C 578) often consider them collectively under the label of *rigid cellular polystyrene* (RCPS). The reason for differentiating between EPS and XPS is because the manner in which the PS is processed to result in EPS and XPS produces final materials with structure, texture and engineering properties that are significantly different as far as geofoam applications are concerned.

A cellular-geosynthetic standard should be limited to a consideration of only one material. The material issues to be considered in a standard primarily involve:

- environmental and safety issues related to the basic manufacturing of material, e.g. the need to "season" a material immediately after manufacturing to allow it to stabilize chemically, thermally and dimensionally;
- environmental and safety issues related to handling the material between the point of manufacture and a project site if they are different;
- durability of the material in the ground; and
- environmental effects of the in-place material on air, ground and ground water.

Note that there are likely to be important differences in the above considerations for geofoams because some geofoam materials are manufactured in a fixed plant by personnel trained and experienced in the manufacturing process and some are foamed in-place, often by personnel unfamiliar with them.

2.2.3 Product

"Product" is defined here as the final object into which the material is formed. Intentionally distinguishing between material and product is not a trivial issue when cellular geosynthetics are concerned. For example, it is possible to mold EPS into an infinite number of shapes or to assemble whole blocks or pieces of blocks into different assemblages. Each one of these shapes or assemblages is a different product with different standards and specification requirements.

A cellular-geosynthetic standard should be limited to a consideration of only one product although that product may have some variation. The classic example is EPS-block geofoam which can be manufactured over a range in densities. Experience indicates that one standard defining several "standard" EPS-block densities is not only acceptable but generally desirable.

The product issues to be considered in a standard primarily involve the ability of that product to reliably and consistently deliver certain geotechnically relevant engineering properties in the areas of overall density, load bearing, thermal resistivity/transmissivity and possibly others depending on the specific function and application. Thus the standard must specify and clearly distinguish between *manufacturing quality control* (MQC) to be undertaken by the cellular-geosynthetic manufacturer and *manufacturing quality assurance* (MQA) to be undertaken by a project owner or their designated agent.

In most applications, load-bearing considerations are by the far the most important consideration. There are several key concepts to keep in mind in this regard:

- Many cellular-geosynthetic products do not "fail" in the traditional material sense of a physical rupture when loaded in compression which is the predominant deformation mode in practice. They simply crush back to the solid material from whence they originated. Therefore, the parameter of *compressive strength* when arbitrarily defined for cellular-geosynthetic materials/products often has no direct, useful meaning from a design perspective. However, compressive strength can play a useful role in MQC/MQA but only when considered together with several other material properties.

- Most cellular-geosynthetic applications are governed by deformations of the cellular-geosynthetic product. This applies to both "small-strain" applications such as lightweight fills and "large-strain" applications such as compressible inclusions. As a result, deformations must always at least be considered if not calculated explicitly. Therefore, material parameters now recognized as appropriate and necessary for deformation analysis, such as *initial tangent Young's modulus* and *elastic-limit stress*, must be included.

- Creep (deformation over time under constant force) is an important consideration in all deformation analyses, especially when polymeric materials are used (which means most geofoams and all geocombs).

2.2.4 Geosynthetic Function

"Geosynthetic function" is defined here as the geotechnical role(s) the cellular-geosynthetic product provides once it is in the ground. The geosynthetic functions identified to date for cellular geosynthetics are as follows:

- compressible inclusion [geofoams only],
- drainage (fluid storage) [geocombs only],
- drainage (fluid transmission) [geofoams and geocombs],
- lightweight fill [geofoams and geocombs],
- noise and small-amplitude vibration damping [geofoams],
- structural/miscellaneous [geofoams only] and
- thermal insulation [geofoams only].

A detailed discussion of these functions is beyond the scope of this report and is presented elsewhere (Horvath 1995, 1999b). However, it is important to note that not all geofoam materials/products can provide each of the above functions attributed to geofoams. In fact, only EPS can provide each of the above geofoam functions by virtue of its versatility to be molded over a range of densities and products. This is a significant reason why EPS has been and still is the geofoam material of choice in the vast majority of applications.

In general, a cellular-geosynthetic standard should be limited to a consideration of only one function. However, in view of the inherent multi-functionality of most cellular geosynthetics (certain true for geofoams such as EPS in particular), it is often necessary to at least consider other functions other than the primary one for which the standard is being written. This is particularly important in design standards when a secondary function is potentially detrimental to the primary function. For example, when EPS-block geofoam is used as a lightweight fill beneath pavements it is necessary to consider the thermal-insulative value of the EPS. This is because the latter may result in differential icing of the pavement surface which is a safety issue.

2.2.5 Application

"Application" is defined here as the specific end use of the cellular-geosynthetic product. In general, for a given cellular-geosynthetic material, product and geosynthetic function it is possible to have multiple applications. A classic example is EPS-block geofoam which can be used as lightweight fill in stand-alone earthworks such as road embankments as well as backfill/fill behind a wide variety of earth retaining structures.

In most cases, it is desirable to have different standards for different families or groups of applications for a given cellular-geosynthetic material/product/function. This is because there are generally several important differences in design and construction concepts between the various application categories. The decision as to how to divide and group applications is best decided by an assessment of design and construction similarities and differences among the various applications. A logical grouping of applications will then emerge from this assessment.

It should be noted that this rational process has, in some cases, not been followed in standards activity to date. For example, NCHRP Project 24-11 and the draft interim standards in AASHTO format that it has produced to date was limited to a consideration of EPS-block geofoam used as lightweight fill for stand-alone road embankments and fills on soft ground. This represents an overly narrow scope of work that was dictated solely by business-political decisions of the funding and management agencies with an "agenda", not objective engineering logic. In all other countries that have developed similar standards to date, road fills of all types, including "side-hill" fills in sloping terrain and on firm ground, are considered. Even more logical would be to develop an even broader set of standards that would consider the use of EPS-block geofoam as lightweight fill for all types of transportation-related earthworks, i.e. including airplanes and trains and not limited to motor vehicles. Therefore, when developing future standards what has been done in the past should not necessarily be considered a model to be followed in the future. In fact, in many cases what has been done in the past is, in some cases, a model of what not to do in the future.

2.2.6 Design

Many engineering design professionals dislike the concept of design standards because they are often interpreted as stifling engineering creativity and professional judgment, and creating the impression that engineering design is a formulaic, "cook-book" endeavor. This is a valid concern and there are certainly examples in the past where this has occurred or was at least attempted. However, design standards are viewed here solely as guidelines to design professionals to assist them with designing with what may be a new (to them) geosynthetic material, product, function and application. As such, cellular-geosynthetic design standards are intended to fulfill more of an educational role as opposed to one of strict prescription. Therefore, such standards should be carefully crafted to outline, in logical order, the issues and items to be considered during design. In addition, design standards should highlight those things that may be unique with a particular cellular geosynthetic compared to designing in traditional ways with traditional materials.

2.2.7 Construction

Thorough, detailed construction standards are particularly vital for emerging technologies such as cellular geosynthetics. There are at least two reasons for this:

- In general, construction contractors and their personnel as well as the owner/owner's agent who will inspect the construction are unfamiliar with the technology and how to properly construct it. Therefore all parties concerned need detailed guidance for the development and execution of appropriate project-specific specifications.

- Experience with geosynthetics in general, and cellular geosynthetics in particular (Horvath 1999a), clearly indicates that the most vulnerable time in the life of a geosynthetic is during construction. The majority of failures for all types of geosynthetics occurs as a result of damage imparted during construction. Therefore, construction standards and the project-specific

As with manufacturing, there are always two aspects to construction quality that must be addressed by a construction-related standard:

- *construction quality control* (CQC) which are those steps to be taken by the construction contractor to ensure compliance with the project-specific contract specifications and

- *construction quality assurance* (CQA) which are those steps to be undertaken by the owner or owner's agent to verify contractor compliance with the project-specific contract specifications.

2.3 ORGANIZATION OF TOPICS INTO STANDARDS

The various components of cellular-geosynthetics standards that were discussed in Section 2.2 need to be organized into logical groupings. Experience suggests that for a given combination of material, product, geosynthetic function and application two separate standards are required:

- a design standard that includes a summary of the key material/product properties to provide guidance for a design professional to can carry out an analysis or design for a particular application and

- a combined material/product and construction standard to be used by a design professional to develop a project-specific specification. Because the construction contractor is typically the one to purchase the cellular-geosynthetic product in addition to being responsible for its placement, it is logical to include the requirements for both the material/product and construction in a single, integrated document.

2.4 COMMENTARY FOR STANDARDS

It is not uncommon for standards to be accompanied by a commentary. As the name implies, this is information provided, often in a manner and style of writing somewhat less formal than the standard, to inform the educated user of the standard as to thought processes that went into a particular section of the standard. Essentially a commentary is meant to be a bridge between general knowledge of the subject of the standard (which the user is presumed to already possess or obtain from a primer on the subject) and specific requirements in the standard. The rationale is that a design professional has a right to understand the logic that went into developing a standard rather than simply being told to accept the standard at face value. This is particularly important when a design professional has to create a project-specific material/product and construction specification from the standard.

Experience indicates that a commentary can take different forms. It may be a stand-alone document, a separate section within the standard or presented in a running, side-by-side basis within the standard. The decision as to the exact format is largely editorial. A commentary is presented in Section 4 of this report to support the contents of the suggested design and material/product/construction standards presented in sections 5 and 6 respectively.

Section 3
Geotechnically Relevant Properties of Block-Molded EPS

3.1 INTRODUCTION

To understand the technical bases for and content of the standards presented in this report, a fairly detailed knowledge of the geotechnically relevant properties of block-molded EPS is required. Because the use of EPS as an engineered-construction material is still relatively new to most civil engineers and other end users, a brief primer covering the geotechnically relevant properties of block-molded EPS is presented in this section. However, those who already have this basic knowledge may wish to skip this section and to go directly to Section 4.

The contents of this section represent a synopsized and updated (to December 1999) version of material given in Horvath (1995). Unless noted otherwise, all material in this section of the report was taken from Horvath (1995) and interested readers are directed to this reference for greater detail as well as the original references on which the results presented herein were based.

A broad overview of different geofoam materials and products and their geosynthetic functions and applications can also be found in *Matériaux* (1997) and Horvath (1999b). A overview of geocombs can be found in *Matériaux* (1997), Perrier (1997) and Horvath (1999b).

3.2 OVERVIEW

The EPS properties of interest in geotechnical applications fall into three broad categories:

- physical,
- mechanical (stress-strain-time) and
- thermal.

Because these properties can be significantly affected by the manufacturing process, this aspect is discussed as well. It should be noted that although the focus of this section is on practice in the U.S.A., all of technology and most of the terminology used is generic and global.

3.3 MANUFACTURING (MOLDING) EPS

3.3.1 Overview

There are two distinct steps involved in manufacturing (molding) EPS involving two separate companies:

- A manufacturer called a *resin supplier* produces the raw material that is formally called *expandable polystyrene* but colloquially referred to as *beads* or *resin*. Expandable polystyrene consists of fine to medium sand-size spherical particles of solid polystyrene with a naturally occurring petroleum hydrocarbon, almost always pentane (Japan is the only known country where an alternative, butane, is used routinely), mixed in as a *blowing agent*. The expandable polystyrene may also contain other additives that are discussed subsequently. Most resin suppliers are large, multi-national chemical companies with a broad range of products.

- A second manufacturer called a *molder* buys the expandable polystyrene and, in a multi-stage process, transforms it into expanded polystyrene (EPS). The final EPS products are broadly categorized as either being prismatic blocks (*block-molded EPS*) or some type of custom shape (*shape-molded EPS*)[d]. In the past, present and foreseeable future, block-molded EPS is the predominant form of EPS used for geofoam applications. The manufacturers of block-molded EPS are called *block molders* and were traditionally relatively small, privately, locally owned businesses serving a relatively limited geographical area. This is changing somewhat in the U.S.A. to ownership by larger corporations with multiple plant locations although there are still more than approximately 100 block molders with no one molder serving the entire country[e].

EPS blocks can be used for a wide variety of purposes and applications, one of which is what is now called EPS-block geofoam. In the U.S.A. at present, EPS-block geofoam is most often marketed by and purchased directly from a local block molder although sale through distributors who handle other geosynthetics and/or construction products as well as large retail chains selling construction materials is becoming more common. Practices vary widely in this regard at the present time, even within a given area where one molder might sell directly and a competitor only through distributors. End users should be aware of the fact that purchasing EPS-block geofoam through a distributor generally results in a greater unit cost for the product because of distributor markup for their overhead and profit. In many cases, there is no value added by a distributor.

For EPS-block geofoam used in road construction, in typical practice in the U.S.A. at the present time it is the general contractor for a project who usually buys the material either directly from a molder or a distributor.

3.3.2 Block Molding

There are a number of aspects of the EPS block molding process that can significantly influence the quality and other performance aspects of EPS-block geofoam. Therefore, a knowledge of the key elements of the molding process is useful.

Manufacturing block-molded EPS is basically a two-step process. The first step is called *pre-expansion* of the expandable polystyrene. In simple terms, pre-expansion is analogous to making popcorn. The expandable polystyrene (a.k.a. beads, resin) raw material is placed into a large container called a *pre-expander* and then heated with steam. The steam causes the blowing agent that is dissolved in each bead of expandable polystyrene to phase change into a gas and expand the polystyrene in the process to approximately 50 times its initial volume, a diameter increase of the order of three to four times. The expanded spheres of polystyrene are colloquially referred to as *pre-puff*. Each pre-puff particle contains numerous closed cells with about 98% of the total volume consisting of gas-filled voids. Initially, the gas is a mixture of the residual blowing agent and air. The density of the pre-puff can be varied within certain limits which will affect the density of the final product. As discussed subsequently, the density of EPS-block geofoam can be an important and useful index property.

The pre-puff is then moved to temporary storage in large fabric bags to allow it to stabilize thermally and chemically. After several hours of storage (the overall quality of the final product is sensitive to storage time), the pre-puff is placed into a mold which is essentially a closed steel

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[d] The ubiquitous white foam coffee cup is perhaps the best known example of a shape-molded EPS product.

[e] There is, however, at least one cooperative of EPS block molders that advertises nationally in the U.S.A. under a common name. This gives the illusion of a national brand. However, products are still manufactured locally by an independently owned and operated business.

box that is a rectangular parallelepiped in shape. Steam is injected into the sealed mold and this simultaneously resoftens the polystyrene and causes some further expansion of the pre-puff. As a result, the spheres of pre-puff fuse thermally and distort somewhat in shape to fill most of the void spaces between the originally spheroidal pre-puff particles. The block is then released from the mold and allowed to "season", i.e. stabilize thermally (dimensional changes of the block occur during cooling) and chemically (residual blowing agent remaining in the cells of the EPS outgasses and is replaced by air). The block also dries during this seasoning period as a relatively significant amount of water vapor and liquid (which can artificially increase the apparent density of the EPS) that is condensed steam from molding remains in the block at the end of molding. The duration of the seasoning can vary widely from hours to weeks depending on the desired stability of the final product. Seasoning is often accelerated by short-term storage in a room with temperatures that are elevated relative to ambient conditions within the molding plant. Note that not all EPS molders in the U.S.A. have such storage rooms. At the end of the seasoning period, a block can be trimmed, cut or used as is as desired.

The final EPS product has the visual texture of individual, fused particles (the former pre-puff particles, each of which is still roughly spherical in shape). Because of this, EPS was, and sometimes still is, occasionally referred to in literature as *molded expanded polystyrene* or *molded-bead expanded polystyrene* although these terms are typically not used in current U.S. practice. This macrofabric of EPS is also the reason that it has been and still is sometimes referred to colloquially as *beadboard*, a term that the EPS industry in the U.S.A. appears to deprecate because of an-often negative connotation associated with this term.

There is a variation of the above manufacturing procedure that is worth mentioning. The above process is the basic one based on using 100% virgin raw material (expandable polystyrene). However, experience indicates that EPS molding always generates some in-plant scrap or waste material. Consequently, to reduce their costs for both waste disposal as well as raw material purchase most block molders in the U.S.A. try to reuse at least some of this scrap. This is accomplished by grinding it up into pieces that are generally sand-size to produce what is colloquially called *regrind*. The regrind is mixed in with virgin pre-puff during the final block molding process. Because the regrind has long since lost any residual pentane, it does not react the same way as virgin pre-puff during the final molding process. Experience indicates that block-molded EPS containing regrind will, all other variables being equal, have poorer properties (the mechanical properties which are the ones of greatest importance in geofoam applications as lightweight road fill are particularly affected) than block-molded EPS made with 100% virgin prepuff. The degradation in mechanical properties occurs gradually as the relative proportion of regrind is increased.

Although the issue of manufacturing quality control (MQC) is discussed in greater detail elsewhere in this report, it is of interest to note here that the final quality (in terms of geotechnically relevant mechanical properties in particular) of an EPS block is influenced by numerous factors and procedures at each of the above steps of the manufacturing process, including what percentage, if any, of regrind is used. However, experience indicates that an appropriate specification for EPS-block geofoam does not have to explicitly address any of the quality issues at intermediate stages of manufacturing, including maximum allowable regrind content. Rather, it is sufficient to specify minimum quality parameters for the final product and then leave it to the molder to take appropriate measures at each step in the manufacturing process to ensure that final quality parameters are met. This conceptual approach to MQC is reflected in the proposed material/product and construction standard that is included in Section 6 of this report.

3.4 PHYSICAL PROPERTIES AND ISSUES

3.4.1 Introduction

The physical properties of EPS-block geofoam can be thought of as being conceptually similar to the traditional index properties of soil (description, classification, particle size, Atterberg Limits, etc.) and thus useful, within a certain context, during the design process involving EPS-block geofoam.

3.4.2 Block Dimensions

The dimensions of an EPS block do not affect its geotechnically relevant engineering properties. However, other design issues such as product unit cost (including delivery to a job site) and in-situ block layout are influenced by block dimensions.

The dimensions of an EPS block are governed primarily by the mold used during manufacturing. There is no standard mold size used worldwide or even within the U.S.A. so some variation between molders must be expected. However, there is an overall trend, at least within the U.S.A., toward using molds that produce somewhat larger blocks (primarily with respect to the smallest (thickness) and largest (length) dimensions) than in the past. Where possible, it is generally desirable to try to use EPS blocks in their full as-molded size, assuming that the blocks meet certain dimensional quality criteria for straightness, etc. Although it is possible to factory cut a seasoned block into a smaller size, such cutting can add significantly to the unit cost of the final EPS-block geofoam product.

For many years, the typical dimensions of EPS-block geofoam available in the U.S.A. were 610 x 1220 x 2440 mm (2 x 4 x 8 ft). The first trend that developed during the 1990s was toward longer blocks, typically 4880 mm (16 ft) in length. More recently, the trend has been toward thicker blocks, with the thickness dimension increasing from 610 mm (24 in) to between 760 and 1000 mm (30 and 40 in) depending on the particular mold used. Thus many EPS blocks produced nowadays in the U.S.A. are almost square in cross-section. Fortunately, in most lightweight fill applications that are the subject of this study it is possible to use these larger blocks for at least most of the fill. However, some factory and field cutting of blocks is generally necessary on every project.

There are basically two ways to deal with the variability in dimensions of EPS-block geofoam (keep in mind that there are more than 100 EPS block molders in the U.S.A.):

- Select a supplier (molder or distributor) of the EPS-block geofoam during the design phase of a project and determine what is the standard block size available from that supplier. The design professional of record for the project then develops the explicit block layout for the project and this information is shown on the design drawings.

- The design professional produces design drawings that show the overall geometry and dimensions of the desired mass of EPS-block geofoam, as well as specifies certain key conceptual elements of the block layout (minimum number of layers, overall geometry of each layer, etc.). The construction contractor on the project is then required to submit shop drawings depicting the actual block dimensions and layout proposed for use. These shop drawings are typically prepared by the EPS molder and would be reviewed and approved per the normal process used for years in many other aspects of engineered construction.

The first alternative is generally not feasible for government projects such as road construction. In addition, experience in the latter part of the 1990s has indicated that more and more EPS block molders in the U.S.A. are developing the capability to provide shop drawings so this alternative is proving to be quite workable in practice. Therefore, only the second alternative is reflected in the proposed standards contained in sections 5 and 6 of this report.

3.4.3 Color

EPS is inherently white in color although it is possible, for a cost, to tint it another color during the manufacturing process. There is no technical merit or benefit in geofoam applications to a color other than white. The only benefit would be for product identification and marketing purposes.

Although EPS-block geofoam of a color other than white is sold in several countries (e.g. certain proprietary products are brown in Canada and pink in the United Kingdom), such products are not known to be available in the U.S.A. This is perhaps partially due to the fact that the most common and obvious colors (blue, green, pink and yellow) have already been used and legally identified (through registered trademark) with extruded polystyrene (XPS) products that are manufactured in the U.S.A.

What has seen sporadic use in the U.S.A. is for a molder to stencil or otherwise mark some or all blocks of EPS-block geofoam with their name or a logo for product identification or marketing purposes. Such markings can also have a technical benefit to identify (by using different colors for the markings) EPS blocks of different density shipped to the same project site (this is done in the U.K. for example). More common, however, for cost reasons is the use of simple color markings to identify EPS blocks of different density shipped to the same project site.

3.4.4 Density

As noted previously, it is possible to manufacture EPS block within a range of densities, primarily through controlling the density of the pre-puff created during the first stage of manufacturing (the pre-expansion process). The overall range in EPS density possible is between approximately 10 to 100 kg/m^3 (0.6 to 6 lb/ft^3) although for practical purposes the range available for lightweight-fill applications is much smaller, of the order of 16 to 32 kg/m^3 (1 to 2 lb/ft^3).

The relevance of EPS density is that experience indicates that the density of EPS-block geofoam can be a very useful index property but if and only if the EPS meets certain minimum quality parameters. Assuming that the appropriate quality standards are met, density of EPS-block geofoam has been shown to correlate well with both geotechnically relevant mechanical and thermal properties. Therefore, EPS-block geofoam density is used extensively throughout this report as an index property but always with the implication the EPS meets the minimum standards specified in the proposed standard included as Section 6 this report.

There are several additional issues to discuss regarding density of EPS-block geofoam. First, a given production run of EPS blocks will always exhibit some variability of final product density from block to block, even if appropriate manufacturing quality controls are being employed. This simply reflects inherent variability in the EPS manufacturing process and can easily be checked by weighing each block to determine its nominal (average) density.

Second, there will be density variations (called *density gradients* in the industry) within each and every block, also a result of inherent variability in the EPS manufacturing process. Density gradients up to approximately ±10% relative to some nominal (average) value are often given in the literature as typical. In addition, it is generally assumed that densities are largest at the center of a block and smallest at the edges. However, with molding equipment currently in use it turns out that neither of these statements is universally correct any more. Density gradients can, in fact, exceed ±10% (the range appears to increase with increasing average density of the block) and can potentially have complex patterns of variation.

Third, most block molders in the U.S. are set up to manufacture EPS to five standard densities specified in the ASTM standard used for this purpose. Thus it is always the most cost effective to develop a design based on these densities whenever possible. It is important to note that this ASTM standard (C 578) is written from the perspective of specifying minimum acceptable values of product density and several other parameters. This has apparently led to certain misconceptions within the EPS industry regarding product quality as discussed in the main report.

3.4.5 Fusion

Another index of overall EPS quality is called *fusion*. This refers to the thermal fusion between pieces of prepuff (and regrind when used) that occurs during the second stage of manufacturing (final block molding). Experience and testing indicates that fusion does not so much influence the mechanical and thermal properties as it does the overall durability and robustness of the finished product.

3.4.6 Flammability

Flammability of a polymeric material such as polystyrene is often measured or expressed by its *oxygen index* (OI). The OI is the minimum relative proportion (expressed as a percent) of oxygen in some mixture of gases that is required to support continuous combustion. Air at sea level contains approximately 21% oxygen so if a material has an OI less than 21% it will burn freely in air until all the material is consumed provided there is an initial ignition source. If the OI of the material is greater than 21%, it will not support continuous combustion after initial ignition (this is generally referred to as being *self extinguishing*) although it may still melt as well as support combustion if an ignition source is continuously present.

Polystyrene has an OI of 18% which means that normal EPS is inherently flammable. However, it is possible to incorporate an inorganic, bromine-based chemical into the expandable polystyrene raw material used to manufacture EPS so that final block product is flame retardant and self extinguishing. Such raw material is referred to as *modified* bead or resin. EPS made with modified bead can still melt, however, at a temperature between approximately +150 and +260°C (+300 and +500°F) although +95°C (+200°F) is generally recommended as a maximum working value. In the U.S.A., ASTM specifications for flame-retardant EPS call for a minimum OI of 24% which is 3% greater than the OI of air. It is of interest to note that flame-retardant EPS cannot be identified visually nor are any other physical, mechanical or thermal properties affected by the bromine additive.

In general, flame-retardant EPS block reportedly may cost up to 10% more than EPS block that is not flame retardant because of higher raw-material costs. Therefore, on a global basis use of flame-retardant EPS block for geofoam applications has not been universal and should never be assumed. For example, in Norway which pioneered the use of EPS-block geofoam as lightweight fill in 1972 flame-retardant EPS-block geofoam is reportedly rarely specified. However, in some countries such as the U.S.A. it has become routine to supply only flame-retardant EPS-block geofoam. There are at least two reasons for this. First, whenever ASTM C 578 is used as a material specification only flame-retardant material will be supplied. Second, if a molder uses normal (non-flame-retardant) raw material it will contaminate the various components of the manufacturing equipment (mold, etc.) and thus potentially compromise a subsequent manufacturing run of flame-retardant EPS. Thus most molders find it easier to simply always manufacture flame-retardant EPS block.

There is another flammability issue separate from the inherent flammability of the EPS block itself. It is related to the outgassing of the blowing agent used in the manufacturing process. The blowing agents used for EPS, primarily pentane but butane in some countries (chiefly Japan), are inherently flammable and potentially explosive hydrocarbons. In addition, the blowing agents are heavier than air so tend to pool or settle around a block as opposed to freely dispersing into the atmosphere. After an EPS block is released from the mold during the second and final stage of manufacturing, the closed cells within the fused pre-puff will still contain some blowing agent. The remaining blowing agent will naturally outgas from the cells and be replaced by air within a relatively short period of time. The exact duration of this outgassing process depends on many factors, especially temperature, but is of the order of days.

As discussed by Horvath (1999a), there was a lightweight fill project in Japan where the EPS blocks were being delivered to the job site and reportedly placed with very little seasoning time after molding due to project needs (this is not uncommon and is known to have occurred on several projects in the U.S.A.). On this specific project in Japan, the outgassed butane blowing agent accumulated in the joints between blocks and was ignited in situ by some on-site ignition source (welding or flame cutting of metal that was unrelated to the geofoam usage or even personal tobacco smoking). Because of this incident, EPS-block geofoam specifications in Japan now contain a minimum required seasoning period before they can be placed on a job site.

3.4.7 Durability

The overall durability of EPS-block geofoam encompasses a range of issues. Flammability was addressed separately in the preceding section as it is primarily a manufacturing issue and not directly related to post-manufacturing durability. Considered in this section are the external factors related to construction and the in-situ environment that may affect the physical, mechanical or thermal properties of EPS-block geofoam after it leaves the molding plant. The effect of EPS-block geofoam on the in-situ environment is discussed separately in the following section.

In general, EPS-block geofoam has proven to be a very robust geosynthetic product, much more problem-free on the whole compared to many other types of geosynthetics where there is a potential for significant physical damage to and detrimental chemical changes within the geosynthetic during and after construction. EPS is inherently non-biodegradable and will not dissolve, deteriorate or change chemically in the ground and ground water. Although EPS will absorb some ground water over time, the product will not change dimensionally and its mechanical properties are unaffected. The EPS will, however, lose some of its thermal efficiency which is irrelevant per se to lightweight fill applications as addressed in this report.

EPS provides no nutritive food source to any living organism or animal. However, certain burrowing insects such as termites and carpenter ants have been found to either tunnel through EPS or nest in it. This has only been observed for relatively thin (of the order of several tens of millimetres (a few inches) thick) geofoam panels used as thermal insulation in residential construction where there is an abundance of dead wood. There is no known case in the world where insect damage has been detected for EPS-block geofoam used as lightweight fill. There was an active discussion of this topic at Session 6 of the International Symposium on EPS Construction Method (*EPS Tokyo '96*) that was held in Tokyo, Japan in 1996 and reported in the final report for this symposium.

It is worth noting that an inorganic chemical additive with the tradename *Timbor* was developed in the U.S.A. toward the end of the 20th century for EPS. The reported benefit of this additive is that it acts as a deterrent to insect infestation of block-molded EPS. The use of this additive in EPS block is proprietary and is available only from certain EPS block molders in the U.S.A. and Puerto Rico at the present time. EPS block manufactured with this additive is marketed under various tradenames including *Bug Block-R*™, *Perform Guard*®, *Teps*™ and possibly others. Some design professionals have elected to specify EPS-block geofoam treated with *Timbor* for lightweight fill applications. The additive does not affect any of the geotechnically relevant physical, mechanical or thermal properties of the EPS. However, the proposed standard presented in Section 6 of this report does not include a requirement for this additive as there has been no demonstrated unilateral need for this in lightweight fill applications. Therefore, a design professional wishing to have EPS-block geofoam with this additive would have to incorporate additional specification language for this. Specifiers of this additive should, however, be aware of the fact that requiring this additive in EPS-block geofoam will, in most parts of the U.S., restrict to one the number of molders who can bid on and supply a project. Because of this elimination of competition plus the inherent cost of the additive itself, the unit cost of the EPS blocks would be expected to be higher, possibly significantly so, than otherwise. However, it is not possible to quantify the likely relative cost increase because there are too many intangible non-technical business issues involved.

There are relatively few conditions against which EPS-block geofoam needs protection. When exposed to UV radiation from sunlight, the surface of an EPS block will turn yellow in color and become somewhat brittle and chalky. However, this process takes from months to years to develop and is limited to the surface (degradation does not progress into the block) so it is only necessary to protect EPS-block geofoam from long-term UV radiation. Relatively brief exposure such as during construction is not a problem.

There are relatively few liquids that will dissolve EPS. The only ones likely to be encountered in lightweight fill geofoam applications are fuels such as gasoline and diesel fuel.

3.4.8 Environmental Effects

Environmental effects related to EPS-block geofoam fall into several categories. First, regarding the material itself polystyrene is not inherently harmful or hazardous. Solid polystyrene is used for eating utensils and food containers, and EPS is used for beverage containers (the ubiquitous white foam coffee cup is a shape-molded EPS product) as well as food packaging. The blowing agents used to manufacture EPS are naturally occurring hydrocarbons, not a synthetic fluorocarbon-family gas which is used as a blowing agent for most other plastic foams. Thus there are no gases that are potentially harmful to the Earth's upper-atmosphere ozone layer that are associated with manufacturing EPS. Furthermore, because the cells within EPS are completely filled with air within a few days after molding there is no concern about long-term outgassing of potentially toxic and hazardous gases as has been a problem with other types of plastic foam.

EPS will not interact in any way with the ground or ground water, and will not leach any chemical into the ground or ground water. If EPS is burned, either accidentally or intentionally as part of a waste-to-energy program, the products of combustion are primarily carbon dioxide and water. In addition, flame-retardant EPS (as would typically be used for lightweight fill geofoam in U.S. practice) will also emit traces of hydrogen bromide. The residual ash from burned EPS contains no heavy metals or other substances generally considered to be toxic or hazardous.

Note that the above comments regarding environmental impact of EPS only apply to "normal" EPS. Information concerning the impact(s), if any, associated with EPS treated with the insecticide noted above would have to be obtained from the proprietary supplier of such EPS.

3.5 MECHANICAL PROPERTIES

3.5.1 Introduction

The mechanical properties of block-molded EPS primarily involve its stress-strain response under various modes and duration of loading. The temperature of the EPS can also affect the mechanical behavior but is generally a secondary issue. As noted previously, water absorption, if any, has no effect on the mechanical properties of the EPS.

3.5.2 Compression

3.5.2.1 Introduction

Loading in unconfined uniaxial compression has been and remains the primary mode of loading for tests performed on EPS-block geofoam for both quality control and research purposes. This is because compression is by far the predominant mode of loading for EPS in load-bearing applications, including when used as lightweight fill. Although no single standard test has been adopted, there are a set of test parameters that are used more often than others and as such comprise a de facto worldwide standard:

- EPS specimens that are cubic in shape and 50 mm (2 in) wide and
- typical laboratory environmental conditions (atmospheric pressure, +23°C (+73°F) temperature, 50% relative humidity).

3.5.2.2 Rapid Loading

3.5.2.2.1 Monotonic

The most commonly performed test on EPS specimens involves strain-controlled loading at a relatively rapid rate, typically 10% per minute, with the load applied in a monotonically increasing fashion until a desired strain level is reached. Figure 3.1 illustrates the results from such a test that was performed to an unusually large strain level (approximately 90%) to illustrate the entire range of EPS behavior. The primary item of note is that the EPS never fails in the traditional sense of other solid materials used in construction (metals, concretes, wood) by a physical rupture of the material. Nor does the EPS behave like soil or other particulate materials where inter-particle slippage occurs and a steady state (critical-state/constant-volume) or residual strength develops at large strains. Rather, the EPS essentially crushes one dimensionally (Poisson's ratio of EPS is discussed in detail subsequently) back to its original solid polystyrene state, and the behavior is continuously work (strain) hardening in nature.

Even though EPS loaded in compression does not fail in the traditional sense of a physical rupture, it has been and still is traditional nonetheless to define a material parameter called *compressive strength* of EPS, σ_c. Compressive strength of EPS is defined as the compressive stress at some arbitrary strain level. There is no universal agreement as to what this arbitrary strain level is. ASTM and most other standards organizations around the world define it as 10% so in this report the compressive strength of EPS is given the notation σ_{c10}. This point on the stress-strain curve is shown with a large black dot in Figure 3.1. It is noteworthy that Norway, where much of the early use of EPS-block geofoam occurred, is one country where the strain criterion used is 5%.

Referring to Figure 3.1, it can be seen that there is nothing particularly noteworthy about a strain level of 10% (or 5% for that matter) other than that it always occurs after a zone of initial yielding of the EPS. This is an important point because early geofoam design methods were based on compressive strength. In many ways, the use of a parameter called "strength" for EPS is unfortunate as it implies an ultimate condition (ULS type failure) involving material rupture. In fact, neither aspect is involved.

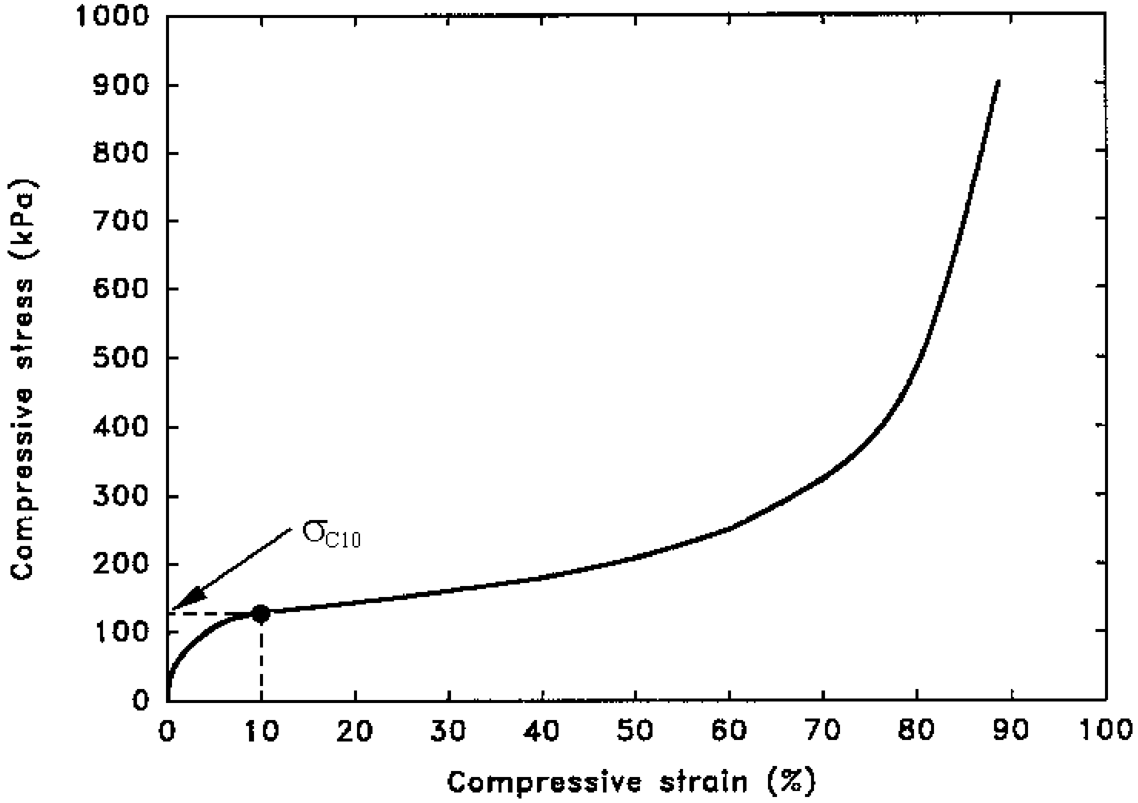

Figure 3.1. Stress-Strain Behavior of 21 kg/m^3 (1.3 lb/ft^3) Block-Molded EPS under Rapid, Strain-Controlled, Unconfined Axial Compression

In recent years, greater research attention has been paid to the initial portion of the stress-strain curve at strains much less than 10%. The consensus that has evolved worldwide is that, with accuracy sufficient for routine design purposes, up to a compressive strain of 1% the stress-strain behavior of EPS-block geofoam is both linear and elastic (recent detailed research suggests that behavior is actually slightly non-linear in the 0% to 1% strain range and linear only up to a strain level of about 0.5%). As a result, a new material parameter for EPS-block geofoam has been defined called the *elastic-limit stress*, σ_e. This is defined simply as the compressive stress at 1% strain as measured in a standard rapid-loading test. Furthermore, the slope of the initial (approximately) linear portion of the stress-strain curve is defined as the *initial tangent Young's modulus*, E_{t_i}.

As shown in Figure 3.2, for all practical purposes there is a linear empirical relationship between EPS density and E_{t_i} assuming that the EPS is of appropriate quality (for the purposes of this report, material satisfying the proposed standard included as Section 6 to this report):

$$E_{t_i} = 450\ \rho - 3000 \qquad \textbf{(3.1)}$$

where E_{t_i} has units of kilopascals (kPa) and ρ = EPS density in kg/m^3.

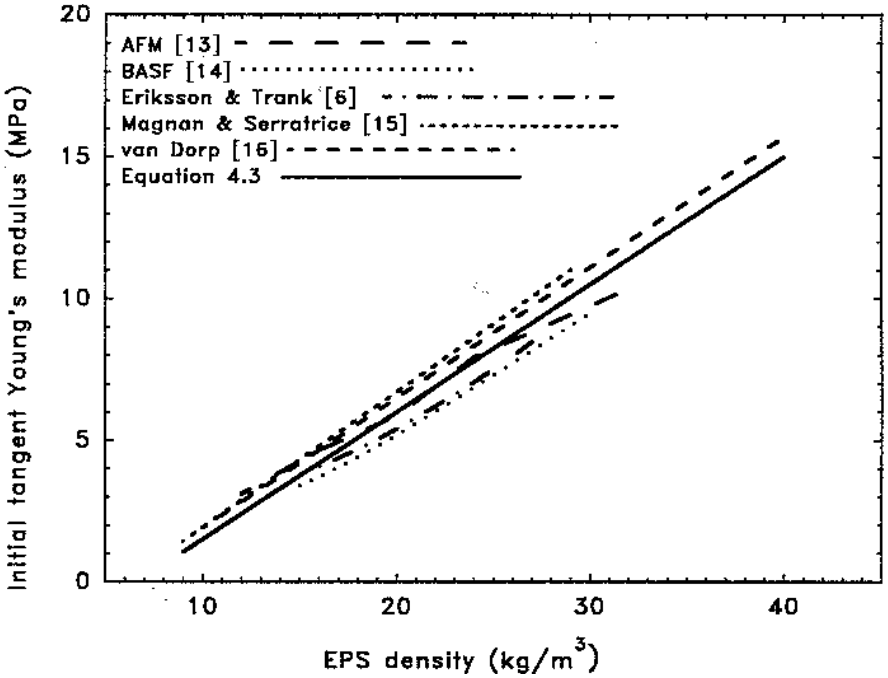

Figure 3.2. Correlation between Density and Initial Tangent Young's Modulus for Block-Molded EPS

Equation 3.1 can be extended to form an equation for the elastic-limit stress that is sufficiently accurate for routine analysis and design purposes:

$$\sigma_e = 4.5\,\rho - 30 \tag{3.2}$$

where σ_e has units of kPa and ρ = EPS density in kg/m^3.

It is of importance to note that the data used to create Figure 3.2 and equations 3.1 and 3.2 were all based on testing relatively small specimens prepared from samples cut from full-size blocks of EPS. There is a lack of information at the present time concerning the stress-strain behavior of full-size EPS blocks although limited unpublished information suggests that full size blocks may be somewhat stiffer, i.e. have a larger initial tangent Young's modulus than either Figure 3.2 or Equation 3.1 would imply.

3.5.2.2.2 Cyclic

For the purposes of this report, cyclic loading is defined as loads that are applied, removed and reapplied in a fairly rapid and repetitive manner. Research to date indicates that as long as the maximum applied stress has a magnitude not exceeding the elastic limit stress, σ_e, there is:

- no plastic (permanent) strain upon stress removal and
- no degradation of the initial tangent Young's modulus.

However, as shown in Figure 3.3 if the stress level goes beyond the elastic range there is both plastic deformation as well as a degradation of modulus. The latter can be seen by the progressive flattening of the unload-reload curves.

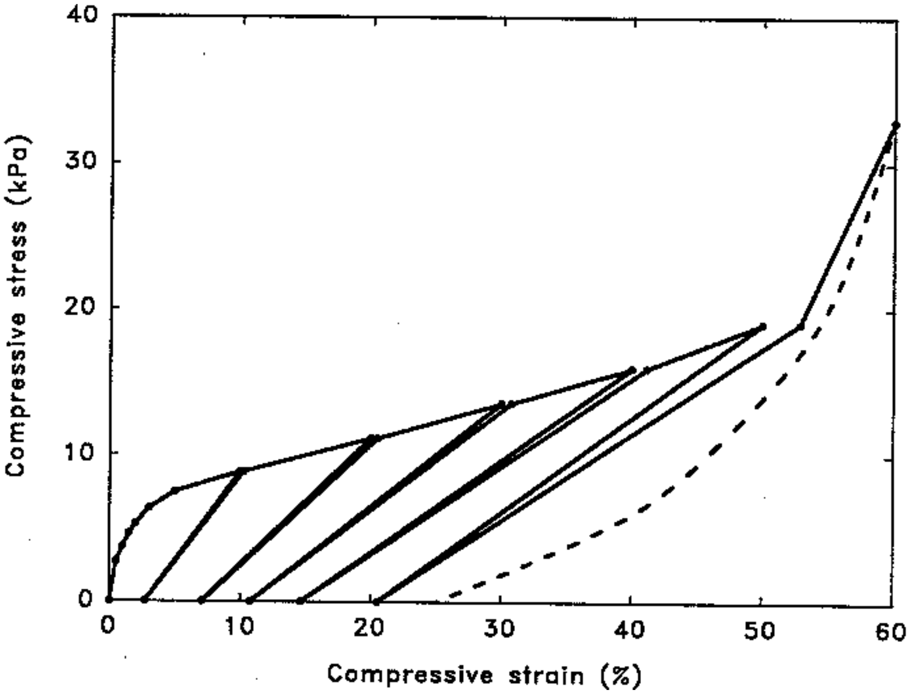

Figure 3.3. Cyclic Load Behavior for 13 kg/m^3 (0.81 lb/ft^3) Block-Molded EPS

It is of importance to note that these observations and conclusions concerning behavior under cyclic loads were all based on testing relatively small specimens prepared from samples cut from full-size blocks of EPS. There is a lack of information at the present time concerning the behavior of full-size EPS blocks.

3.5.2.2.3 Poisson's Ratio

There has been considerable research into the Poisson ratio, ν, of EPS block. The findings can be summarized as follows:

- Within the elastic range, ν is relatively small (of the order of 0.1) and often taken to be zero for practical design purposes, e.g. in the French national design manual. However, if a more accurate estimate of ν is desired, the following empirical relationship, which indicates that ν increases slightly with increasing EPS density, can be used:

$$\nu = 0.0056\ \rho + 0.0024 \qquad \textbf{(3.3)}$$

where ρ = EPS density in kg/m^3.

- If an estimate of the coefficient of lateral earth pressure at rest, K_o, is desired, the following equation which is valid for any elastic material can be used:

$$K_o = \frac{\nu}{1-\nu} \tag{3.4}$$

This means that under confined (at-rest) conditions horizontal stresses will be approximately one-tenth the vertical stresses, a fact that has been confirmed by full-scale case-history observations.

- Beyond the elastic range, ν rapidly decreases to zero. In some tests performed in the past by the author and to very large strain levels, necking of the test specimens (which implies a negative Poisson's ratio) has been observed.

It is of importance to note that the above observations and conclusions concerning Poisson's ratio were all based on testing relatively small specimens prepared from samples cut from full-size blocks of EPS. There is limited information available at the present time concerning the stress-strain behavior of full-size EPS blocks although case history observations, primarily in Norway, suggest that Poisson's ratio is indeed relatively small in magnitude compared to most other civil engineering materials.

3.5.2.2.4 Time-Dependent Behavior (Creep and Relaxation)

Another area of significant material research in recent years has been the time dependent response of EPS-block geofoam to compressive loads. There are two phenomena of interest:

- *Creep* which is the additional strain or deformation that occurs with time under an applied stress or load of constant magnitude.

- *Relaxation* which is the reduction in applied stress or load with time under a constant magnitude of strain or deformation.

In applications such as considered in this report, only creep is of interest and will be the only time dependent phenomenon considered here.

Creep tests on EPS-block geofoam are typically performed in unconfined axial compression. Typical results are shown in Figure 3.4. Research has indicated that the minimum duration of creep tests for EPS-block geofoam should be 10,000 hours (approximately 14 months) with 15,000 hours (approximately 21 months) or longer preferred. This is to provide greater confidence in extrapolating creep behavior for the design life of many geotechnical structures which can be of the order of 100 years or more.

Experience indicates that the most useful way to portray creep-test data is by constructing a family of isochronous stress-strain curves for tests performed on EPS specimens of the same density. An isochronous curve is the estimated stress-strain behavior assuming a range in stresses was applied for a specific duration of time. Figure 3.5 illustrates a typical family of isochronous stress-strain curves together with a portion of the standard rapid-loading test for comparison.

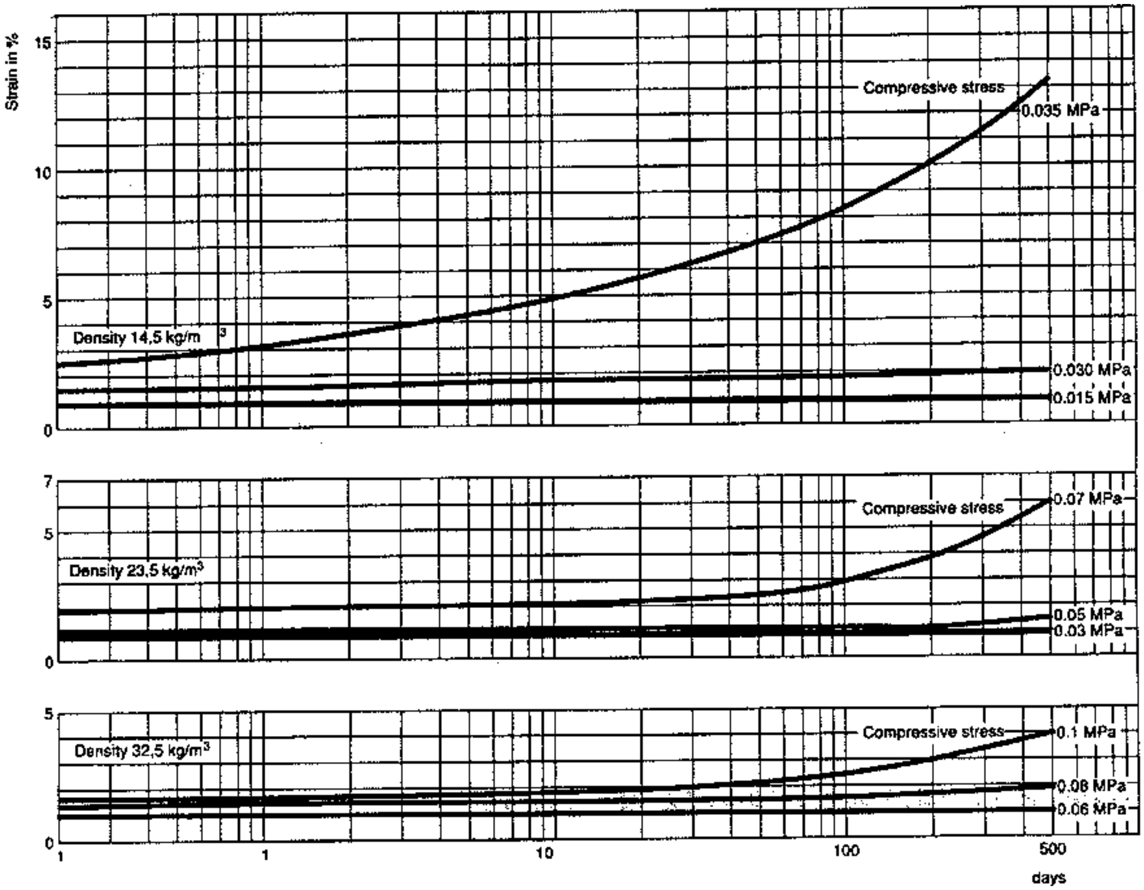

Figure 3.4. Results of Typical Unconfined Axial Compression Creep Tests on Block-Molded EPS

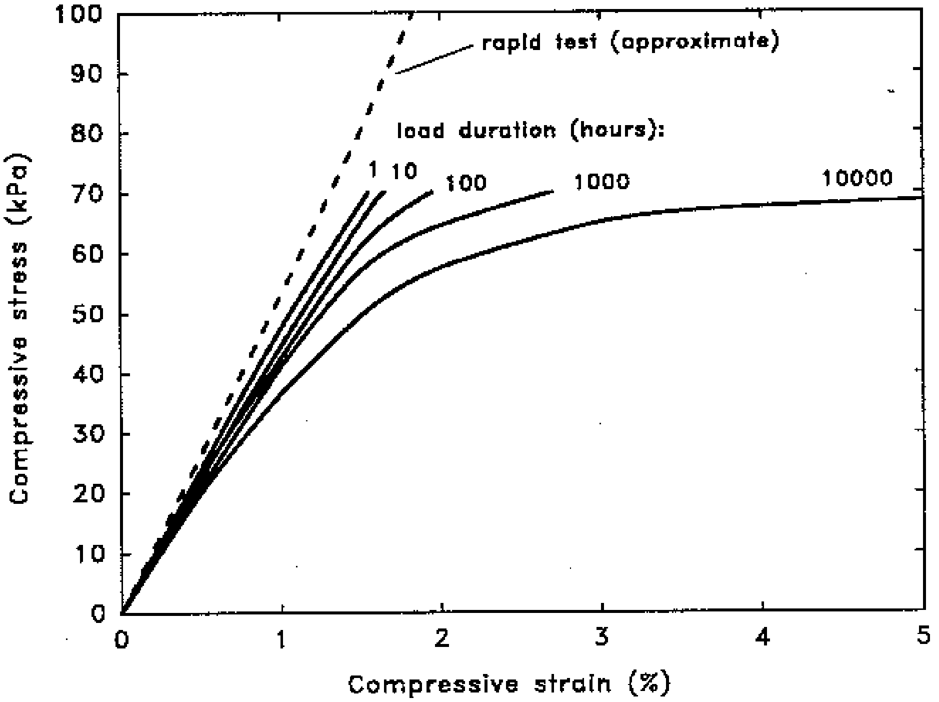

Figure 3.5. Isochronous Stress-Strain Curves for 23.5 kg/m^3 (1.47 lb/ft^3) Block-Molded EPS Based on Unconfined Axial Compression Creep Tests

Based on an assessment of creep behavior for many specimens of EPS-block geofoam, the following conclusions can be drawn:

- If the applied stress is such that it produces an immediate strain of 0.5% or less, creep strains will be essentially negligible even when projected for 50 years or more.
- If the applied stress is such that it produces an immediate strain between 0.5% and 1%, creep strains will be of a magnitude (of the order of 0.5% to 1%) that would normally be considered tolerable in lightweight fill geofoam applications even when projected for 50 years or more.
- If the applied stress is such that it produces an immediate strain greater than 1%, creep strains rapidly increase and become of the order that would generally be considered excessive for lightweight fill geofoam applications.

As a result, it can be seen that creep considerations will tend to limit stresses to that which produces a strain of 1%, i.e. the elastic-limit stress, σ_e.

It is of importance to note that the above observations and conclusions concerning creep were based primarily on testing relatively small specimens prepared from samples cut from full-size blocks of EPS. There is limited information available at the present time concerning the stress-strain behavior of full-size EPS blocks although case history observations, primarily in Norway, suggest that the above conclusions are reasonable.

3.5.2.2.5 Temperature-Dependent Behavior

It is well known that the stress-strain behavior of polymeric materials in general, and polymeric geosynthetics in particular, is temperature dependent. In general, creep rates increase with increasing temperature and decrease with decreasing temperature. Available information suggests that very little creep testing of EPS block has been done to date at temperatures other than ambient in a typical laboratory environment (+23°C (+73°F) ±). What limited testing at elevated (relative to typical laboratory) temperatures has been done indicates that the behavior of EPS block is consistent with trends of polymeric materials in general, i.e. creep rates increase with increasing temperature. A likely reason for the dearth of creep tests at elevated temperatures is likely due to the fact that most EPS-block geofoam applications were, until the 1990s, in relatively cool Northern Hemisphere locations where annual average air temperatures are of the order of +5°C (+41°F) to +15°C (+59°F) maximum. Creep at these temperatures would be expected to be somewhat less than that at ambient laboratory temperatures and long term case history observations (mostly from Norway) confirm that.

3.5.3 Tension

Although tensile loading generally does not occur when EPS block is used in geofoam applications, tensile loading is an important mode of loading for evaluating EPS fusion, a manufacturing quality parameter. Thus tensile loading can be an important MQC/MQA test. However, it appears to be relatively little used as such because of both the difficulty in fabricating the hourglass-shaped test specimens required for tensile testing as well as the availability of other types of tests (most notably flexure which is discussed subsequently) that essentially test for the same thing and are easier to perform. As with compressive loading, laboratory tests for tensile loading are performed at a relatively rapid rate. Tensile strength is defined as the tensile stress at which physical material rupture occurs.

Figure 3.6 illustrates the linear relationship between tensile strength and EPS density. Also shown for comparison is the relationship for compressive strength using the ASTM criterion of 10% strain.

3.5.4 Flexure

Although tensile strength is the fundamental indicator of EPS fusion and thus a useful MQC/MQA parameter, the test itself is somewhat cumbersome as discussed in the previous section. As a result, flexural tests on beam-shaped specimens are performed instead as a practical and pragmatic alternative. The relevant ASTM standard test setup used is such to produce maximum bending moment and, therefore, maximum tension in the extreme bottom fiber of the EPS beam. As with other basic tests, the loading rate to failure (physical rupture of the EPS beam) is fairly rapid. As can be seen in Figure 3.6, flexural strength correlates acceptably with tensile strength which validates the assumption that flexural tests can be used routinely as a measure of bead fusion during the manufacture of EPS.

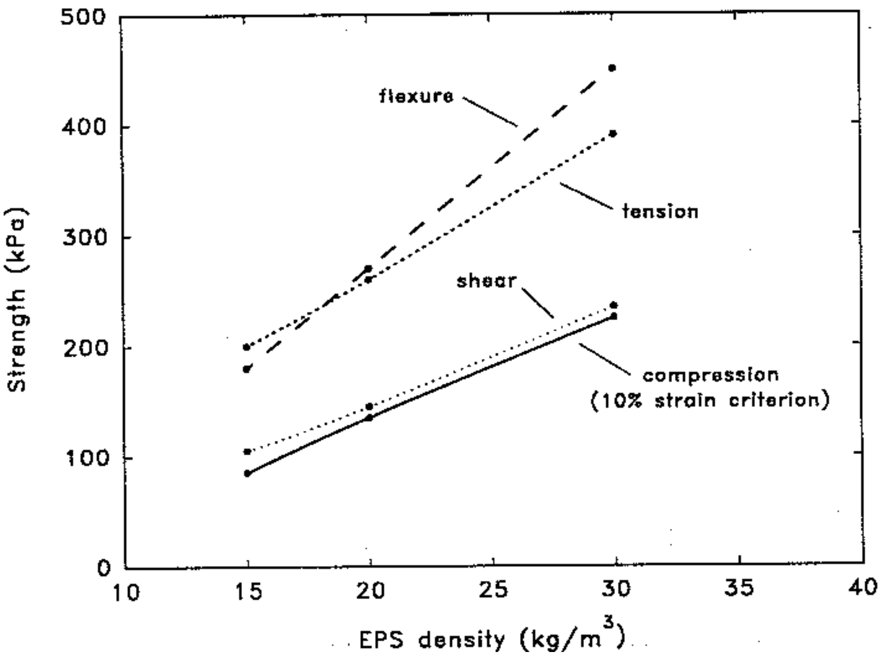

Figure 3.6. Strength of Block-Molded EPS in Various Test Modes as a Function of Density

3.5.5 Shear

3.5.5.1 Introduction

There are two modes of shear that are of interest:

- internal shear strength within a specimen of EPS and
- external shearing (sliding) resistance between EPS blocks or between an EPS block or dissimilar material (soil, other geosynthetic, etc.).

These are discussed separately.

3.5.5.2 Internal

The internal shear strength of EPS is measured by loading a test specimen fairly rapidly until the maximum shear stress is reached, whether or not this stress produces a physical rupture of the test specimen. The correlation between shear strength of EPS block and EPS density is shown in Figure 3.6. Because the shear strength of EPS block exhibits a correlation with compressive strength, experience indicates that the shear strength test is rarely performed in practice whether for MQC/MQA or engineering design.

3.5.5.3 External

Numerous researchers have studied the shearing resistance between pieces of EPS block. Unfortunately, the lack of any kind of test standard has meant that a diversity of test variables (specimen size, specimen preparation (which affects smoothness of the specimen surface), test setup, loading rate, etc.) were used. In particular, whether the EPS surfaces are the relatively smooth molded face of a full-size block or the rougher face of a piece of EPS cut from a block is intuitively believed to have the primary effect on measured results. However, it appears that most if not all of the tests were performed at a fairly rapid rate and researchers seem to agree that the shearing resistance was defined adequately by the classical Coulomb (dry) friction equation:

$$\text{shear stress} = \text{normal stress} \cdot \mu \qquad \textbf{(3.5)}$$

where μ = friction coefficient = tan δ where δ = EPS-on-EPS friction angle.

There was also a consensus that μ was independent of EPS density and normal stress, although the normal stress is assumed in all cases to have been of such a magnitude that excessive deformation of the EPS did not occur. All reported values fall within the range between $\mu = 0.5$ to 0.7, with $\mu = 0.64$ the value reported in the most extensive and detailed published study to date which was performed in Japan. The corresponding values of $\delta = 27°$ to 35° with $\delta = 32°$ found for the Japanese study. For routine design, $\delta = 30°$ appears to be an acceptable value to use.

A corollary of EPS-on-EPS shearing is the shearing resistance between an EPS block and dissimilar material. The only published tests to date were for sand. The results indicated that $\delta = \phi$ where ϕ = the Mohr-Coulomb angle of internal friction of the sand. Whether this is the peak or constant-volume (critical-state) value was not identified clearly in published work to date. It appears reasonable that the choice would depend on the relative magnitude of shear strain, with a peak value (which is stress dependent) appropriate for small strains and a constant-volume value (which is usually assumed to be stress independent) for large strains.

A significant gap in the published literature exists for interface friction values between EPS block and other materials likely to be encountered in lightweight fills such as planar geosynthetics (chiefly geotextiles and geomembranes) as well as cast-in-place portland cement concrete. There exists a serious and immediate need for fundamental research into these issues.

3.6 THERMAL PROPERTIES

Although the thermal insulation function of EPS-block geofoam is not a primary concern to the subject of this report, some knowledge of the geothermal properties of EPS is necessary. The key aspects of the thermal behavior of EPS-block geofoam are:

- The coefficient of thermal conductivity of EPS block in the as-molded (dry) state varies with both EPS density and ambient temperature as shown in Figure 3.7.
- EPS block will absorb water with time once placed in the ground. The magnitude of absorbed water (which is traditionally expressed on a relative volume basis, not relative weight basis as for soil) can vary widely and is a function of many variables, with thickness of the piece of geofoam one of the more important. Therefore, it is not possible to give typical values or even a range of values for absorbed water that apply to the entire spectrum of EPS-block geofoam usage. However, in all cases the coefficient of thermal conductivity increases with increasing water content which means that the EPS loses some of its thermal efficiency.

Overall, EPS-block geofoam is a very efficient thermal insulator compared to soil. A typical rule of thumb is that EPS-block geofoam is 30 to 40 times more efficient thermally compared to soil, e.g. 1 mm or inch of EPS will have the same thermal-insulation effect as 30 to 40 mm or inches of soil.

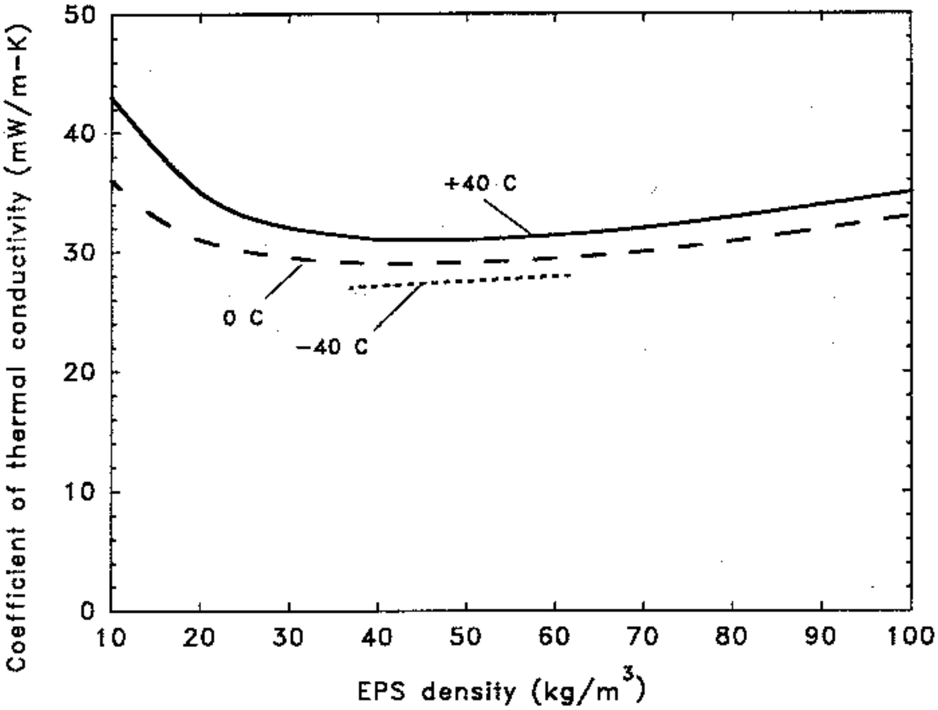

Figure 3.7. Coefficient of Thermal Conductivity, *k*, for Dry, Block-Molded EPS

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Section 4

EPS-Block Geofoam as Lightweight Fill for Roads: Commentary for Proposed Standards

To begin with, the proposed standards developed by Horvath et al. (2000) and presented in sections 5 and 6 of this report were developed completely from scratch as opposed to the approach favored by other standards organizations of simply modifying an existing standard that is irrelevant in many ways to the generic, commodity use of block-molded EPS in lightweight fill applications. Although more work, the approach taken by Horvath et al. was chosen intentionally so that every word in the standards would have to be put there deliberately with a clearly thought out purpose and justification beforehand. Before standard writing began, the EPS-geofoam lightweight-fill standards of Japan and several European countries as well as specifications from several recent projects in the U.S.A. were obtained and reviewed. A special questionnaire was prepared and sent to every state highway department in the U.S.A. plus others (including the U.S. EPS industry) to solicit the widest possible variety of inputs and opinions. This questionnaire was unanticipated extra work. However, this was done because it was felt that soliciting input from those actually involved or potentially involved in EPS-geofoam projects was vitally important to the overall success of NCHRP Project 24-11. Too many times academic research is carried on in a vacuum with little contact with reality. Finally, extensive meetings and discussions with the EPS industry provided significant technical input.

The following key items emerged from this effort and form the basis for the draft interim AASHTO standards that were subsequently produced:

- It is necessary to understand that the word "geofoam" is not synonymous with EPS as some have and, unfortunately, continue to suggest. It is now understood that this word has a surprisingly long and involved application history, including legal trademarking, that dates back at least to the 1970s. Geofoam has been and still is used to refer to many materials and products other than EPS, even a product line of bedding sold in India. So it is important that standards and contract documents clearly state the type of geofoam being discussed.

- Block-molded EPS is a generic, commodity material that has been manufactured worldwide for over 50 years and has numerous applications other than as geofoam. This includes everything from the ubiquitous white foam "coffee cup" to cushion packaging. It is possible to mold EPS with a surprisingly large range in final product quality depending on the end-use needs. This is significantly different than for other geosynthetic materials and products which were developed solely with geotechnical/geosynthetic applications in mind. The generic, commodity nature of EPS means that standards and specifications for geofoam applications have to very focused and crystal clear as to their requirements. This is especially important as geofoam applications are relatively "high tech" and demanding as far as EPS is concerned.

- From the perspective of an engineer designing with block-molded EPS geofoam as a lightweight fill for a road, the key material issues are how much stress can be applied before irreparable crushing of the EPS cell structure occurs and material creep becomes a problem in the long term. This stress level, which is an inherent material property of EPS, was defined by Horvath (1995) as the elastic-limit stress of EPS. In addition, the stiffness or modulus of the EPS at stress levels below the elastic-limit stress is also important. It is of great interest to note that both the elastic-limit stress and modulus are negatively and potentially significantly affected by regrind content (more about regrind later).

- Knowing or specifying material density alone is insufficient for design in the same way that knowing soil density alone is not sufficient for performing a geotechnical analysis or design.

- Compressive strength is irrelevant for design as it is defined at a stress level 10 times greater than that used for small-strain applications such as lightweight fills. However, it is somewhat useful as an MQC and MQA parameter. Rather interestingly, compressive strength is relatively unaffected by regrind content which is but one of several reasons why specifying compressive strength alone can be highly misleading and potentially dangerous in practice.

- A new nomenclature system was developed for identifying the different generic types of what is now referred to as "geofoam-grade" EPS for use in small-strain applications such as lightweight fills for roads. This was to clearly identify that a consistent, high-quality product is required for the severe load-bearing conditions under roads. The Roman-numeral material-type nomenclature of ASTM Standard C 578 (which has been used as a stand-in EPS-geofoam standard for some time now) was abandoned intentionally as it is non-intuitive, does not even clearly distinguish between EPS and XPS which are both covered by this standard and carries too much "baggage" in the form of bad habits (more on that later also). The nomenclature ultimately selected includes two or three numbers that indicate the minimum guaranteed elastic-limit stress of the material in kilopascals. Multiplying that number by 100 gives the design modulus of the material in kilonewtons per square metre. How much simpler and more intuitive can it get? Literally all the information one needs to design is in the nomenclature. As information, it turns out that the new European standard for EPS geofoam is using a similar if not identical nomenclature.

- Specifying a maximum allowable regrind content, something that seems to be in vogue these days with some, was judged to be inappropriate so was not included in the draft interim AASHTO material standard. The simple reason is ... why include it? There are at least three reasons not to:

  - It is unnecessary meddling in manufacturing. For example, when structural steel is specified the mill is not told how much scrap it can or cannot use to make steel. Rather, only the final material requirements are stated. The same philosophy was adopted for EPS geofoam. Only the minimum necessary material properties are stated. How a molder actually achieves this is up to them.

  - Specifying maximum regrind content can create a false illusion and sense of security that "quality" EPS will result. The reality is that it is completely possible to manufacture substandard (from a geofoam-application perspective) EPS even if no regrind were used. This is because there are many other manufacturing variables in addition to regrind that affect the quality of EPS so to explicitly specify one and not all the others is illogical.

  - Perhaps most damning is the fact that there is no known post-molding MQA test protocol for measuring regrind content on a either a volume or mass basis. So it makes no sense to specify a material parameter that cannot be independently measured or otherwise verified after manufacture. Furthermore, it is judged unacceptable to "take the molder's word for it" when it comes to regrind content as some have done in the recent past and continue to do. Such an attitude and philosophy is counter to good practice when it comes to civil engineering materials.

- The "2-by-4" syndrome (e.g. saying that 1.35 lb/ft^3 (22 kg/m^3) EPS is equivalent to 1.5 lb/ft^3 (24 kg/m^3) EPS) that seems to have become a fixture in U.S. EPS manufacturing was abandoned. This is a bad and potentially dangerous habit in load-bearing applications such as geofoam that is definitely not in the best interests of either the EPS industry or designer who are collectively custodians of the public trust and safety when it comes to road construction. A careful review of how and why this syndrome came to be suggested that the spirit of ASTM Standard C 578 was being abused even if the "letter of the law" was not. Keep in mind that C 578 is a building thermal-insulation standard and the thermal-insulative properties of EPS are relatively insensitive to material density. However, the mechanical (stress-strain-time) properties of EPS are very sensitive to material density and it is the mechanical properties that govern in geofoam applications. Thus there is no acceptable reason for this 2-by-4 syndrome and civil engineers should not and will not tolerate it. If a civil engineer specifies EPS with a minimum density of 1.5 lb/ft^3 (24 kg/m^3), they do not expect and will not accept 1.35 lb/ft^3 (22 kg/m^3) as "meeting spec" because the load-bearing differences of these two densities are noticeable. On the other hand, when someone specifies EPS for building insulation using ASTM Standard C 578 such density variations are of relatively little import as the EPS usually does not have to carry much, if any, load. This is another reason why a totally new nomenclature for geofoam-grade EPS was adopted, to distance the AASHTO standards from the bad habits of ASTM Standard C 578.

- So called "third-party certification", which in this context means that an EPS molder has an independent testing agency such as Factory Mutual, RADCO or Underwriters Laboratory monitor the molder's overall MQC protocols on an ongoing basis, should be kept in perspective. While on one hand it does signify a molder's overall commitment to making quality product it should not be used as a total substitute for MQA by the owner or owner's agent. Among other things, third-party certification typically only addresses overall manufacturing standards and does not focus on EPS molded for geofoam applications. In fact, because EPS-block geofoam standards are still evolving third-party certification may not even cover testing for the critical parameters of elastic-limit stress or initial tangent Young's modulus. So in some ways, third-party certification is a somewhat hollow process when it comes to the very demanding requirements of load-bearing geofoam applications. Also, project-specific experience within the past few years in the U.S.A. indicated that several EPS molders with third-party certification delivered EPS-block geofoam that did not meet specification to road projects. So it is always necessary to "keep the honest people honest" with some MQA although the draft interim AASHTO standard does differentiate between molders with and without third-party certification.

- When developing test protocols for MQC and MQA, the de facto 2-inch (50 mm) cube was retained as the basic test specimen. This was done solely for pragmatic reasons as any commercial geotechnical or material testing laboratory in the U.S.A. can deal with test specimens of this size. In addition, there is now almost 30 years of successful use of EPS-geofoam as lightweight fill for roads that is based on test results from such test specimens. The NCHRP Project 24-11 research team fully realized based on published research that dates back to the 1980s that testing larger pieces of EPS and, ultimately, full-size blocks produces moduli at least 50% to 100% stiffer than a 2-inch cube. Again, this topic was discussed in some detail Horvath (1995) and is hardly "new knowledge" as some now claim. Also, keep in mind that there are innumerable parallels in other aspects of geotechnical engineering where soil specimens only inches (tens of millimetres) thick are used routinely to reliably generate material properties that are analytically extrapolated to soil layers tens of feet (metres) thick.

- A mandatory 72-hour block-seasoning requirement was instituted in the interest of safety of all concerned. There is sufficient information to suggest that outgassing of the residual pentane blowing agent, which is a flammable and potentially explosive gas, continues for some time after a block is released from a mold.

- Only flame-retardant EPS is allowed. Although decades of experience worldwide indicate that this is not necessary from a geotechnical perspective, given the litigious nature of U.S. society it is considered prudent.

- The SI version of metric units is primary throughout the draft interim AASHTO standards and imperial units are secondary. This is to be consistent with the legislated shift to metrication already in progress in U.S. road design and construction.

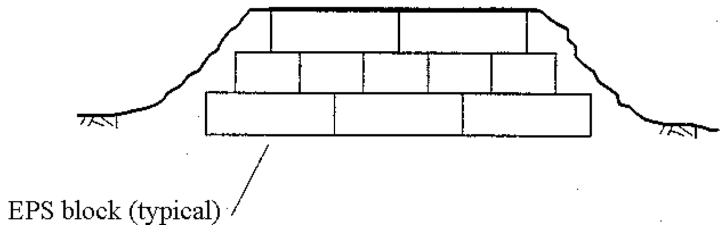
There are many more issues that could be enumerated but the above are key and hopefully help the end user to understand that every word and number in the draft interim AASHTO standards was put there with forethought and deliberation. Whether there is agreement with the words and numbers is a separate issue. The NCHRP Project 24-11 research team fully understands and expects that because these standards represent such a radical departure and improvement from the current confused situation that "fine tuning" after these standards begin to be used is inevitable and, in fact, desirable. The primary reason that TRB made copies of the Project 24-11 Phase I report (Horvath et al. 2000) available and why key sections are being presented in this report is to solicit feedback from all end users whether designer, manufacturer or construction contractor.

Section 5
EPS-Block Geofoam as Lightweight Fill for Roads: Proposed Design Standard

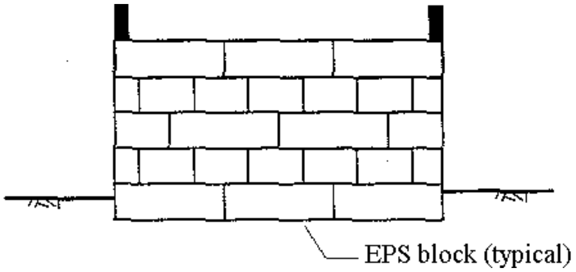
5.1 INTRODUCTION

The material in this section of the report is intended to provide design guidance to civil engineers already experienced in geotechnical engineering when designing lightweight fills that incorporate EPS-block geofoam within their cross section. The contents of this section are not intended to be a substitute for design experience and professional judgment.

The types of fills considered in this document are limited to embankments and approaches to conventional jointed-deck bridges (including fill behind the abutments of such bridges) with cross-sections as shown in Figure 5.1 where the underlying natural ground consists of relatively compressible and weak soil. For the purposes of this standard, such earthworks will be referred to simply as "embankments on soft ground".



(a) Sloped-side fill



(b) Vertical-face fill

Figure 5.1. Typical EPS-block Geofoam Applications Involving Embankments on Soft Ground

As noted previously, these design guidelines were prepared as part of Phase I of NCHRP Project 24-11 and are subject to revision during Phase II of this project. A final (Phase II) report will be submitted to the TRB some time in 2002. It is expected that an edited version of the Phase II report will eventually be published by the TRB in their NCHRP report series. However, this is unlikely before late 2002 or early 2003 at the earliest.

In addition, these guidelines are intended to be used in conjunction with the provisional material/product and construction standard in AASHTO format that was also developed as part of Phase I of NCHRP Project HR 24-11. This standard is presented in Section 6 of this report.

5.2 BACKGROUND INVESTIGATIONS

5.2.1 Introduction

Prior to beginning design of a proposed embankment on soft ground, certain background investigations need to be conducted and the relevant results communicated to the embankment designer. This section summarizes the background studies required for typical projects. Special projects may require modification of these studies and/or additional studies. In addition, various design jurisdictions (e.g. state departments of transportation) may find it useful to reallocate responsibilities from those given here to better match jurisdictional practice or historical precedent.

5.2.2 Transportation Engineering

5.2.2.1 Planning

Included in this category are basic definitions of the project requirements with an emphasis on those that may be restrictive due to particular policy applied to a specific project. Items include:

- whether the project involves the rehabilitation or widening of an existing road or an entirely new or relocated road,
- general vertical and horizontal road geometry,
- unusual or non-standard vehicle loading,
- design life of the embankment if not permanent,
- restrictions on the posted speed limit and
- restrictions on the number of traffic lanes.

Also included here are known restraints and considerations for the general area where construction will occur. Examples of the latter include:

- any restrictions on maximum duration of construction time, season of construction, days of construction (e.g. no weekends or holidays), times of day for construction and access roads prohibited for construction traffic;
- any restrictions on physical limits on the right of way to be occupied by the permanent structure as well as land available for temporary construction purposes (areas for temporary storage, etc.);
- identification of known surface and subsurface structures (buildings, utility lines, etc.), especially those that might be particularly sensitive to settlement (e.g. natural gas

transmission lines) and thus impact design; and

- identification of overhead obstructions that could impact design or construction, both "hard" (e.g. electrical transmission wires) and "soft" (e.g. glide paths to airports).

5.2.2.2 Traffic

This includes a detailed assessment of:

- vertical, horizontal and cross-sectional geometry of the road surface;
- posted speed limit;
- maximum vehicle loading;
- estimated annual traffic mix and volume expressed as some equivalent annual axle loading; and
- ancillary road-hardware (shoulder guardrails or barriers, median barriers, overhead lighting, signage) requirements.

5.2.2.3 Site Civil

This includes assessment of:

- existing topography;
- minimum desired pavement life based on policy of the owning agency;
- criterion for defining pavement failure (e.g. rutting of a certain depth) for pavement-life calculations;
- owner preferences, if any, for pavement type;
- pavement drainage requirements; and
- below-ground utility requirements for pavement drainage, electrical conduits for overhead lighting and signage, and any lines that may cross the proposed right-of-way.

5.2.3 Hydraulic Engineering

Considered here are adjacent or nearby surface-water bodies, particularly rivers and tidal water bodies, that may be subject to significant increases in elevation of their water surface at some time during the design life of the structure due to extreme events such as floods or storms. The hydraulic specialist should estimate the design water elevation for extreme events based on a probability of occurrence that is consistent with the design life of the embankment.

5.2.4 Structural Engineering

If the project involves use of the EPS-block geofoam as backfill behind the abutment of a bridge, the structural engineering specialist designing the bridge should be contacted about overall details such as:

- the type of bridge superstructure,
- nature of the approach slab (if any),
- any special geotechnical requirements regarding settlement of the bridge or approach slab and
- the velocity of extreme wind events for which the bridge is being designed.

Even if the proposed embankment does not involve a bridge, the structural specialist should still be consulted for input concerning design wind velocity for the project area.

5.2.5 Geotechnical Engineering

5.2.5.1 Site Characterization

5.2.5.1.1 Geotechnical

The geotechnical site characterization program should focus on three areas:

- defining the nature and geometry of the relevant soil and rock strata;
- defining variations with depth of stress history, compressibility and shear strength of the soft-soil strata in the proposed area of construction;
- determining the piezometric profile through all relevant soil strata, including potential seasonal and other variations in the ground water table; and
- assessing relevant seismic design issues based on owning-agency policy and/or the methodologies given by Kavazanjian et al. (1997).

5.2.5.1.2 Geoenvironmental

The geoenvironmental site characterization program should focus on identifying any potential sources of ground and ground water contamination within the area of proposed construction. If any excavation into or placement of EPS blocks below ground water (including an allowance for future rises in ground water) is anticipated, particular attention must be placed on the nature and concentration of contaminants in the ground water that may affect disposal during construction dewatering or durability of the EPS.

5.2.5.2 Design Criteria and Considerations

5.2.5.2.1 Proposed Fill

Relevant geotechnical design criteria for the proposed embankment must be established with regard to:

- maximum allowable total settlement of the completed structure and
- minimum Allowable Stress Design (ASD) safety factor for slope stability of the completed structure.

5.2.5.2.2 Adjacent Structures, Utilities and Facilities

An assessment should be made of any adjacent structures, utilities and transportation facilities (roads, railroads), both existing or proposed, that may be affected by the loads imposed on the ground by the proposed embankment.

5.2.5.2.3 Subgrade

An assessment should be made of any subgrade issues over which the use of EPS-block geofoam in the embankment would have little or no benefit. This includes but is not limited to issues such as:

- creep of existing soft soils,
- seismic liquefaction of any coarse-grain strata above or below the soft soils and
- long-term decomposition and concomitant vertical compression of any underlying non-soil waste materials.

Note that these issues will also tend to affect alternative designs discussed in Section 5.2.5.3. The need for pre-construction ground improvement to correct any potential problems should be identified (Kavazanjian et al. 1997, Elias et al. 1998).

5.2.5.3 Alternatives Assessment

Design alternatives to the use of EPS-block geofoam should be identified, a preliminary design for each alternative performed and a cost estimate for each alternative prepared to provide baseline information against which the geofoam alternative will be assessed. As discussed by Holtz (1989), typical alternatives include:

- an embankment consisting of traditional soil fill plus the use of ground improvement (Elias et al. 1998). The possibility that an all-soil embankment would require a different cross-sectional geometry (e.g. flatter side slopes) and thus a larger volume of material as well as additional right-of-way acquisition should be considered. Note that the direct and indirect costs of time for ground improvement strategies such as preloading and staged construction as well as the cost of necessary geotechnical instrumentation to monitor ground improvement should be included in this assessment. A discussion of the necessary instrumentation can be found in Dunnicliff (1982, 1988);
- other lightweight fill materials (Elias et al. 1998). The unique issues associated with alternative fill materials (e.g. compressibility, environmental impact, weather restrictions on construction) should also be considered; and
- a structure (bridge or viaduct) supported on deep foundations.

5.3 EMBANKMENT DESIGN

5.3.1 Design Methodology

At the present time, design of earthworks incorporating EPS-block geofoam are only designed deterministically using service loads and the traditional Allowable Stress Design (ASD) methodology with safety factors.

5.3.2 Overview of Design Process

As shown in Figure 5.2, an embankment can be visualized as consisting of three major components, each with its own unique composition and role in the overall structure:

- The existing soil subgrade which may have had some ground improvement applied prior to placement of the fill mass.

- The proposed fill mass which typically consists predominantly of EPS-block geofoam although some amount of soil fill is often used between the top of the existing soil subgrade and bottom of the EPS blocks for overall economy.

- The proposed pavement system which includes all material layers, bound and unbound, placed above the geofoam. The surface pavement layer can be either asphaltic concrete (AC) or portland-cement concrete (PCC), although AC predominates in practice for the same economic reasons it does for roads in general. Also included as part of the pavement system is any separation layer used between the top of the EPS blocks and bottom of the lowest layer of pavement material (typically an unbound soil).

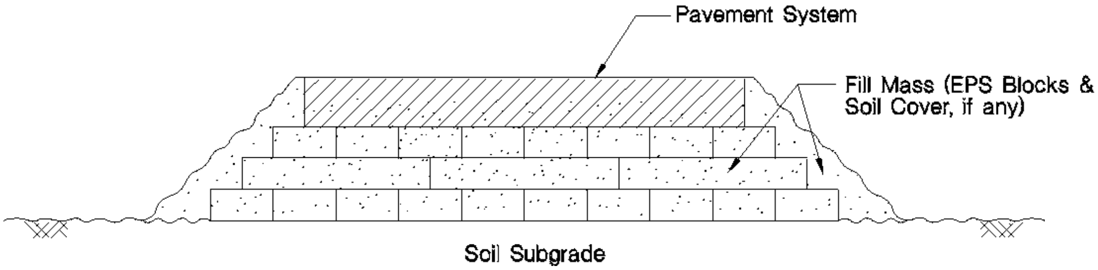


Figure 5.2. Major Components of an EPS-Block Geofoam Embankment

The embankment overall as well as its components individually must be designed to prevent failure. As used herein, the term failure includes both:

- *serviceability failure* (e.g. excessive settlement of the embankment, premature failure of the pavement system). In this report, this will be referred to as the *serviceability limit state* (SLS) and

- *collapse* or *ultimate failure* (e.g. slope instability of the edges of the embankment). In this report, this will be referred to as the *ultimate limit state* (ULS).

To design against failure, the overall design process is divided into three segments:

- Design for external (global) stability of the overall fill. This considers how the combined fill mass and overlying pavement system interact with the existing soil subgrade. This includes consideration of SLS issues such as global (overall) total and differential settlement as well as ULS issues such as bearing capacity and slope stability under various load cases. These failure considerations together with other project-specific design inputs discussed in Section 5.2 such as right-of-way constraints, limiting impact on underlying and/or adjacent structures and construction time largely govern the overall cross-sectional geometry of the fill as well as the relative amount of geofoam used within the fill. Because EPS-block geofoam is typically more expensive than soil on a cost-per-unit-volume basis for the material alone, it is desirable to optimize the design to minimize the volume of EPS used yet still satisfy design criteria concerning settlement and stability.

- Design for internal stability within the fill mass. The primary consideration here is proper selection and specification of EPS properties so that the geofoam mass can support the overlying pavement system without excessive immediate and time-dependent (creep) compression that could lead to excessive settlement of the surface (an SLS consideration).

- Design of an appropriate pavement system for the subgrade provided by the underlying geofoam. The design criterion here is to prevent premature failure of the pavement system, as defined by some rutting criterion (an SLS type failure) or cracking criterion (a ULS type failure). Also, when designing the pavement cross-section overall consideration must be given to providing sufficient support, either by direct embedment or structural anchorage, for any road hardware such as guardrails, barriers, median dividers, lighting, signage and utilities as discussed in Section 5.2.

Because each of the three components is actually part of a single structure, there is interaction between them. Therefore, a design that optimally both satisfies technical requirements and minimizes costs will generally require some iteration.

5.3.3 Design for External Stability

5.3.3.1 Embankment Geometry

5.3.3.1.1 Cross-Sectional Geometry

The first decision to be made involves the cross-sectional geometry of the overall embankment in a plane perpendicular to the proposed road alignment. The primary decision is whether the embankment will have sloped sides (Figure 5.1(a)) or vertical sides (Figure 5.1(b)). The latter type of embankment is known as a *geofoam wall*.

There are benefits and drawbacks to each type of design. In general, the geofoam wall requires less right of way and a smaller volume of fill. However, the cost of covering the vertical faces of the EPS blocks with some type of structural material (which can impart a significant concentrated vertical force on the soft subgrade) as well as the need for an PCC slab on top of the EPS blocks (for anchorage of road hardware) offset some of the savings. If a sloped-side embankment is used, the angle of the overall slope should be no steeper than 2 (horizontal) to 1 (vertical). This is governed not by the geofoam but the ability to vegetate the soil cover used over the EPS blocks.

5.3.3.1.2 Longitudinal Geometry

The longitudinal geometry of the fill along the proposed road alignment primarily involves how the transition between the geofoam and non-geofoam sections of the road are handled. Where the transition is to soil, the EPS blocks should be stepped as shown in Figure 5.3 to minimize the differential settlement. The specific pattern used should be determined on a project-specific basis based on calculated differential settlements. Using the criteria given by Briaud et al. (1997), the calculated settlement gradient within the transition zone should not exceed 1 (vertical) to 200 (horizontal).

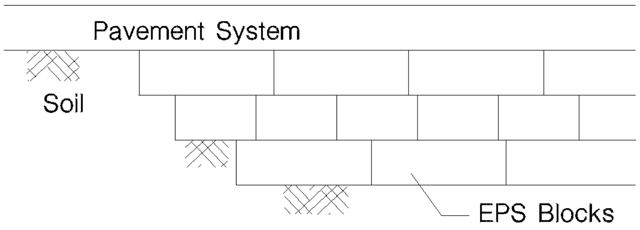


Figure 5.3. Typical EPS Block Transition to a Soil Subgrade

There are additional considerations in cases where the EPS blocks terminate against the back of a bridge abutment. For the end of the fill adjacent to the abutment, the blocks can be butted directly against the drainage geocomposite that should be placed against the back of the abutment. Note that only a geosynthetic sheet drain should be used as an aggregate chimney drain would impose a load on the underlying subgrade due to the weight of the column of aggregate. For the end of the fill farthest from the abutment, the slope of the interface between the EPS blocks and underlying soil subgrade will affect the calculated lateral earth pressures on the backs of the abutment (see Section 5.4).

5.3.3.2 Embankment Facing

5.3.3.2.1 Overview

The sides of the EPS blocks always need to be covered in the long term for durability as well as aesthetic considerations. The nature of the cover differs significantly depending on the cross-sectional geometry of the embankment.

5.3.3.2.2 Sloped-Side Embankments

Embankments with a traditional trapezoidal cross-section as shown in Figure 5.1(a) typically utilize a relatively thin veneer of soil over the stepped edges of the EPS blocks. This soil is typically vegetated with grasses as part of construction for long-term erosion protection of the soil surface. The minimum thickness of the soil cover should be in the range of 300 to 500 millimetres (12 to 18 inches). Note that the vertical stress imposed by this soil layer must be included in calculations for settlement and global stability as discussed in Section 5.3.3.3.

Typically, the soil is placed directly on the horizontal and vertical surfaces of the EPS blocks although some designers have placed a geomembrane at this interface. In arid or semi-arid regions where it may be difficult to sustain vegetative growth for erosion control, one technique that has proven effective is to place a geocell over the slope surface. The cells can be filled with either soil or portland cement concrete.

5.3.3.2.3 Geofoam Walls

A wide variety of structural materials have been used to both cover the vertical exposed faces of the EPS blocks as well as provide an architectural finish. However, there is no published standard or even preferred design detail for this. The first decision to be made is whether the surface layer will be self-supporting or physically attached to the EPS blocks. However, in neither case is the stability of the EPS blocks dependent on the cover layer. In addition, the vertical stress due to the weight of the cover layer must be included in calculations for settlement and global stability as discussed in Section 5.3.3.3.

5.3.3.3 Design Loads

5.3.3.3.1 Gravity

Gravity loads are calculated based on a preliminary assumed cross-section of the embankment, including the pavement system and any cover over the sides of the embankment. Although the pavement system has not been designed at this point, it will typically range from 600 to 1500 millimetres (2 to 5 feet) in thickness with 1000 mm (1 ft) being a typical value. The various component layers of the pavement system can be assumed to have a total (moist) unit weight of 20 kN/m^3 (125 lb/ft^3) for initial design purposes. The dry unit weight of the EPS can be taken to be 200 N/m^3 (1.25 lb/ft^3). Cases where long-term water absorption by the EPS needs to be considered are discussed in Section 5.3.3.4.

5.3.3.3.2 Traffic

For global settlement and stability calculations, the effect of vehicle loads on the road surface is negligible compared to the dead load of the pavement system and thus are generally ignored in these calculations. However, vehicle loads can be included if desired by dividing the total assumed weight of a vehicle by its footprint area to arrive at an equivalent uniform vertical stress that can be included in calculations.

5.3.3.3.3 Water

By their nature, soft-ground conditions where EPS-block geofoam is used often have ground water at or close to the ground surface. In addition, such sites are often close to surface water bodies such as rivers that are subject to periodic significant changes in water level due to storms and floods (extreme events). Therefore, both normal as well as extreme-event water levels must be considered in design. When considering extreme-event water levels, the potential for the embankment acting as a de facto flood levee and developing an unbalanced water head across the embankment cross-section should be considered. An unbalanced head could result in translation (horizontal sliding) of the embankment (see also Section 5.3.3.3.5) and/or erosion.

Materially, EPS is different than soil in that its void spaces are essentially sealed against any significant water intrusion. Therefore, if subjected to submergence in water EPS blocks will float readily. As a rule of thumb, for every 100 millimetres (4 inches) of submergence of an EPS block there must be 50 millimetres (2 inches) of soil or pavement on top of the EPS blocks to counteract buoyancy effects. Thus the use of EPS-block geofoam alone may not be feasible in areas where there can be relatively potential variations in ground water elevations during the design life of the structure. In such cases, another lightweight fill material with an open texture to better accommodate inundation is required at least for the lower portion of the embankment that may be inundated. Alternatively, it may be necessary to tie down the assemblage of EPS blocks using passive (initially unstressed) vertical ground anchors.

5.3.3.3.4 Seismic

For global seismic analyses, an embankment containing EPS-block geofoam is treated the same as a traditional soil embankment. This means that the appropriate ground motion at the base (subgrade level) of the embankment is determined using the methodology given by Kavazanjian et al. (1997). Then the appropriate seismic acceleration coefficients, k_h and k_v, are determined and applied to the gravity loads calculated per Section 5.3.3.1.

5.3.3.3.5 Wind

Due to the extremely low density of EPS, the potential for translation (horizontal sliding) of the entire embankment in a direction perpendicular to the proposed road alignment should be considered. The horizontal loads from wind are calculated using the following empirical equations:

$$p_U = 0.75v^2 \sin\theta_U \tag{5.1}$$

$$p_D = 0.75v^2 \sin\theta_D \tag{5.2}$$

with v = the wind speed in metres per second, p_U and p_D have units of kilopascals and the other variables defined in Figure 5.4.

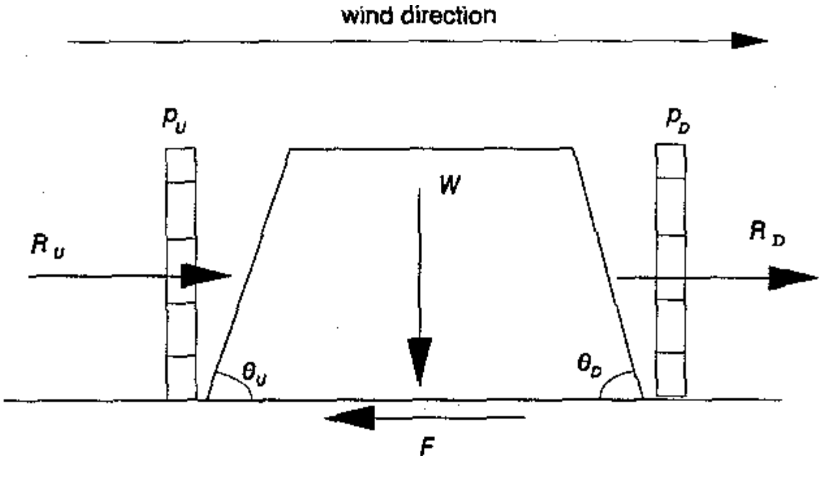


Figure 5.4. Definition of Parameters for Wind Analysis (Horvath 1995)

5.3.3.4 Failure Mechanisms

5.3.3.4.1 Overview

The loads discussed in Section 5.3.3.3 are used in various combinations to evaluate several SLS and ULS failure mechanisms.

5.3.3.4.2 Serviceability

The primary type of SLS failure is excessive total and/or differential settlement of the embankment. Typically, an assessment of this is made using a combination of gravity and traffic (if desired) loads with the expected normal ground water conditions. Any portion of the EPS blocks that is permanently submerged under these ground water conditions is assumed to have a total unit weight of 1000 N/m^3 (6 lb/ft^3), not the dry value of 200 N/m^3 (1.25 lb/ft^3) suggested in Section 5.3.3.3.1 for general gravity stress calculations, to conservatively allow for long-term water absorption. The resulting net vertical effective stresses are applied to the subgrade surface as a perfectly flexible loaded area and settlements are calculated in the usual manner. Note that any net excavation of the existing subgrade prior to constructing the embankment should be considered.

5.3.3.4.3 Collapse

There are several ULS type failure mechanisms to consider. They fall into three broad categories:

- downward vertical movement of the entire embankment into the subgrade due a deep-seated rotational type slope stability failure along an edge of the embankment, a bearing capacity failure of the entire embankment or lateral squeeze of the underlying soft soil;

- upward vertical movement of the entire embankment due to a rise in ground water table, especially during an extreme event; and

- translation (horizontal sliding) of the entire embankment due to an extreme event involving either wind or an unbalanced water head.

Analysis of any of the mechanisms producing downward vertical movement are typically based on the conservative assumption that the materials comprising the embankment have zero shear strength. Therefore, the embankment is modeled simply as a vertical effective stress (i.e. a "perfectly flexible loaded area") applied to subgrade level. The appropriate analyses for slope stability, etc. are then performed in the usual manner with the underlying subgrade soil providing the only resistance to failure. Safety factors considered appropriate are the same as for conventional all-soil embankments.

The safety factor against uplift is the ratio of the total vertical stress from the embankment applied to subgrade level (the unit weight of submerged EPS is conservatively taken as the dry value, i.e. 200 N/m^3 (1.25 lb/ft^3)) divided by the uplift water pressure under some extreme event. Typically, low safety factors (1.0 to 1.1) are considered acceptable for this load case given the low probability of occurrence of the event.

The safety factor against translation is the ratio of shearing resistance along the interface between the bottom of the EPS blocks and the soil subgrade to the total horizontal driving force. This would be either the sum of p_U and p_D for wind (Figure 5.4) or the net unbalanced water pressure.

5.3.4 Design for Internal Stability

5.3.4.1 Overview

Design for internal stability involves three broad areas of consideration:

- The individual EPS blocks must be sufficiently interlocked both vertically and horizontally so that they collectively respond as a single, coherent mass when subjected to the external loads discussed in Section 5.3.3.3. This involves consideration of both the overall block layout (which primarily controls interlocking in a vertical direction) and inter-block shear (which primarily controls interlocking in the horizontal direction).

- The pavement system must not slide horizontally on the upper surface of the EPS mass if the embankment is subjected to seismic shaking (a ULS type failure).

- The compressive stresses within the EPS mass must be below the elastic-limit stresses given in Table 5.1 under all applied loads so that excessive creep and/or plastic (non-recoverable) strains do not develop during the design life of the embankment (an SLS type failure).

Designing for these various issues is discussed in detail in the following sections.

Table 5.1. Design Values of EPS-Block Geofoam Compressibility Parameters for Internal Stability Calculations

AASHTO material type designation (proposed)	Design values of engineering parameters	
	Elastic-limit stress, kPa (lb/ft^2)	Initial tangent Young's modulus, MN/m^2 (k/ft^2)
EPS40	40 (800)	4 (80)
EPS50	50 (1000)	5 (100)
EPS70	70 (1400)	7 (140)
EPS100	100 (2000)	10 (200)

5.3.4.2 Block Layout

Experience indicates that use of an appropriate layout of EPS blocks will essentially guarantee interlocking in the vertical direction. Overall guidelines are:

- All blocks should butt tightly against adjacent blocks on all sides.

- Blocks should be placed with their smallest (thickness) dimension oriented vertically.

- A minimum of two layers of blocks must always be used for lightweight fills beneath roads.

- Overall, the blocks must be placed in a pattern such that continuity of the vertical joints between blocks is minimized. This is typically accomplished by:

- aligning all the blocks within a given layer with their longitudinal axes parallel but offsetting the ends of adjacent lines of blocks,
- orienting the longitudinal axes of all blocks in a given layer perpendicular to the longitudinal axes of the blocks within layers placed above and/or below, and
- aligning the blocks within the uppermost layer transverse to the longitudinal axis of the road.

Figure 5.5 shows a generic block layout that reflects each of these items.

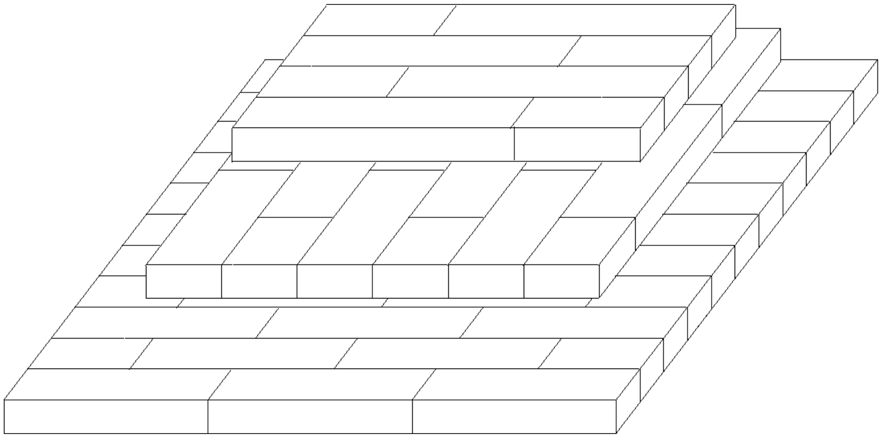


Figure 5.5. Isometric View of Typical EPS Block Layout for a Road Embankment

With regard to who actually designs the block layout, traditionally this was done by the design engineer for the project. However, this is appropriate only of the designer knows the exact block dimensions beforehand. In current U.S. practice, there will generally be more than one EPS block molder who could potentially supply a given project. In most cases, block sizes will vary somewhat between molders due to different make, model and age of molds. Therefore, the trend in U.S. practice is to leave the exact block layout design to the molder. The design engineer simply:

- shows the desired limits of the EPS mass on the contract drawings, specifying zones of different EPS densities as desired;
- includes the above conceptual guidelines in the contract specifications for use by the molder in developing shop drawings; and
- reviews the submitted shop drawings during construction.

5.3.4.3 Inter-Block Shear

Shear along the horizontal interfaces between layers of EPS blocks is the basic and primary mechanism for interlocking the blocks to resist horizontal loads. Although the Mohr-Coulomb friction angle, δ, for EPS-on-EPS sliding is comparable to that of sand ($\delta \cong 30°$), the shear resistance (= vertical normal effective stress · tan δ) is generally relatively small in magnitude because the vertical stresses are relatively small (for all practical purposes just the dead load from the pavement system). Experience indicates that this resistance is insufficient to resist significant driving forces that result from horizontal loads such as from an extreme-event wind (Figure 5.4) or seismic shaking. Both resisting and driving forces should be calculated at several levels through the vertical profile of the embankment. Forces from wind can be calculated as discussed in Section 5.3.3.3.5. Forces from seismic shaking can be calculated as discussed in Section 5.3.4.4.

If the calculated resistance forces are insufficient to resist the driving forces, additional resistance is required. This is generally accomplished by adding barbed metal plates along the horizontal interfaces between EPS blocks. Such plates provide an apparent Mohr-Coulomb adhesion, c_a, at the interface that supplements the inherent inter-block friction. At the present time, all such plates available in the U.S.A. are of proprietary designs. Therefore, the resistance provided by such plates must be obtained from the supplier or via independent testing. Due to the relative costs of these plates, they should only be used where calculations indicate their need.

5.3.4.4 Seismic Response

The internal seismic response is more complex than the overall external response discussed in Section 5.3.3.3.4. This is because the horizontal seismic acceleration at the crest of the embankment will generally be greater than that at the base as was determined in Section 5.3.3.3.4. Therefore, the crest acceleration must be calculated. In routine practice, this is done using a classical single-degree-of-freedom (SDOF) model. First, the fundamental period of the embankment, T_o, is determined using the following equation:

$$T_o = 2\pi \left\{ \frac{\overline{\sigma}_{v_p}\left(1 \pm k_v\right)H'}{E_{t_i}\, g} \left[4\left(\frac{H'}{B}\right)^2 + \frac{12}{5}\left(1+\nu\right) \right] \right\}^{0.5} \qquad \textbf{(5.3)}$$

where:

B = width of crest of embankment (see Figure 5.6),
E_{t_i} = initial tangent Young's modulus of the EPS (a value of 5 MN/m^2 (100 k/ft^2) can be used for preliminary assessments),
g = gravitational constant,
H' = effective height of the embankment (as defined in Figure 5.6),
k_v = vertical seismic acceleration coefficient at the base of the embankment (see Section 5.3.3.3.4),
T_o = fundamental period of the embankment,
ν = Poisson's ratio of the EPS (a value of 0.1 can be used for preliminary assessments) and
$\overline{\sigma}_{v_p}$ = effective vertical normal stress on the top of the EPS mass due to the weight of the overlying pavement system.

Note that Equation 5.3 will yield three values for T_o for $+k_v$, $-k_v$ and $k_v = 0$. These three values should be used with a site-specific response spectrum (Kavazanjian 1997) to determine the maximum theoretical horizontal acceleration at the crest.

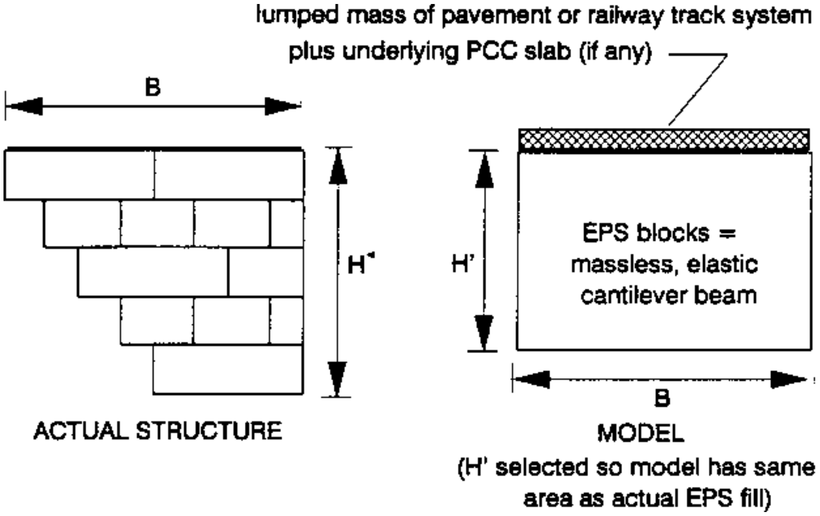


Figure 5.6. Approximate (Simplified) Seismic Modeling of an EPS Fill

For analysis purposes, the horizontal acceleration within the embankment can be assumed to vary linearly between the base and crest values. At any level within the embankment, the interpolated value of horizontal acceleration can be multiplied by the mass of material (pavement system, EPS, etc.) above that level to give the horizontal driving force due to seismic loading. This can then be compared to the horizontal shear resistance as discussed in Section 5.3.4.3.

5.3.4.5 Load Bearing

The primary issue with regard to internal stability is load bearing of the EPS blocks in vertical compression. The basic procedure is to calculate the vertical normal stresses at various levels and horizontal positions within the EPS mass (typically the interface between the top of the EPS/bottom of the pavement system is the most critical) and select a density of EPS to use such that the maximum vertical stresses are less than the elastic limit stress given in Table 5.1.

Traffic (vehicle) loads will typically be a major consideration for internal stability calculations for road embankments. The magnitude and tire footprint of the design vehicle can be based on either the design policy of the owning agency or information in textbooks such as Huang (1993). The variation of vertical stresses below the pavement surface can be adequately approximated using the traditional 2 (vertical) : 1 (horizontal) distribution. This distribution is used both within the pavement system as well as the assemblage of EPS blocks.

Because the total calculated vertical stresses will decrease with depth within the EPS mass as well as be less under side slopes as opposed to beneath the paved area, it is possible to use multiple densities of EPS blocks, e.g. lower density blocks at greater depths and/or under side slopes. This will reduce overall costs of the EPS-block geofoam. However, for constructability it is recommended that no more than two different density EPS blocks be used on the same project. Note also that the use of *EPS40* for the main portion of the embankment beneath paved areas is not recommended under any circumstances.

5.3.5 Pavement System Design

5.3.5.1 Overview

Design of the pavement system is conceptually straightforward as the EPS mass is simply treated as an equivalent soil subgrade for pavement design purposes. Thus the basic design approach is to simply calculate the thinnest pavement system that will provide the desired pavement design life for the anticipated traffic. However, there are several other design issues that are either unique to the use of EPS-block geofoam or its properties as a subgrade material. These additional design issues also need to be considered and, in some cases, will result in a pavement system thicker than the basic pavement design.

5.3.5.2 Basic Pavement Design

For pavement design purposes, the EPS mass can be treated as an equivalent soil subgrade with stiffness properties comparable to a medium-stiff clay. Table 5.2 gives the recommended design values of the equivalent soil subgrade parameters to use based on the density of EPS immediately below the pavement system. In particular, the design engineer should investigate the cost effectiveness of using *EPS100* for the uppermost layer of blocks within the horizontal limits of the paved area. Not only will this provide a somewhat stiffer subgrade immediately beneath the pavement system where it has the maximum theoretical benefit but it will provide a stiffer working surface during construction. This would offer additional protection during the critical, potentially damaging construction phase.

Table 5.2. Equivalent Soil Subgrade Values of EPS-Block Geofoam for Pavement Design

AASHTO material type designation (proposed)	Design values of engineering parameters		
	CBR (%)	Young's modulus, MN/m^2 (k/ft^2)	Resilient modulus, MN/m^2 (k/ft^2)
EPS50	2	5 (100)	5 (100)
EPS70	3	7 (140)	7 (140)
EPS100	4	10 (200)	10 (200)

Note: The use of *EPS40* directly beneath paved areas is not recommended and thus this material type does not appear in this table.

5.3.5.3 Additional Design Issues

5.3.5.3.1 Separation/Stiffening Layer

In many cases, it is desirable to place a layer of some material between the top of the EPS blocks and the bottom of the pavement system. This layer can serve either or both of two distinct purposes:

- Lateral confinement of the unbound pavement layer(s) which results in stiffer behavior of these layers and overall improved performance of the pavement system.

- Separation of the EPS and pavement to prevent:

- finer soil particles from the unbound layer(s) of the pavement system from infiltrating any gaps that may occur at vertical joints between EPS blocks due to infiltrated water (rain or melted snow/ice runoff) and

- liquids, particularly vehicle fuel spilled on the pavement surface, from attacking the EPS.

The need for stiffening the unbound pavement layer(s) should be investigated on a project-specific basis to evaluate whether stiffening or a thicker unbound layer(s) is more cost effective. If stiffening is considered, various materials can be used for this purpose as would be the case for a pavement underlain by a soil subgrade. A geogrid or soil-filled geocell will likely be the more cost effective materials to use. The geocell would be placed directly on top of the EPS blocks whereas the optimum location of the geogrid within the unbound layer would have to be determined as part of design. The geocell alternative offers the additional advantage of providing a relatively stiff working surface once the cells are filled with soil. This would offer additional protection for the EPS blocks during the critical, potentially damaging construction phase.

In general, separation is only required if the unbound pavement layer(s) contain a relatively large proportion of smaller particles (fine sand and smaller). In this case, an appropriate geotextile would be the separation material of choice although the friction angle, δ, between the geotextile and EPS would have to be investigated. Where seismic or other horizontal loads are significant, the potential for horizontal sliding along the planar geotextile-EPS interface may be critical.

Protection of the EPS from vehicle fuel spills is not judged to be a potentially significant problem in most applications. At the design engineer's discretion, a geomembrane of appropriate composition can be used. However, the friction angle, δ, between the geomembrane and EPS would have to be investigated. Where seismic or other horizontal loads are significant, the potential for horizontal sliding along the planar geomembrane-EPS interface may be critical. An estimate of the seismic-induced permanent deformation can be obtained using a Newmark sliding-block analysis (Newmark 1965). This analysis requires a friction angle for the geomembrane/geofoam interface. The calculated deformation should not exceed about 50 mm (2 in) to ensure the integrity of the geomembrane. If the permanent deformations exceed 50 mm (2 in), another geomembrane should be selected to increase the geomembrane/geofoam interface strength and reduce the permanent deformations.

Although a lightly reinforced (wire mesh) portland-cement concrete slab 100 to 150 millimetres (4 to 6 inches) thick can be used to provide both stiffening and separation, this is a relatively expensive alternative that should only be considered when anchorage of road hardware (see Section 5.3.5.3.3) is required.

5.3.5.3.2 Differential Icing

Differential icing is the term used to describe the overnight formation of hoarfrost (ice) on a pavement surface underlain by certain non-soil materials when adjacent sections of pavement underlain by soil do not develop hoarfrost. Differential icing can occur even when overnight air temperatures do not drop below freezing and thus can potentially occur within most of the U.S.A. Note that the potential for differential icing is not limited to pavements underlain by EPS-block geofoam.

Two elements are required to reduce or eliminate the potential for differential icing:

- The unbound layer(s) of the pavement system must have at least some fine-grain soil particles to retain water (a necessity for its relatively significant heat capacity). However, there are no published criteria for gradations considered acceptable.

- The overall pavement system must have a certain minimum thickness. Recommended minima range from 400 to 800 millimetres (16 to 32 inches), with thickness increasing with anticipated traffic volume. A minimum of thickness of 600 mm (24 inches) is suggested for U.S. practice.

5.3.5.3.3 Surface and Subsurface Infrastructure

The thickness of the pavement system should consider both surface and subsurface infrastructure (road hardware) such as:

- catch basins and drainage pipes for the pavement. Wherever possible, drainage pipes in particular should be located within the pavement system. Embedment within the EPS blocks, while possible, is generally considered undesirable; and

- the embedment of signage, lighting, medians and barriers. Unless the required embedment can be accommodated entirely within the pavement system, it may be necessary to construct a lightly reinforced slab over the EPS in which to anchor these structures.

5.3.6 Design of Subgrade and Embankment Instrumentation

As a general rule, it is not necessary to place geotechnical instrumentation for the purpose of monitoring the performance of an EPS-block geofoam fill during and/or after construction. The use of EPS-block geofoam in road construction is not a novel or experimental technology. However, instrumentation can be used at the discretion of the design engineer if there is some clearly defined local need. If instrumentation is planned, it is important to note several well-established rules:

- The parameter(s) to be measured (settlement, lateral movement, etc.) must be clearly identified in advance and relevant to the specific project.

- No instrument should be used nor parameter measured unless there has been a prior estimate of the expected magnitude or range in magnitude of the parameter, including as a function of time, temperature or other environmental condition where appropriate.

- The instrument used must have an accuracy and precision appropriate to the expected magnitude of the parameter to be measured.

- There must be a sufficient budget not only for acquiring and placing the instrumentation but for the acquisition of data and its timely engineering interpretation as well. This is particularly important if it is desired to obtain data for some time after the project is completed and placed in service.

If instrumentation is considered for a project, two references that are particularly comprehensive on the subject and applicable to transportation structures are Dunnicliff (1882, 1988).

5.4 ABUTMENT DESIGN

5.4.1 Introduction

In applications where the EPS-block geofoam is used as part of an approach fill to a bridge, the

EPS blocks should be continued up to the drainage layer that is placed along the back of the abutment (a geosynthetic sheet drain, not natural aggregate, should be used for this drainage layer to minimize loads as well as facilitate construction). In addition to significantly reducing the vertical stresses on the subgrade adjacent to the back of the abutment, the lateral earth pressures against the back of the abutment will also be significantly reduced.

To calculate these earth pressures for design, the basic assumption is that the pressures come from two sources:

- the dead load of the pavement system and EPS blocks (the latter negligibly small in magnitude) pressing directly on the back of the abutment and

- the active earth pressure from the soil at the end of the geofoam fill away from the abutment, transferred through the geofoam fill to the back of the abutment.

These are shown conceptually in Figure 5.7. The magnitudes of these loads vary depending on whether gravity or seismic loading is assumed.

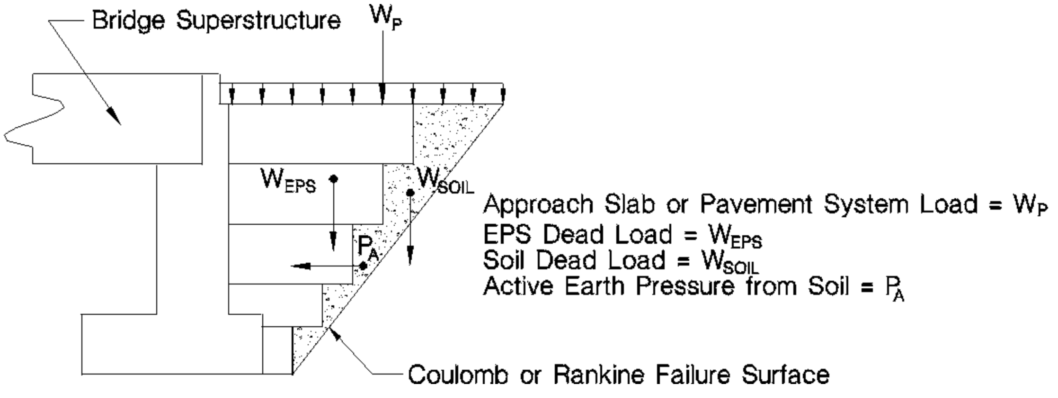


Figure 5.7. Loads on an EPS-Block Geofoam Fill Bridge Approach System

5.4.2 Gravity Loads

For the basic gravity load case, the assumed load components are (refer to Figure 5.8):

- the vertical effective overburden stress of the pavement system creates a horizontal at-rest stress directly on the back of the abutment,

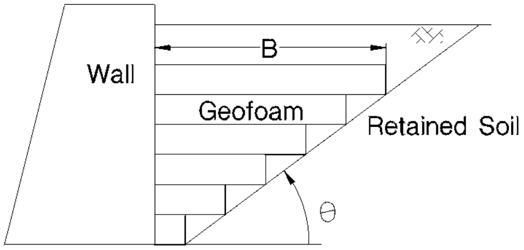
- the vertical effective overburden stress from the pavement system acting on the top of the geofoam creates a uniformly distributed horizontal component throughout the entire thickness of the geofoam,

- the horizontal stress from the EPS blocks is neglected as being negligible in magnitude and

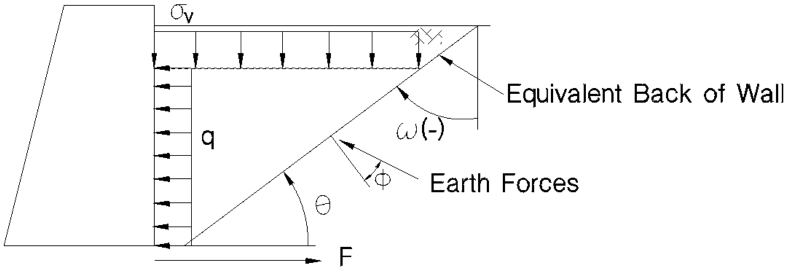
- the inclined interface between the EPS blocks and soil subgrade is treated as the equivalent planar back of a gravity retaining wall with a soil-"wall" friction angle, δ, equal to the Mohr-Coulomb friction angle, ϕ, of the soil. The active earth pressure acting along this interface is calculated using Coulomb's solution for the coefficient of active earth pressure, K_A:

$$K_A = \left[\frac{\sin(\theta - \phi)\cdot\left(\frac{1}{\sin\theta}\right)}{\sqrt{\sin(\theta+\delta)} + \sqrt{\frac{\sin(\phi+\delta)\cdot\sin(\phi - i)}{\sin(\theta - i)}}} \right]^2 \qquad \textbf{(5.4)}$$

The horizontal component of the active pressure is conservatively assumed to be transmitted through the geofoam to the back of the abutment.



(a) Actual Problem



(b) Analytical Model

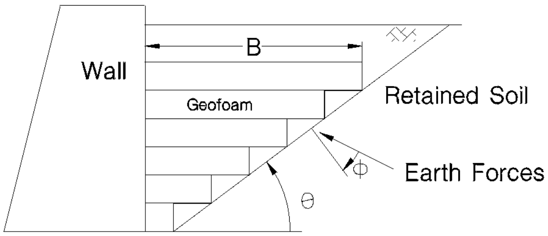
Figure 5.8. Gravity Load Components on a Wall

5.4.3 Seismic Loads

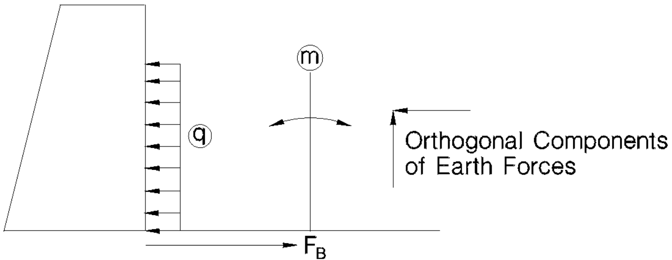
Under seismic loading, the following additional loads must be considered in addition to the gravity loads discussed in Section 5.4.2 (see Figure 5.9):

- inertia forces acting on the back of the abutment from the pavement system and EPS blocks (the latter generally small in magnitude and negligible). These are estimated using the procedure described in Section 5.3.4.4. These inertial forces are assumed to be reduced by horizontal sliding resistance developed along the geofoam-subgrade interface; and

- a seismic component of active earth pressure acting along the assumed planar interface between the EPS blocks and soil subgrade. The classical solution by Mononobe-Okabe is used for this purpose.



(a) Actual Problem



(b) Analytical Model

Figure 5.9. Seismic Load Components on a Wall

5.5 CONSTRUCTION

5.5.1 Overview

To ensure satisfactory performance of an embankment incorporating EPS-block geofoam, the design engineer should be aware of various important construction details and issues. As with all other types of geosynthetics, experience indicates that the majority of problems and failures of the EPS-block geofoam component of geotechnical structures have involved construction issues.

5.5.2 Pre-Construction Meeting

Once the project construction begins, a meeting should be held at the project site prior to the delivery and installation of the EPS blocks. This meeting should, as a minimum, involve the construction contractor and owner's agent who will perform the quality assurance for both the EPS manufacturing (MQA) as well as construction (CQA). Ideally, the design engineer, EPS molder and EPS supplier (if different from the molder) should also be present. The purpose of this meeting would be to review all details relative to the manufacturing and placement of the EPS-block geofoam. This is important as the use of EPS-block geofoam in road embankments is still a relatively new technology in many parts of the U.S.A. Consequently, it is important that all involved in a project be aware of the key issues for a successful application of this technology.

5.5.3 Site Preparation

Proper site preparation of the subgrade on which the first layer of EPS blocks is placed is crucial to the proper placement of all subsequent layers as well as the post-construction performance of the overall embankment. The subgrade must be relatively dry, planar and free of relatively large soil or rock particles that can damage the EPS blocks. Specific criteria are given in the accompanying material/product and construction standard (see Section 6 of this report).

Frequently, a sand bed of the order of several tens of millimetres (a few inches) thick must be placed on the existing subgrade to provide a bedding material of the proper gradation that can be smoothed relatively easily. In many cases, it is necessary to place an appropriate geotextile between the existing soils and the sand bedding material to provide separation between the two materials.

5.5.4 EPS Block Handling and Storage

Experience indicates that damage during shipping, on-site handling and temporary on-site storage of EPS blocks can be a problem yet is something that is easily avoidable and thus unnecessary. However, project specifications must contain appropriate language to the effect that EPS blocks with indentations and pieces broken off will be rejected by the owner's agent on site.

Another important issue is to avoid all sources of heat or open flame that could cause the EPS to melt or even burn. Although it is U.S. practice to require that only flame-retardant EPS-block geofoam be used, such material will not be fireproof and thus will still burn if subjected to a sustained source of flame. Another flammability issue relates to outgassing of the residual pentane blowing agent if the EPS blocks have not been appropriately seasoned prior to delivery to the project site.

5.5.5 EPS Block Placement

Care is required during placement of all EPS blocks to ensure that the blocks are butted tightly to all adjacent blocks. Every reasonable effort should be made to prevent gaps from occurring along the vertical joints between blocks.

5.5.6 Pavement System

In general, the pavement system can be constructed in the normal manner with only a few cautions related to the presence of the EPS blocks. First, care must be exercised when placing the initial lift of the unbound pavement layer(s) to prevent damage to the surface of the EPS blocks as well as any separation layer that may be placed on the EPS blocks. Generally this means that no vehicles or construction equipment should be allowed to traffic directly on the EPS blocks or separation layer (if any). Typically placement of the first lift of unbound material is accomplished by pushing the material ahead using a relatively small bulldozer or front-end loader.

When verifying compaction of the unbound pavement material, note that nuclear moisture-density gauges that are often used for this purpose have been found to sometimes yield incorrect results. This is because in some gauges, the water content of the soil is inferred from a count of radioactive scattering caused by hydrogen atoms. In normal soil, hydrogen only occurs in water. However, because EPS contains hydrogen spurious results can be produced. It is suggested that this issue be discussed with the manufacturer of the nuclear moisture-density gauges to be used on a project to see if this is a potential problem. It is often desirable to check the initial readings obtained with such gauges using a traditional mechanical procedure such as a sand-cone apparatus to obtain the total (damp) unit weight or density of the unbound material followed by oven or other traditional methods for drying of a soil specimen to determine its water content.

5.6 POST-CONSTRUCTION

5.6.1 Monitoring

As noted in Section 5.3.6, it is generally unnecessary to formally monitor the performance of a fill incorporating EPS-block geofoam after construction. However, because the use of such fills is still relatively new to most civil engineers and owning agencies in the U.S.A. it would be useful for developing local experience as well as with projects with unusual or unique aspects.

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Section 6
EPS-Block Geofoam as Lightweight Fill for Roads: Proposed Material, Product and Construction Standard

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6.1 SCOPE

6.1.1. This is a combined material, product and construction standard covering block-molded expanded polystyrene (EPS) for use as a geofoam geosynthetic product (EPS-block geofoam) in road applications involving embankments and related bridge approach fills on soft ground. This is a material purchasing standard and project-specific review of its use is required.

6.1.2. This is not a design standard but includes technical information used in design. This standard is intended to be used in conjunction with the contents of Section 5 of this report.

6.2 REFERENCED DOCUMENTS

6.2.1. AASHTO Standards: none

6.2.2. ASTM Standards:
- C 578-95 - Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation

6.2.3. NCHRP reports:
- NCHRP Project No. HR 24-11 - Guidelines for Geofoam Applications in Embankment Projects

6.3 TERMINOLOGY

For the purposes of this standard, the following terminology is used for the various parties involved:

- Contractor: The company having the direct contractual relationship with the Owner for construction of the proposed embankment and responsibility for its overall construction.

- Designer: The organization (typically a government agency or private consulting company) having responsibility for the design of those portions of the project that include the proposed embankment.

- Molder: The company actually manufacturing the EPS blocks used as the EPS-block geofoam for the proposed embankment.

- Owner: The government agency having contractual authority over the proposed embankment at the time of its construction. This may or may not be the government agency having final ownership or jurisdiction over the operation and maintenance of the proposed road. For example, a state department of transportation (DOT) may oversee construction on behalf of a local (county, town) jurisdiction. In this case, the DOT would be considered the Owner for the purposes of this standard.

- Owner's Agent: The organization (typically a government agency or private consulting company) having responsibility for inspection during construction of the proposed embankment. This may or may not be the Designer.

- Supplier: The company having the contractual relationship with the Contractor for the supply of the EPS-block geofoam. This may be the Molder directly or an intermediary company (typically a distributor of construction and/or geosynthetic products manufactured by others).

6.4 PRODUCT MANUFACTURING QUALITY CONTROL REQUIREMENTS

6.4.1. Manufacturing quality control (MQC) of the EPS-block geofoam product is the primary responsibility of the molder. The purpose of this section is to define the parameters for use by a molder in developing an MQC plan. These parameters will also be those measured as part of the manufacturing quality assurance (MQA) to be conducted by the owner's agent. MQA requirements are detailed in sections 6.5, 6.6 and 6.8 of this standard.

6.4.2. All EPS-block geofoam shall consist entirely of expanded polystyrene. At the discretion of the molder, the EPS-block geofoam may consist of some mixture of virgin raw material (expandable polystyrene a.k.a. bead or resin) and recycled EPS (regrind). However, if regrind is to be used this shall be clearly stated by the molder as part of the Phase I MQA pre-construction pre-certification process described in Section 6.6. The source of the regrind (block- versus shape-molded EPS, in-plant versus post-consumer) shall also be stated clearly.

6.4.3. All EPS-block geofoam shall be adequately seasoned prior to shipment to the project site. For the purposes of this standard, seasoning is defined as storage in an area suitable for the intended purpose as subsequently defined herein for a minimum of 72 hours after an EPS block is released from the mold. Seasoning shall be done within a building or other structure that protects the EPS blocks from moisture as well as UV radiation. The area in which EPS blocks are stored for seasoning shall also be such that adequate space is allowed between blocks and positive air circulation and venting of the structure provided so as to foster the outgassing of blowing agent and trapped condensate from within the blocks. The owner's agent shall be allowed to inspect the structure to be used for seasoning upon request and during normal business days and hours. The molder may request a shortened seasoning period if the EPS blocks are seasoned within an appropriate heated storage space and the molder demonstrates to the satisfaction of the owner's agent that the alternative seasoning treatment produces blocks that equal or exceed the quality of blocks subjected to the normal 72-hour seasoning period.

6.4.4. All EPS-block geofoam shall satisfy the product flammability requirements specified in ASTM C 578. Table 6.1 indicates the AASHTO material type designations used for the different densities of EPS blocks that are covered by this standard. Only these material type designations shall be used in any correspondence or other communication related to this project. For a given material type, the dry density of each EPS block (as measured for the overall block as a whole) after the period of seasoning as defined in Section 6.4.3 shall equal or exceed that shown in Table 6.1. The dry density shall be determined by measuring the mass of the entire block by weighing on a scale and dividing the mass by the volume of the block.

Table 6.1. Proposed AASHTO Material Type Designations for EPS-Block Geofoam

AASHTO material designation (proposed)	Minimum allowable dry density of entire EPS block, kg/m^3 (lb/ft^3)
EPS40	16 (1.0)
EPS50	20 (1.25)
EPS70	24 (1.5)
EPS100	32 (2.0)

6.4.6. Table 6.2 gives the minimum allowable values of various material parameters corresponding to each AASHTO material type shown in Table 6.1. These material parameters are to be obtained by testing specimens prepared from samples taken from actual blocks produced for the project covered by this standard for either MQC by the molder or MQA by the owner's agent as described in Section 6.8 of these standards. All test specimens shall be seasoned as specified in ASTM C 578. Dry density, compressive strength and flexural strength shall be measured as specified in ASTM C 578. The specimens used for compressive testing shall be cubic in shape with a 50 mm (2 in) face width. A strain rate of 10% per minute shall be used for the compressive strength tests. Both the elastic-limit stress and initial tangent Young's modulus shall be determined in the same test used to measure compressive strength. The elastic-limit stress is defined as the measured compressive normal stress at a compressive normal strain of 1%. The initial tangent Young's modulus is defined as the average slope of the compressive stress versus compressive strain curve between 0% and 1% strain.

Table 6.2. Minimum Allowable Values of MQC/MQA Parameters for Individual Test Specimens

AASHTO material designation (proposed)	Dry density, kg/m^3 (lb/ft^3)	Compressive strength, kPa (lb/in^2)	Flexural strength, kPa (lb/in^2)	Elastic-limit stress, kPa (lb/in^2)	Initial tangent Young's modulus, MN/m^2 (lb/in^2)
EPS40	15 (0.90)	69 (10)	173 (25)	40 (5.80)	4 (580)
EPS50	18 (1.15)	90 (13)	208 (30)	50 (7.25)	5 (725)
EPS70	22 (1.35)	104 (15)	276 (40)	70 (10.15)	7 (1015)
EPS100	29 (1.80)	173 (25)	345 (50)	100 (14.50)	10 (1450)

6.4.7. Each EPS block shall meet dimensional tolerances as determined in three distinct areas:

- Variations in linear dimensions as defined in Section 6.4.8.
- Deviation from perpendicularity of block faces as defined in Section 6.4.9.
- Overall warp of block faces as defined in Section 6.4.10.

6.4.8. The thickness, width and length dimensions of an EPS block are defined herein as the minimum, intermediate and maximum overall dimensions of the block, respectively, as measured along a block face. These dimensions of each block shall not deviate from the theoretical dimensions by more than ±0.5%.

6.4.9. The corner or edge formed by any two faces of an EPS block shall be perpendicular, i.e. form an angle of 90°. The deviation of any face of the block from a theoretical perpendicular plane shall not exceed 3 millimetres over a distance of 500 millimetres (0.125 inches in 20 inches).

6.4.10. Any one face of a block shall not deviate from planarity by more than 5 millimetres when measured using a straightedge with a length of 3 metres (0.25 inches in 10 feet).

6.5 PRODUCT MANUFACTURING QUALITY ASSURANCE: GENERAL REQUIREMENTS

6.5.1. Manufacturing quality assurance (MQA) of the EPS-block geofoam product will be conducted to verify the molder's MQC procedures. The owner's agent will have primary responsibility for all MQA unless the owner notifies the contractor otherwise. The owner's agent will communicate directly only with the contractor in matters and questions of MQA unless all parties agree otherwise.

6.5.2. MQA of the EPS-block geofoam will consist of two phases. Phase I MQA consists of pre-certification of the molder and shall be conducted prior to shipment of any EPS blocks to the project site. Phase I MQA is covered in Section 6.6 of these standards. Phase II MQA shall be conducted as the EPS blocks are delivered to the project site and is discussed in Section 6.8 of these standards.

6.6 PRODUCT MANUFACTURING QUALITY ASSURANCE: PHASE I

6.6.1. No EPS blocks shall be shipped to the project site until such time as all parts of Phase I MQA as specified in this section have been completed in the order listed.

6.6.2. The contractor shall first indicate in writing to the owner's agent whether or not the molder has a third-party certification program in force.

6.6.3. If third-party certification is offered, this notification shall be accompanied by documentation that indicates the business entity providing the third-party certification and describes in detail the steps to be taken by this agency to verify the molders compliance with the specific requirements of this standard. Acceptance of the molder's third-party certification by the owner's agent will waive the need for pre-construction product submittal and testing as specified in Section 6.6.4.

6.6.4. If the molder does not have third-party certification or the certification is deemed unacceptable by the owner's agent, the contractor shall deliver a minimum of three full-size EPS blocks for each AASHTO EPS-block geofoam type to be used on the project to a location specified by the owner's agent. These blocks shall in all respects be the same as blocks to be supplied to the project, including required seasoning as described in Section 6.4.3. The owner's agent will weigh, measure, sample and test a random number of blocks to evaluate the ability of the molder to produce EPS-block geofoam of quality as specified herein. The sampling and testing protocol will be the same as for Phase II MQA as discussed in Section 6.8.

6.6.5. If required by the contract documents, the contractor shall submit shop drawings indicating the proposed location and layout of all EPS blocks to be placed during the project. These drawings shall be reviewed by the owner's agent. The block layout shall be designed so that the following general design details are taken into account:

- the plane on which a given layer of blocks is placed must be parallel to the longitudinal axis of the road alignment;
- there must be a minimum of two layers of blocks at all locations;
- within a given layer of blocks, the longitudinal axes of all blocks must be oriented so as to be parallel to each other;
- within a given layer of blocks, the vertical joints between the adjacent ends of blocks within a given row of blocks must be offset to the greatest extent practicable relative to blocks in adjacent rows;
- the longitudinal axes of blocks for layers above and/or below a given layer must be oriented perpendicular to the longitudinal axes of blocks within that given layer; and
- the longitudinal axes of the uppermost layer of blocks must be oriented perpendicular to the longitudinal axis of the road alignment.

6.6.6. Prior to delivery of any EPS-block geofoam to the project site, a meeting shall be held between, as a minimum, the owner's agent and contractor. The supplier and/or molder of the EPS-block geofoam may also attend at the contractor's discretion to facilitate answering any questions first hand. The purpose of this meeting shall be to review the Phase I MQA results and discuss the Phase II MQA as well as other aspects of construction to ensure that all parties are familiar with the requirements of this standard. At the satisfactory conclusion of this meeting, the contractor shall be allowed to begin on-site receipt, storage (if desired) and placement of the EPS-block geofoam.

6.7 PRODUCT SHIPMENT AND STORAGE

6.7.1. Each EPS block shall be labeled to indicate the name of the molder (if there is more than one supplying a given project), the date the block was molded, the mass or weight of the entire block (in kilograms or pounds as desired and stated in the project specifications) as measured after a satisfactory period of seasoning as specified in Section 6.4.3, the dimensions of the block (in millimetres or inches as desired and stated in the project specifications) and the actual dry density/unit weight (in kilograms per cubic metre or pounds per cubic foot as desired and stated in the project specifications). Additional markings using alphanumeric characters, colors and/or symbols shall be applied as necessary by the supplier to indicate the location of placement of each block relative to the shop drawing indicated in Section 6.6.4 of this standard as well as the density of the block if multiple block densities are to be supplied for a given project. If multiple block densities are to be supplied, the use of no marking shall be considered an acceptable marking for one of the densities as long as it is used for the lower (lowest) density EPS blocks supplied to the project.

6.7.2. At all stages of manufacturing, shipment and construction the EPS blocks shall be handled in a manner so as to minimize physical damage to the blocks. No method of lifting or transporting the blocks that creates dents or holes in the block surfaces or losses of portions of the block shall be allowed.

6.7.3. If the EPS blocks are to be stockpiled at the project site until placement, a secure storage area shall be designated for this purpose. The storage area shall be away from any heat source or construction activity that produces heat or flame. In addition, personal tobacco smoking shall not be allowed in the storage area. EPS blocks in temporary on-site storage shall be secured with sandbags and similar "soft" weights to prevent their being dislodged by wind. The blocks shall not be covered in any manner that might allow the build up of heat beneath the cover. The blocks shall not be trafficked by any vehicle or equipment. In addition, foot traffic by persons shall be kept to a minimum.

6.7.4. EPS is not an inherently dangerous or toxic material so there are no particular safety issues to be observed other than normal construction safety and protection against heat and flame as specified in Section 6.7.3. However, extra caution is required during wet or cold weather. Surfaces of the EPS blocks tend to be more slippery wet than dry. In addition, when air temperatures approach or go below freezing, a thin layer of hoarfrost (ice) can readily develop on the exposed surfaces of EPS blocks if the dewpoint is sufficiently high. Thus the surfaces of the EPS blocks can pose particular slip hazards in this condition.

6.8 PRODUCT MANUFACTURING QUALITY ASSURANCE: PHASE II

6.8.1. Phase II MQA will be performed by the owner's agent as the EPS blocks are delivered to the project site. Phase II MQA will consist of four subphases (IIa through IId, inclusive). The contractor shall cooperate with and assist the owner's agent in implementing Phase II MQA.

6.8.2. Phase IIa MQA will consist of on-site visual inspection of each block delivered to the project site to check for damage as well as visually verify the labeled information on each block. Any blocks with damage or not meeting specifications will be rejected on the spot.

6.8.3. Phase IIb MQA will consist of on-site verification that the minimum block dry density as well as the physical tolerances specified in sections 6.4.8 through 6.4.10, inclusive, meet specifications. At least one truck load will be checked with additional blocks checked if initial measurements indicate lack of compliance. The contractor shall supply a scale on site with sufficient capacity and precision for weighing of EPS blocks. This scale shall be recently calibrated and certification of such calibration made available to the owner's agent.

6.8.4. Phase IIc MQA will consist of sampling the EPS blocks and laboratory testing specimens prepared from these samples. Sampling will be at the locations shown in Figure 6.1. The laboratory tests will check for compliance with the parameters shown in Table 6.2. The contractor shall cooperate with and assist the owner's agent with obtaining the necessary samples. Testing will be by or under the direction of the owner's agent. For each density of EPS used on a project, at least one block will be selected for sampling from the first truckload of EPS blocks of that density delivered to the job site. Additional blocks may be selected for sampling during the course of the project at the discretion of the owner's agent at a rate of sampling not to exceed one sample for every 250 cubic metres (325 cubic yards) of EPS delivered. Portions of sampled blocks that are otherwise acceptable can be used as desired by the contractor. The owner's agent will make every reasonable effort to conduct the laboratory testing expeditiously. However, if unsatisfactory test results are obtained the contractor may be directed to remove potentially defective EPS blocks and replace them with blocks of acceptable quality at no additional expense to the owner.

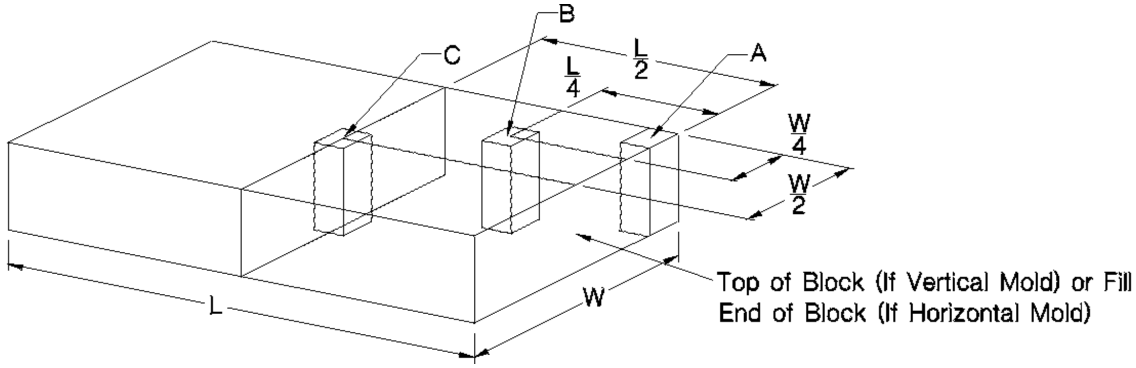

Figure 6.1. Recommended Block Sampling and Test Specimen Locations

6.8.5. Phase IId MQA will consist of preparation of an as-built drawing or drawings as well as additional record keeping to document the location of all EPS blocks placed for the project. The contractor shall cooperate with and assist the owner's agent with this

6.9 CONSTRUCTION QUALITY REQUIREMENTS

6.9.1. The contractor shall be directly responsible for all construction quality control (CQC). Items covered by CQC include all earthwork and related activities other than manufacturing and shipment of the EPS-block geofoam. Items of particular relevance to the placement of EPS-block geofoam are given in sections 6.10 through 6.12, inclusive, of this standard.

6.9.2. The owner's agent will be responsible for providing construction quality assurance (CQA) of the contractor's construction activities.

6.10 SITE PREPARATION

6.10.1. If required by the contract drawings, the natural soil subgrade shall be cleared of vegetation and any large or sharp-edged soil particles, and reasonably planar prior to placing a geotextile and/or sand bedding layer. If no sand bedding layer is used, the natural subgrade shall be cleared such that there is no vegetation or particles of soil or rock larger than coarse gravel in size exposed at the surface.

6.10.2. Regardless of the subgrade material (natural soils or sand bed), the subgrade surface on which the EPS blocks will be placed shall be sufficiently planar (smooth) prior to the placement of the first block layer. The required smoothness is defined as a vertical deviation of no more than ±10 mm over any 3 m (±0.25 in over 10 ft) distance.

6.10.3. There shall be no debris of any kind on the subgrade surface at the time EPS blocks are placed.

6.10.4. Unless directed otherwise by the owner's agent, there shall be no standing water or accumulated snow or ice on the subgrade within the area where EPS blocks are placed at the time of block placement.

6.10.5. EPS blocks shall not be placed on a frozen subgrade except in the case of construction over continuous or discontinuous permafrost terrain and as directed by the owner's agent.

6.11 PLACEMENT OF EPS-BLOCK GEOFOAM

6.11.1. EPS blocks shall be placed at the locations shown on either the contract drawings or approved shop drawings submitted by the contractor. Particular care is required if EPS blocks of different density are to be used on the project.

6.11.2. EPS blocks shall be placed so that all vertical and horizontal joints between blocks are tight.

6.11.3. The surfaces of the EPS blocks shall not be directly traversed by any vehicle or construction equipment during or after placement of the blocks.

6.11.4. With the exception of sand bags or similar "soft" weights used to temporarily restrain EPS blocks against wind, no construction material other than that shown on the contract drawings shall be placed or stockpiled on the EPS blocks.

6.11.5. At no time shall heat or open flame be used in proximity to the EPS blocks so as to cause melting or combustion of the EPS.

6.11.6. The final surface of the EPS blocks shall be covered as shown on the contract drawings. Care shall be exercised during placement of the cover material so as not to cause any damage to the EPS blocks.

6.12 PAVEMENT CONSTRUCTION

6.12.1. The pavement system is defined for the purposes of this standards as all material placed above the EPS blocks within the limits of the roadway, including any shoulders.

6.12.2. The pavement system shall be constructed above the EPS-block geofoam as shown on the contract drawings. Specifications covering construction of the pavement system are given elsewhere in the contract documents.

6.12.3. No vehicles or construction equipment shall traverse directly on the EPS blocks or any separation material placed between the EPS blocks and the pavement system. Soil or aggregate for the pavement system layers shall be pushed onto the EPS blocks or separation layer using appropriate equipment such as a bulldozer or front-end loader. A minimum of 300 millimetres (12 inches) of soil or aggregate shall cover the top of the EPS blocks or separation layer before compaction commences.

Section 7
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Appendix A
A Primer on Regrind and Its Effects on the Geotechnically Relevant Properties of EPS

A.1 REGRIND: THE ISSUE

One controversial item in EPS-geofoam specifications for lightweight fills that has emerged only in the last few years is whether or not a maximum regrind content should be included. Curiously, this issue never existed until a high-profile road project in the U.S.A. included a not-to-exceed regrind percentage in its EPS-geofoam specification. This specification has, unfortunately, propagated through the U.S. civil engineering community and, as a result, created needless confusion where none existed before. It also created the need for this discussion is to set the record straight on the subject and explain why specifying a regrind percentage is, at best, simply unnecessary and, at worst, misleading. These are the reasons why the draft interim AASHTO material standard for EPS-block geofoam first published by Horvath et al. (2000) and contained in this report does not even mention regrind.

A.2 REGRIND: DEFINITIONS AND BASICS

The manufacturing process for EPS is described in detail in Horvath (1995) and summarized in Section 3 of this report so is not provided here. Regrind is a colloquial term for scrap EPS that is literally ground up into sand-size particles and added to the virgin polystyrene (PS) prepuff during the final manufacturing stage of molding EPS into blocks or shapes (blocks are used most often for geofoam applications at the present time). Although most regrind used in the U.S. appears to be pre-consumer, in-plant recycled material there is nothing that inherently precludes post-consumer recycled material from being used for this purpose.

There is one and only one reason why regrind is used: it's cheap filler, solely for the financial profit and convenience of the EPS molder. Although solid PS represents only about 2% of the volume of a piece of EPS (the other 98% is air in the long term), the raw-material cost of virgin PS has a significant impact on the final cost of EPS (more than one-half the final unit cost of EPS is attributable to raw material costs). This is because PS comes from the refining of crude oil and thus is strongly influenced by the cost of oil. So all things being equal an EPS molder will always try to use the largest percentage of regrind possible when making EPS as it simultaneously reduces their raw-material cost per unit volume of EPS as well as the disposal cost for the in-plant scrap that every EPS molder generates making various products.

To be fair, it is important to note that the use of relatively cheap filler in civil engineering materials is neither new nor inherently bad. Concretes (the word is used here in its original, generic meaning of a mixture of some cementing agent plus aggregate) are by their very nature composed predominantly of cheap filler. For example, the primary reason why coarse and fine aggregates are used in portland-cement concrete (PCC) is because they are a lot cheaper than portland cement. So PCC is a more cost effective alternative than using a mortar that is pure portland cement plus water. But...and this is a very important point discussed in more detail in the following section...in a properly designed PCC mix the portland-cement paste bonds to the aggregate surfaces to form a rock-like final product whereas EPS regrind does not bond well with virgin prepuff when EPS is molded. This is where the problems come in as far as the technical impact of using regrind in EPS is concerned.

A.3 REGRIND: ITS IMPACT ON GEOFOAM-GRADE EPS

For generic small-strain geofoam applications such as lightweight fills, regrind is not a positive ingredient to EPS. It is not even a benign ingredient. Research indicates that regrind has the most significant effect on the mechanical properties of EPS and always for the worse. Unfortunately, it is these very same mechanical properties that are the most important in geofoam applications which are inherently load bearing.

There are several reasons why regrind negatively affects the quality of the finished EPS:

- The grinding process tears and crushes the original cellular structure of the EPS. Torn and crushed cells have much lower stiffness than the intact cells in virgin prepuff.

- Regrind has long since lost all of its hydrocarbon blowing agent. Consequently, during the final molding process it does not soften and fuse with adjacent particles to the same extent that virgin prepuff does. As a result, the overall *bead fusion* of the finished EPS is poorer than if all virgin prepuff were used. The resulting new EPS with regrind has a more-crumbly and less-durable texture. This is the primary reason why *flexural testing* of beam-shaped EPS specimens is an important part of any material-quality testing protocol for EPS-geofoam applications. "Flex testing", as it is referred to colloquially in practice, is the primary way to check for bead fusion.

- All EPS is inherently white regardless of its density and flame retardancy. It is thus possible that regrind of incorrect density and/or material that is not flame retardant may be mixed in and compromise the density and/or flame retardancy of the new EPS. Recall that EPS is not inherently flame retardant and there is a lot of non-flame-retardant EPS, especially shape-molded packaging and food containers (e.g. the ubiquitous white foam coffee cup), that can be recycled into regrind. A further complication is that much of the scrap EPS that exists in the U.S.A. was not even molded here but arrived here as packaging for some imported product. Thus its manufacturing lineage may be impossible to trace.

- If post-consumer regrind is used, plastic foams other than EPS may be mixed in and further contaminate the new EPS.

Experience indicates that the most important negatives of regrind are its effects on the small-strain stiffness region that is precisely the most important stress-strain area for generic small-strain geofoam applications such as lightweight fills. The effect is shown qualitatively in Figure A.1 which assumes that EPS specimens of identical densities are being compared.

Note that the stiffness (initial tangent Young's modulus) of EPS, which is simply the initial slope of the stress-strain curve, decreases (becomes flatter in Figure A.1) with increasing regrind content. This means that the elastic-limit stress also decreases and the creep susceptibility increases. Each of these has a potentially devastating effect as far as small-strain load bearing of the EPS is concerned. The rather amazing thing, however, is that the compressive strength (typically defined as compressive stress at 10% strain) is affected little if at all by regrind content. This is because by the time an EPS specimen is strained 10% in compression significant crushing of the cell structure has occurred so whether the crushing occurred before manufacturing (which applies to the regrind content) or during the test itself (which applies to the virgin-material fraction) apparently is of little import.

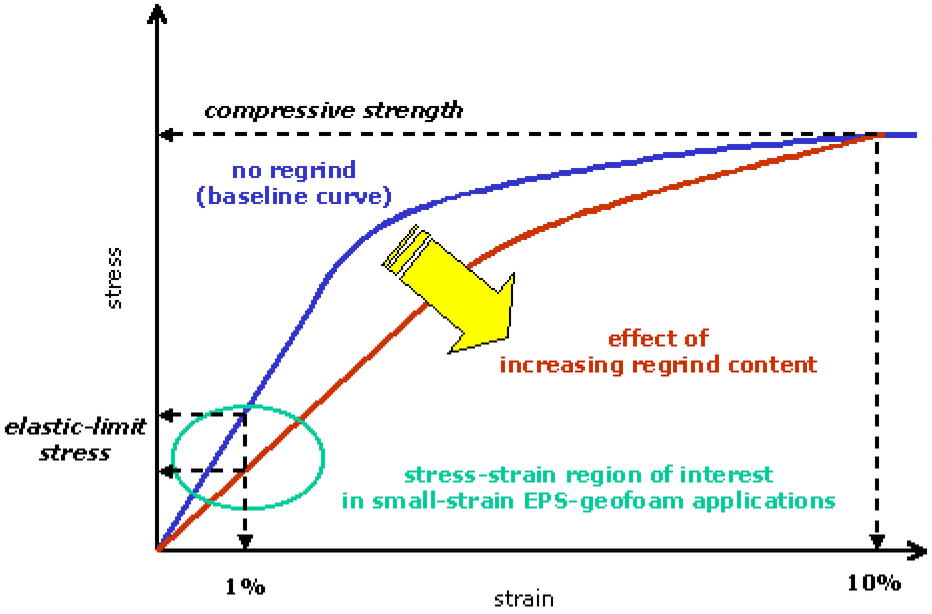

Figure A.1. Effect of Regrind Content on the Load-Deformation Characteristics of Block-Molded EPS

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Appendix B
Tabular Summary of Proposed MQC/MQA Procedures for EPS-Block Geofoam as Lightweight Fill for Roads

A draft version of the tables presented in this appendix were developed by Mr. David Arellano, P.E. who is a doctoral student at the University of Illinois at Urbana-Champaign and one of the Principal Investigators for NCHRP Project 24-11. Table B.1 presents a concise summary of the proposed manufacturing quality assurance (MQA) protocol described in detail in Section 6 that is to be followed by a project owner or the owner's agent when using EPS-block geofoam as lightweight fill for roads on sift ground. Table B.1 was prepared so that the logical flow of MQA during the various stages (phases) of a project could be easily seen.

Table B.1. Proposed Manufacturing Quality Assurance (MQA) Protocol for EPS-Block Geofoam Used for the Function of Lightweight Fill in Road Embankments on Soft Ground

Phase	Start of Phase	Description	Requirements	Possible Actions
I	Prior to shipment to the project site	Pre-certification of the molder	For molder seeking third-party certification approval Molder shall: • Identify the organization providing this service. • Provide detailed information as to the procedure and tests used by this organization to verify the molder's compliance with the specific requirements of this standard. • Provide written certification that all EPS blocks supplied to the project will meet the requirements specified in the project specifications. -------------------------------------- For molder without third-party certification or with certification deemed unacceptable by owner's agent • Contractor shall deliver a minimum of three full-size	• Acceptance of the molder's third-party certification by the owner's agent will waive the need for pre-construction product submittal and testing. • No EPS blocks shall be shipped to the project until such time as all parts of Phase I MQA have been completed.

			EPS blocks for each AASHTO EPS-block geofoam type to be used on the project to a location specified by the owner's agent. • Owner's agent will weigh, measure, sample and test a random number of blocks. Sampling and testing protocol will be the same as for Phase IIc MQA. • Molder should submit a letter stating that all EPS blocks supplied for the project are warranteed to meet specification requirements and what MQC measures they employ.	
IIa	As the EPS blocks are delivered to the project site	On-site visual inspection of each block delivered to the project site to check for damage as well as visually verify the labeled information on each block	Approved third-party certification • Each truckload. Owner's agent should inventory each and every block. ------------------------------------- No approved third-party certification • Each truckload. Owner's agent should inventory each and every block.	• Any blocks with significant physical damage or not meeting specifications will be rejected on the spot.
IIb	As the EPS blocks are delivered to the project site	On-site verification that the minimum block dry density as well as the physical tolerances meet specifications	Approved third-party certification • Each truckload. Initially, only one block per load. ------------------------------------- No approved third-party certification • Each truckload. Each block for the first load then at least one block per load for subsequent truckloads.	• If the selected block meets specifications with respect to its size and shape, and the mass/weight agrees with that marked on the block, no further checking of the load for these parameters is required and the shipment is approved conditionally. • If the selected block does not meet specification, then other blocks in the truckload should be checked and none used until the additional checking has determined which blocks

				are unsatisfactory. • At the completion of this subphase, the construction contractor should be conditionally allowed to proceed with installing blocks.
IIc	As the EPS blocks are delivered to the project site	Confirming the EPS engineering design parameters related to stiffness as well as the quality control strength parameters	Approved third-party certification • Discretion of owner's CQA agent. For example, can be omitted entirely on a small project, can perform testing only at the beginning of a project, or can be done on an ongoing basis. -------------------------------------- No approved third-party certification • Performed on all projects throughout the entire duration of the project • For each AASHTO EPS-block geofoam type at least one block will be selected for sampling from the first truckload. • Additional blocks may be selected at a rate of sampling not exceeding one sample for every 250 cubic metres (325 cubic yards). • Sampling to be performed per the locations indicated in Figure B.1. • Lab tests should be performed to check for compliance with the parameters shown in Table B.2 to include the elastic-limit stress, initial tangent Young's modulus, compressive strength, and	• Portions of sampled blocks that are otherwise acceptable can be used as desired by the contractor. • If unsatisfactory test results are obtained, the contractor may be directed to remove potentially defective EPS blocks and replace them with blocks of acceptable quality at no additional expense to the owner.

			flexural strength.	
IId	As the EPS blocks are placed	As-built drawing(s)	• Owner's agent with the cooperation of the contractor will prepare as-built drawing(s) as well as perform additional record keeping to document the location of all EPS blocks placed for the project.	

Table B.2. Correlation between Current ASTM and Proposed AASHTO EPS Material Designations

Material designation		Minimum allowable density, kg/m^3 (lb/ft^3)	
AASHTO (proposed)	**ASTM C 578**	**Each block as a whole**	**Any MQC/MQA test specimen**
EPS40	I	16 (1.0)	15 (0.90)
EPS50	VIII	20 (1.25)	18 (1.15)
EPS70	II	24 (1.5)	22 (1.35)
EPS100	IX	32 (2.0)	29 (1.80)

Table B.3. Minimum Allowable Values of MQC/MQA Parameters for Individual Test Specimens

AASHTO material designation (proposed)	Dry density, kg/m^3 (lb/ft^3)	Compressive strength, kPa (lb/in^2)	Flexural strength, kPa (lb/in^2)	Elastic-limit stress, kPa (lb/in^2)	Initial tangent Young's modulus, MN/m^2 (lb/in^2)
EPS40	15 (0.90)	69 (10)	173 (25)	40 (5.80)	4 (580)
EPS50	18 (1.15)	90 (13)	208 (30)	50 (7.25)	5 (725)
EPS70	22 (1.35)	104 (15)	276 (40)	70 (10.15)	7 (1015)
EPS100	29 (1.80)	173 (25)	345 (50)	100 (14.50)	10 (1450)

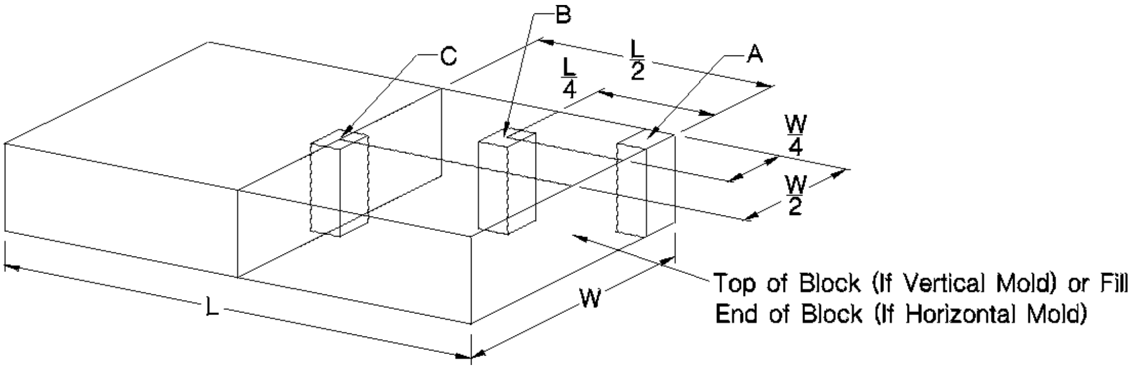

Figure B.1. Recommended Locations for EPS Block Sampling for MQA Test Specimens