Emerging Trends in Failures Involving EPS-Block Geofoam Fills

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Abstract: *Expanded polystyrene* (EPS) is a closed-cell polymeric ("plastic") foam that, in its generic block-molded form, has seen increasing use worldwide as a *cellular geosynthetic* in the *geofoam* category. This growth is due to the fact that block-molded EPS is unique among geofoam products for the large and diverse variety of functional applications for which it is technically well suited and relatively economical as well as for its proven long-term in-ground durability. However, as often happens when there is rapid growth in a technology based on a generic commodity product such as block-molded EPS, its use outstrips the acquisition of critically important technical knowledge by end users. This can result in inefficient and even incorrect use that can lead to failures in project applications. There is evidence that this cause and effect is currently occurring in the United States at least for some widely used EPS-block geofoam functional applications such as lightweight fill for road construction. This paper contains a summary of the technical issues that are significant factors in the observed failures of EPS-block geofoam fills, with an emphasis on emerging trends observed in recent years. This presentation is intended to provide critical information for design professionals, material suppliers, construction contractors, and owners alike so that they are aware of the key technical issues that require careful attention when designing EPS-block geofoam fills in practice.

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Background

The use of nontraditional materials and products derived from them in engineered construction has proliferated in recent years. This includes both new materials as well as new uses for existing materials. A material in the latter category is expanded polystyrene (EPS), the familiar white polymeric foam long used to create block- and shape-molded products for thermal insulation of building envelopes (roofs, walls, and below-grade areas) as well as common consumer applications such as beverage cups and cushion packaging. The recent significant growth in the use of EPS in engineered construction has been in geotechnical applications where, in its generic block-molded product form, it has evolved as the geofoam material and product of choice in most functional applications identified to date (Horvath 1995).

Finding new uses in engineered construction for an existing material or product presents unique challenges for the design professional. In general, patents on the basic material and its most common derivative products have long since expired which means both the material and its products are generic commodities in the marketplace. As a result, there is typically no single organization that has the proprietary business-related incentive to expend significant financial resources to support an active ongoing program of research, education (technology transfer), and standard development for the material and products as new uses evolve and grow over time. The problem that results from this situation is that, on the one hand, the material may have a well-established history of use and confidence but for products and applications not directly or entirely relevant to its new use(s) in engineered construction. This then places a significant burden of responsibility on the design professional who is using the new (to them) technology to proactively seek out current and correct technical information for use in design and to craft an appropriate project-specific material-and-construction specification. Unfortunately, experience indicates that in such situations incomplete or even incorrect technical information may be used and, as a result, there is potential for inefficient and even incorrect use of a technology that can result in failure of a project application. This occurs because it is common that the use of a technology in its early stages of development and application in practice outstrips the acquisition and dissemination of knowledge and development of material-and-construction standards.

Purpose and Scope of Paper

There is growing evidence that, in the United States at least, there has been an increase in the number of failures involving EPS-block geofoam used for its most common functional application as lightweight fill, primarily for roads. Available information indicates that these recent failures were caused by lack of a thorough understanding of all the factors that must be considered when designing and specifying block-molded EPS as a geofoam product for such applications. This paper is intended to provide a summary of those technical factors that appear to be the cause of

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observed failures. The goal of this paper is not to fix blame for these failures but to contribute to fixing the problems, primarily that of inadequate education (technology transfer), which have led to these failures by educating all parties involved in the design and implementation of EPS-block geofoam fills as to the key technical issues that must be considered on any project. The outcome of increased educational efforts such as this paper will hopefully be a reduction in the occurrence of future failures so that the state of practice in the United States is more consistent with that observed in other parts of the world where failures involving EPS-block geofoam fills for roads simply do not occur.

Overview of Key Details for EPS-Block Geofoam Fills

Introduction

To understand how and why failures involving EPS-block geofoam fills occur and what corrections are necessary in practice to prevent their future occurrence, it is necessary to understand key project-management and technical details for designing such fills. Toward that end a brief summary of essential details will be presented before discussing failure issues. Basic information concerning block-molded EPS and a detailed discussion of how to design an EPS-block geofoam fill can be found in Stark et al. (2004a). Although that reference was developed specifically for the application of road embankments on soft ground the information presented is applicable to a much broader range of applications and is thus a useful primer for one not familiar with EPS-block geofoam fills.

Project Organization

It is important to understand at the outset that the successful design and execution of a fill incorporating EPS-block geofoam is always a team effort involving several diverse business entities that nowadays may be located anywhere in the world. Each entity must perform their part of the work correctly if the final constructed facility is to perform as intended. Thus, understanding how a typical project where block-molded EPS is used as a geofoam product is organized and conducted is necessary for understanding both the division of responsibilities required for satisfactory delivery of the final project and where and by whom errors can be made that can lead to failures.

In the most basic terms there are four primary project participants in the process of designing and constructing a fill incorporating EPS blocks:

- The "design professional" retained by or on behalf of the project owner who performs the design and crafts the basic construction documents (overall plans and material-and-construction specification).
- The "manufacturer" of the EPS blocks (called a *block molder* or simply *molder*). As discussed in Horvath (2009), to make EPS blocks a molder utilizes a petroleum- ("crude oil-") based raw material that itself involves three separate business entities to create so that these entities are effectively secondary project participants.
- The "construction contractor" is responsible for both purchasing (typically directly from the molder) and placing the EPS blocks using a detailed block-placement plan shown on approved shop drawings prepared by or on behalf of the contractor. Depending on the size and complexity of the project the actual contractor involved in the acquisition and placement of the EPS blocks may be a subcontractor to a general contractor or construction manager.
- The "project owner" or their designated representative (which may or may not be the design professional) who is responsible for all *manufacturing quality assurance* (MQA) and *construction quality assurance* (CQA) related to the EPS blocks and their placement that includes, among other things, review and approval of the block-placement shop drawings submitted by the contractor.

Perhaps the single most important point to recognize is that when block-molded EPS is used as a geofoam product for the functional application of lightweight fill it is, as was noted previously, a generic commodity product that can, in concept, be manufactured more or less identically by many molders. With few exceptions, most areas in the continental United States can be reasonably supplied ("reasonably" in this context relates to shipping costs) by two or more molders which provide the cost-based competition that is typically a desirable benefit of using any generic commodity material or product. However, the generic nature of EPS blocks may not be readily obvious as most molders in the United States now use a unique brand name or trade name for their product. This is done only for marketing purposes to, among other things, create a product identity and illusion of uniqueness. The only exception to the inherent generic nature of block-molded EPS is that a limited number of molders are licensed to use certain proprietary additives for insecticide purposes in the EPS-molding process (Horvath 2009).

The fact that EPS blocks used as a geofoam product for lightweight-fill applications are a generic commodity product is not intended to imply anything negative. The vast majority of materials and their derivative products used in engineered construction (e.g., structural steel, Portland-cement concrete (PCC), asphaltic concrete, and wood) are generic commodities so design professionals are familiar and comfortable with using commodity materials and products in engineered construction. However, experience has been that many design professionals are unaware of the commodity nature of EPS-block geofoam for most applications when they first work with the technology, so they are unfamiliar with the breadth and depth of their responsibilities.

There are several important consequences of the generic commodity nature of EPS blocks used as lightweight fill:

- The design professional alone is responsible for all aspects of design, including, but not limited to, selecting the minimum grade(s) of EPS necessary to support the design loads. From a design perspective EPS grades are comparable to different yield strengths of structural steel or unconfined compressive strengths of PCC. Recently, there have been signs of a trend in the United States toward outsourcing and making the details of the final design the responsibility of a consultant hired by the construction contractor as opposed to the responsibility of the design professional as was traditionally the case. Note that this outsourcing is separate from and in addition to the long-standing practice of outsourcing the determination of specific block sizes and producing shop drawings of block layout, tasks that have long been something relegated to the contractor. This is because there is no standard size of EPS blocks made in the United States. Thus, during the design phase the design professional has no idea of the actual block sizes that will be used as this will only be determined when the contractor actually buys blocks from a specific molder. This broader outsourcing of design responsibility is conceptually identical to the practice used for some time now for other geotechnologies such as earth-retaining structures (e.g., "vendor-designed" retaining walls using mechanically stabilized earth or segmental retaining wall technologies) and various types of ground modification/improvement. However, it should be understood that the project design professional must still be sufficiently familiar with the EPS-block geofoam design process to be able to knowledgeably review shop-drawing submittals by the contractor and their consultant. This is because if there are any problems related to the performance of a fill incorporating EPS-block geofoam the project design professional will inevitably be drawn into the ensuing legal process.

- The design professional alone is responsible for developing a complete project-specific material-and-construction specification for the EPS. A detailed guideline standard for this has been publicly available for use since ca. 2000 (Stark et al. 2004b). This standard has already been used successfully for several major road projects such as the well-known Big Dig in Boston. Fine tuning of the original version of this standard (Stark et al. 2004b) based on lessons learned on these major projects is reflected in a revised and updated version published recently (Arellano et al. 2009). This standard is currently being supported and promoted by the U.S. Federal Highway Administration (FHWA) for use in road projects, but it is applicable to a broader range of lightweight fills for nonroad applications. Unfortunately, experience indicates that the majority of U.S. road projects involving EPS-block geofoam fills in recent years have relied not on this standard but on either a specification developed by the local DOT or one downloaded from an EPS molder's website on the world wide web. This was likely done because the project design professional was not sufficiently expert or experienced with specifications for EPS-block geofoam so they simply used a document that was readily accessible or perhaps even provided to them. In the former case of a DOT-developed specification the writer's experience has been that individual state specifications are often technically inadequate or incomplete compared to the guidelines contained in Stark et al. (2004b) and Arellano et al. (2009). In the latter case of a molder-supplied specification the writer's experience has been that such documents often contain, for obvious business reasons, language that includes proprietary requirements that significantly limits competition as only relatively few molders (usually only one in a geographic area or region) are capable of supplying EPS blocks that meet the specified proprietary requirements.
- Regardless of the size of the project there must always be adequate MQA and CQA programs crafted by the project design professional and executed on behalf of the project owner prior to and during the course of construction to ensure that the molder supplies EPS blocks that meet the specified requirements and the contractor executes the work properly. Such quality-assurance oversight in engineered construction is always especially critical when price-based commodities such as block-molded EPS are used. Although the molder and contractor may have their own internal *manufacturing quality control* and *construction quality control* protocols neither the molder nor contractor should never be relied on as the sole source of quality oversight on a project.
- Unlike most other geosynthetic products that have only one primary use, i.e., as a geosynthetic, block-molded EPS (which was invented ca. 1950) has long-standing myriad uses unrelated to geotechnical applications as a geofoam geosynthetic and even unrelated to engineered construction. In fact, it has been estimated unofficially that in the United States at present the geofoam market accounts for perhaps only 10% of the total EPS production in the United States which makes the geofoam market a very minor segment of a typical molder's annual average business. This combined with the generic commodity nature of block-molded EPS means that a molder should not, in general, be relied on for any significant, meaningful, unbiased technical support by licensed design professionals for questions related to design for geofoam applications.

In summary, as with other generic commodity materials and products used routinely in engineered construction the burden of responsibility for designing and constructing with EPS-block geofoam for lightweight fills (and many other functional applications) rests largely and primarily with the design professional on a project. The need for a thorough adequate project-specific material-and-construction specification and strict enforcement of that specification throughout the entire course of construction cannot be overemphasized. This is because the typical arrangement on a project calls for the contractor to purchase the EPS blocks directly from a molder in the same way the contractor purchases other commodity materials and products, i.e., based on price. This means the material or product used will only be as good as the enforced specification that defines its acceptable properties.

Stability of the Final Structure

Overview

Virtually all geofoam applications involving block-molded EPS are *load bearing* in nature so the key technical issues related to EPS-block geofoam are similar conceptually to those encountered with other load-bearing geosynthetics. Thus, as with many geosystems that utilize geosynthetic products the design of an "earthwork" incorporating EPS blocks requires consideration of both internal and external stabilities. "Stability" is used here in its broad context to include both displacement/deformation-based serviceability failure [the serviceability limit state (SLS)] and a collapse failure (the ultimate limit state).

A thorough discussion of the stability issues that need to be considered for road embankments on soft ground is contained in Stark et al. (2004a) and a preliminary discussion of issues related to slope stabilization is contained in Arellano et al. (2009) with an outline in Arellano et al. (2010). Although these references focus on roads they are applicable to a much broader range of fills incorporating EPS blocks and are thus recommended reading for a thorough understanding of the subject. Consequently, only a brief summary of stability issues is presented here with an emphasis on those that have proven to be important with regard to recent failures.

Internal Stability

The internal stability of an assemblage of EPS blocks is primarily a SLS issue involving material displacement and deformation ("stiffness") and not strength. Thus, this aspect must be dealt with on an allowable stress design/working stress design basis as it does not lend itself to load and resistance factor design/ultimate strength design. In fact, "strength" in the classical material-rupture sense is rarely an issue with geofoam applications of block-molded EPS. This is because virtually all geofoam applications of block-molded EPS involve uniaxial compression as the primary, if not exclusive, mode of loading. Fig. 1 illustrates the uniaxial compressive stress versus axial compressive strain behavior of block-molded EPS under relatively rapid strain-rate-

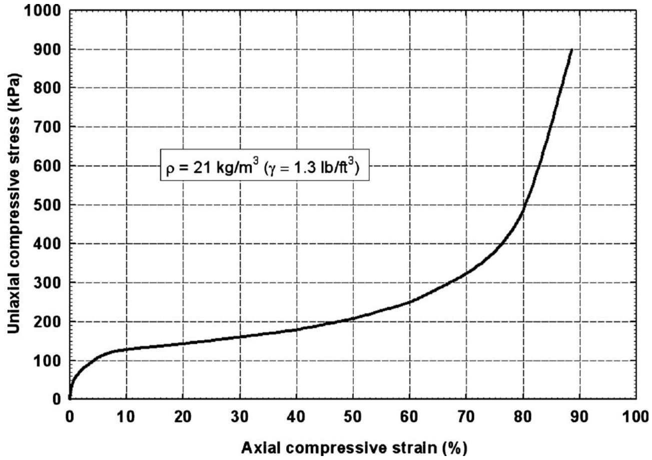

Fig. 1. Typical behavior of block-molded EPS under rapid loading

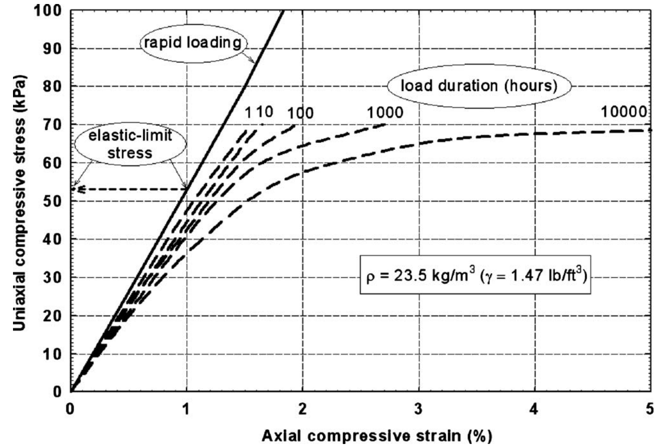

Fig. 2. Typical small-strain behavior of block-molded EPS

controlled loading (typically 10% strain/min) that is the de facto standard testing condition for specimens of block-molded EPS. The single most remarkable aspect of the behavior shown in Fig. 1 is that EPS loaded in compression never fails in the classical material-rupture sense. Rather the initially significant void volume of the EPS (typically of the order of 98% of the total volume) is reduced by crushing as load is applied so that the material essentially returns to the original solid-polystyrene state. Not obvious from Fig. 1 is that Poisson's ratio of block-molded EPS under increasing strain is zero or even negative (which means that the test specimen "necks" inward horizontally). Thus, strength in a classical sense clearly has no definition for block-molded EPS loaded in compression. Nevertheless, historically a compressive strength of block-molded EPS has been defined as the compressive stress at some arbitrary strain level (usually 10% but sometimes 5%). As can be readily seen in Fig. 1, strain levels of either 10 or 5% are simply arbitrary points on the overall stress-strain curve that have no distinguishing feature other than the fact that they occur immediately after a zone of initial material yielding.

Because analysis and design using block-molded EPS as a geofoam product are always strain (stiffness) based and never strength based it has become common to divide geofoam applications into what are called *small-strain* and *large-strain* applications based on the relative operational compressive strain level used in that application. The use of block-molded EPS as lightweight fill is a small-strain application. Fig. 2 illustrates the general compressive stress-strain behavior within this range.

The current standard practice for designing within the small-strain range calls for limiting the maximum compressive strains caused by service loads anywhere within an assemblage of EPS blocks to no more than 1% using material properties defined in the de facto standard rapid-loading test defined previously and shown by the solid curve in Fig. 2. There are several reasons for this:

- Strain beyond this limit will begin to cause significant irreversible/nonrecoverable compression of the EPS due to immediate material yielding caused by permanent inelastic deformation of the unique cellular structure of the EPS.
- Strains beyond this limit will begin to cause compression of the EPS that will increase significantly over time due to creep. The effects of creep can be seen in the dashed isochronous stress-strain curves in Fig. 2 for several increments of time up to 10,000 h (slightly more than one year).
- Stress-strain behavior up 1% compressive strain is nominally linear elastic. This means that repetitive loads such as from traffic will not cause permanent displacement of the EPS.

In practice, the way that this guideline of staying within 1% compressive strain is typically achieved is by making sure that the calculated normal stresses from service loads everywhere within the assemblage of EPS blocks are below what is called the *elastic-limit stress* of the EPS. The elastic-limit stress is shown in Fig. 2 and is defined as the uniaxial compressive stress at 1% axial compressive strain in the standard rapid-loading test. Note that the elastic-limit stress and the related stiffness parameter of *initial secant Young's modulus* (taken as the average, overall slope of the initial nominally linear-elastic portion of the stress-strain curve shown in Fig. 2 up to 1% strain) of block-molded EPS are not constants as EPS blocks can be molded within a range of densities. All things being equal, there is a strong correlation between EPS density and elastic-limit stress (Horvath 1995; Stark et al. 2004a). However, this caution cannot be made too strongly; the correlation between EPS density and the stiffness parameters of elastic-limit stress and initial secant Young's modulus should never be taken as guaranteed as even at a certain EPS density there are numerous manufacturing variables that can affect the stiffness of the EPS (Horvath 2009). Therefore, EPS density alone should never under any circumstances be used as a reliable measure of the small-strain stiffness of block-molded EPS. Appropriate laboratory tests to explicitly measure material stiffness (i.e., elastic-limit stress and initial Young's modulus) should always be used.

External Stability

The primary external-stability consideration is that an assemblage of EPS blocks must be placed in such a manner so that the individual blocks behave as a single coherent mass under all expected loading condition to the greatest extent practicable for the life of the structure. Clear guidelines for block layout and confinement to achieve this have evolved over time and are well documented (Horvath 1995; Stark et al. 2004a). Special considerations for seismic loading (so that the blocks do not slide apart) as well as the potential for block flotation due to changes in groundwater levels must be carefully adhered to when such conditions are anticipated during the design life of a structure.

Construction

Construction is typically the most vulnerable time in the life of any geosynthetic product and this is certainly the case for EPS blocks used as lightweight fill. Damage to an EPS block is both sudden and irreversible. An EPS block can be permanently damaged by any number of causes such as rough handling, improper storage, overstressing by construction equipment trafficking directly on it, and flotation by water and even air if not temporarily secured prior to and during placement. It is also important to note that unlike many other geosynthetics there is no proven repair technique for an EPS block that is damaged. This makes the avoidance of construction-related damage to EPS blocks all the more important as any defects in EPS blocks that are placed will remain and likely only get worse during the life of the structure. Again, clear guidelines for proper handling and on-site storage techniques have evolved over time and are well documented (Stark et al. 2004a) as well as reflected in guideline material-and-construction standards (Stark et al. 2004b).

Postconstruction

Compared to many other polymeric and metallic geosynthetics all indications are that block-molded EPS is extremely durable once placed in the ground and adequately covered (Horvath 1995). There is a relatively small suite of substances (primarily various petroleum-hydrocarbon liquids such as gasoline) that are known to cause material degradation of EPS. Other than that there are no known substances typically found in the ground or groundwater that will degrade EPS so in routine practice there is no allowance made for any physical material degradation or change in material properties over time, and as a result there is currently no defined lifespan or limits on service life for block-molded EPS placed in the ground.

Review of Prior Assessments and Investigations of Failure

As part of the ongoing efforts of the past few decades to develop block-molded EPS as a geofoam product there have been prior general "lessons learned" assessments (Horvath 1999a,b) as well as explicit studies of known failures (Horvath 1999c, 2004). These studies, which actually included all geofoam materials and products (not just block-molded EPS) and all geofoam functional applications (not just lightweight fill for roads), indicated that failures can be first divided into the categories of "avoidable" and "unexpected." The former category involves failure mechanisms that could or should have been anticipated by those involved in the project that incurred the failure based on the then-current state of knowledge. In such cases the failure can be considered fully preventable and culpability for the failure lies with one or more of the project participants (design professional, molder, contractor, and owner/owner's representative). The latter category involves failure mechanisms that were novel or otherwise unexpected, unanticipated, or unknown at the time they were discovered or occurred during actual project applications or testing. Failures in this category, as unfortunate as they might be, can be considered to be part of the normal process of knowledge growth in any evolving technology, with no clearly culpable project participant. It is simply a fact of pushing the edge of the envelope of technology that failures will occasionally occur despite the best efforts and due diligence of all involved to avoid them.

Perhaps the single most striking outcome of these earlier studies of geofoam failures was that there were so few of them even though all geofoam materials and products and all functional applications going back to the use of insulated pavements beginning in the early 1960s and lightweight fills beginning in the early 1970s were included. This is remarkable because this period of time encompassed the earliest stages of development of geofoam geotechnology when both errors of omission and unanticipated failures would be expected to be relatively more common. It appears that the reason for the overall relatively low incidence of failure is that the earliest years of relatively extensive geofoam usage occurred primarily in Western European countries and Japan where the technology was carefully and scientifically studied and tightly controlled by either government agencies or industry groups with a proprietary technical and/or business interest in success. In summary, most of the early usage of geofoams in general occurred in settings where technology played a more important role than marketing or business.

Summary of Recent Failure Experiences

Introduction and Overview

There has been a noticeable increase in the number of failures involving geofoam that have come to the writer's attention in recent years either directly or indirectly (there may well be more that are unknown to the writer). Each failure involved the use of block-molded EPS as lightweight fill in road construction in the United States.

It is tempting to simply correlate and associate this increased incidence of project failures to the dramatic increase in the use of EPS-block geofoam in the United States in recent years. One might reason or argue that more projects simply mean more opportunities for failure on a purely statistical basis. However, upon careful examination of the facts of the matter it appears that a significant, if not primary, factor causing these failures is the fact that the market structure for EPS-block geofoam in the United Sates is very different than in other parts of the world where there is not only a much longer history of geofoam usage in general but also relatively failure-free usage. Specifically, in the United States there has never been a central unifying control or oversight of EPS-block geofoam usage from either a federal-government agency or the industry that makes block-molded EPS. Such control or oversight, which is done primarily to ensure that design professionals utilize correct design-and-specification methodologies, has existed in every other developed country where geofoam usage in general is much farther advanced than in the United States. Although detailed design guidelines (Stark et al. 2004a) and accompanying recommended material-and-construction standards (Stark et al. 2004b) have been publically available in the United States for use in a preliminary form at least since ca. 2000 experience has demonstrated that knowledge and use of this material are neither universal nor mandatory. On the other hand, in Western European countries and Japan there has been much more rigid oversight and control of projects where block-molded EPS was used for road construction.

As a result of these significant differences in practice between the Unites States and other developed countries, it appears that there has been divergence, not consolidation, of thought in the United States in recent years as to how to design and specify EPS-block geofoam for lightweight fills. In particular, there is clear evidence from specifications obtained during the research for past [Project No. 24-11(01)] and current [Project No. 24-11(02)] National Cooperative Highway Research Program projects related to using EPS-block geofoam in road construction for which the writer has been involved as a coprincipal investigator that the trend in the past decade has been for different states as well as EPS molders to develop their own specifications rather than embrace and promote the one recommended by Stark et al. (2004b) that was developed as part of NCHRP Project No. 24-11(01). Although the document of Stark et al. (2004b) has been supported and promoted by the FHWA in recent years it is on a strictly voluntary recommendation-only basis and as such local DOTs and their consultants are free to use it as is, modify it, or ignore it in favor of an alternative standard as they choose.

That this increasingly fragmented approach to designing and, especially, specifying EPS-block geofoam fills is having a negative effect in the form of failures is borne out by the fact that all of the recent failures that the writer is aware of are in the category of avoidable as defined and discussed previously. Thus, each was preventable had publicly available knowledge simply been applied during design and construction. These recent failures have been categorized and are summarized in the following sections. Due to the sensitive nature of failures, some of which are still unresolved in terms of potential legal action, specifics as to project names and locations are intentionally omitted from this paper. This is also in keeping with the spirit and intent of this paper not to fix blame but to make a contribution toward fixing the problem(s) that have contributed to these failures.

Issues Related to Internal Stability

The majority of recent failures appear to be the result of inadequate or improper design of the EPS blocks for internal stability, specifically, improper matching of vertical normal stresses imposed on the EPS blocks to the elastic-limit stress of the EPS which resulted in the EPS being overstressed. This overstressing and resulting compressive strain beyond the elastic limit shown in Fig. 2 produced unexpected excessive compression of the EPS and concomitant excessive total and differential settlement of the fill surface (which was typically a paved road) which only increased over time due to material creep. In several cases the compression and resulting settlement have been sufficiently severe to require remedial actions that ranged from repaving the road surface; removing and replacing the EPS; and even removing the EPS and using another design alternative completely due to loss of faith in using EPS. However, the most remarkable thing about these failures when viewed collectively is that each appears to have been entirely preventable based on the prevailing state of knowledge. It is very important to note that such failures involving overstressing of the EPS were never observed in prior studies of geofoam failures (Horvath 1999c, 2004). Thus, it can be argued that even one failure attributed to overstressing of the EPS is one too many based on both past worldwide experiences with EPS-block geofoam lightweight fills which date back to at least 1972 as well as the availability of detailed technical information that, if properly followed, should prevent such failures from occurring.

Overstressing of EPS blocks in geofoam applications can occur as a result of any one of the several different scenarios involving various combinations of culpability from the parties involved in a project. Therefore, there are lessons to be learned for all involved in such projects. The different failure-causing scenarios that have been identified to date are the following:

- The design professional did not perform any explicit design of the EPS blocks but simply specified an EPS material type based on some precedent or other nonproject-specific information.
- The design professional performed what they believed was a project-specific design but did not know how to properly match calculated stresses with EPS material type(s).
- The design professional performed a proper project-specific design and selected appropriate EPS material type(s) but did not develop a proper material-and-construction specification to ensure that EPS blocks with the required stiffness properties (elastic-limit stress and initial secant Young's modulus) would be provided. This scenario typically involves specifying based on EPS density alone which, as was noted previously, is simply never correct due to all the variables that can occur in the EPS production process (Horvath 2009).
- The design professional performed a proper project-specific design, selected appropriate EPS material type(s), and developed an appropriate project-specific material-and-construction specification but the molder did not supply blocks of the required quality. The unacceptable blocks were placed anyway due to the fact that an adequate project MQA process either did not exist or did not detect the material flaws. In extreme cases is it possible the project MQA process was simply ignored and the flawed material knowingly used usually to expedite construction. Note that the owner/owner's representative may have culpability in this scenario.
- The design professional performed a proper project-specific design, selected appropriate EPS material type(s), and developed an appropriate project-specific material-and-construction specification and the molder-supplied blocks of the required quality. However, construction equipment was allowed to traffic on the EPS blocks with either no or insufficient soil cover on the blocks. That this occurred could be the result of either the project specifications not outlawing such practice or an adequate project specification not being enforced by the owner/owner's representative. The outcome is that same in either case.

Again, it is stressed that an important characteristic of block-molded EPS is that once it is damaged in any way, including by overstressing, it can never be repaired to restore its original properties and, in fact, its stiffness properties can continue to deteriorate over time due to creep. In the above-described scenarios involving overloading of the EPS once the cellular structure of the EPS has been deformed due to compressive stresses beyond its elastic range not only is the deformation permanent it then allows significant creep strains to develop. This can be seen in Fig. 2 for stress levels beyond the elastic-limit stress.

An issue that is closely related to the discussion of excessive compression of EPS and the surface settlement it produces that warrants some discussion concerns the use of a reinforced PCC slab between the top of the assemblage of EPS blocks and overlying materials (soil cover, pavement system, etc.). Such a slab is popularly called a *load-distribution slab* (LDS) in U.S. practice although there has been no known published research to conclusively demonstrate the actual function of such slabs in general and whether they actually provide more load distribution than simply an equivalent thickness of soil. A detailed discussion of the historical basis and evolution of the LDS and its hypothesized role can be found in Horvath (1995) and Stark et al. (2004a).

In summary and contrary to a popular opinion held by some a LDS is never "mandatory" with an EPS-block geofoam fill that will have an overlying pavement system. There have been decades of successful use of EPS-block geofoam fills that did not use such slabs (Stark et al. 2004a). In addition, the presence or absence of a LDS means absolutely nothing in and of itself in terms of satisfactory performance of a pavement overlying EPS blocks, and the absence of a LDS is never the de facto cause of poor performance of a road pavement overlying EPS blocks. The writer was personally involved in a recent (2007) forensic investigation of a failed road pavement overlying an EPS-block geofoam fill in a northeastern U.S. state. The cause of the pavement failure was a straightforward overstressing of the EPS blocks and concomitant excessive total and differential settlement of the asphaltic-concrete pavement due to a total thickness of material overlying the EPS that exerted a vertical normal stress in excess of the elastic-limit stress of the EPS that was specified. This particular project used a "standard" 150-mm (6-in.) reinforced LDS and its presence obviously did not prevent an unsatisfactory performance of the overlying pavement system. In fact, to the extent that reinforced PCC has a density somewhat greater than that of earth materials only contributed to the overstressing of the EPS blocks that produced the failure.

Issues Related to External Stability

Known recent failures that involve the postconstruction external or global stability of a fill containing EPS blocks appear to be quite rare. In recent years in the United States there was one known failure that involved the flotation of the entire fill due to a rise in groundwater several years after the fill was constructed. Available information indicates that this was due to a failure by the designers to properly consider the potential for this failure mechanism. This failure was sufficiently severe and damaging to the road surface that the entire fill and overlying pavement was removed and a different technical solution that did not involve the use of EPS blocks was used to rebuild the road.

Issues Related to Construction

There have been a number of recent failures of EPS fills while still under construction. It is likely such failures have been underreported as the ones that are known happened on large high-profile road projects about which the writer had direct knowledge or were made public for other reasons. Most failures in this category involved unanticipated block movement due to fluids (air and water). Site flooding as a result of a heavy rain that caused previously placed blocks to float and move out of position was the underlying cause in all cases. In one extreme and unusual case this water flotation was combined with high winds that actually lifted dislodged blocks and resulted in a fatality (a construction worker who was struck by an airborne block).

In addition to these failures related to flotation there have been a number of failures where EPS blocks were overstressed by construction equipment trafficking on the blocks either directly or with inadequate soil cover. These have been mentioned and included previously in the discussion of internal stability because the damage to the EPS blocks caused by construction exhibited itself as excessive settlement once material (soil, pavement, etc.) was placed on top of the EPS blocks that had been overstressed and compromised.

Issues Related to Postconstruction

There has been no known failure of an EPS-block geofoam fill due to physical material degradation once placed in the ground.

Lessons Learned and Recommendations for Future Action

In summarizing and closing this paper it is important to note at the outset that block-molded EPS has been used successfully as a lightweight-fill material around the world since at least 1972. There have been countless projects where the material has been used to directly support not only roads but railways, airfields for large commercial jet aircraft, bridges, and even buildings. Clearly, these many successful projects indicate that EPS-block geofoam is a well-proven reliable geotechnology when properly designed, specified, supplied, and constructed. Therefore, the discussion of failures in this paper should not be construed as questioning or casting aspersions on the viability of the basic underlying technology. Rather this paper is intended to be a contribution to ensuring that this geotechnology continues to be used properly.

All of the failures observed in U.S. practice in recent years and summarized in this paper were in the category of avoidable because the underlying cause of the failure was always something already known and documented and therefore something that could and should have been anticipated. What is particularly remarkable is that the category of failure with the most numerous occurrences (internal stability involving overstressing of the EPS blocks) was simply not observed at all in prior assessments of failure (Horvath 1999c, 2004). This means that there has actually been a regression in technology in recent years, in the United States at least, as the knowledge of how to properly design and specify EPS-block geofoam fills to avoid overstressing has been available since the 1970s and, up until recently it appears, this knowledge was sufficiently well known by design professionals so as to avoid the occurrence of such failures in the past.

The overall lesson learned here is that there needs to be a greater effort to disseminate existing knowledge to all involved in the design, supply, construction, and ownership of fills incorporating EPS-block geofoam but most important to design professionals. Because block-molded EPS when used as a lightweight-fill material is a generic commodity product it is the design professional on a project who bears the primary responsibility for the successful implementation of the technology. The information on how to design and build such fills is widely available (Stark et al. 2004a) with additional and updated information by Arellano et al. (2009), as are guideline standards for both material and construction (Stark et al. 2004b; Arellano et al. 2009). It appears that the highest priority is for design professionals to become thoroughly familiar with the proper selection and specification of EPS grades to support design loads to avoid overstressing EPS blocks through shortcomings in either design, material specification, or material-quality testing. In particular, design professionals need to appreciate that EPS density is, in and of itself, never an adequate parameter to define the relevant small-strain stiffness properties of block-molded EPS that are so crucial to successful design. As discussed in detail by Horvath (2009), there are many manufacturing factors that can cause block-molded EPS with the same density to have significantly different stiffness properties in the small-strain region used in lightweight fills.

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