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Load bearing analysis of EPS-block geofoam embankments

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ABSTRACT: This paper presents a deformation-based load bearing analysis procedure that utilizes the elastic limit stress, i.e. the compressive stress at 1 percent strain, to design expanded-polystyrene (EPS)-block geofoam for roadway embankments. The procedure consists of determining the maximum vertical stress from dead and traffic loads at various levels within the EPS fill mass and selecting an EPS type that exhibits an elastic limit stress that is greater than the calculated vertical stress at the depth being considered. The higher the required elastic limit stress, the greater the required block density. However, the cost of EPS block increases with increasing density. Therefore, an advantage of the recommended deformation-based design procedure is that the calculation of stresses and strains within the EPS mass allows the selection of the type of EPS blocks to be optimized by selecting blocks with a lower density for the lower portions of the embankment and the higher density blocks for the upper part of the embankment. The selection of EPS blocks with the lowest possible density yields a cost efficient EPS block geofoam embankment.

1 INTRODUCTION

The American Society of Testing and Materials (ASTM) defines geofoam as a block or planar rigid cellular foam polymeric material used in geotechnical engineering applications. It also defines expanded polystyrene (EPS) as a type of foamed plastic formed by the expansion of polystyrene resin beads in a molding process (American Society for Testing and Materials 2007). The predominant geofoam that has been used for lightweight fill in geotechnical applications is EPS-block geofoam. Although EPS-block geofoam for road construction is an established technology and despite the extensive and continuing worldwide use of EPS-block geofoam since the early 1970s, it has been underutilized in U.S. practice because a comprehensive design guideline for its use as lightweight fill in roadway embankments has not been available. To meet this need, the American Association of State Highway and Transportation Officials (AASHTO), in cooperation with the Federal Highway Administration (FHWA), funded a study through the National Cooperative Highway Research Program (NCHRP), to develop a comprehensive design procedure for the use of geofoam in roadway embankments. The NCHRP Project 24–11(01) results are included in two reports. One report includes only the design guideline and the material and construction standard (Stark et al. 2004b). The second report includes the background for the design guideline and standard as well as a summary of the engineering properties of EPS-block geofoam and an economic analysis (Stark et al. 2004a).

The primary objective of this paper is to present a deformation-based load bearing capacity analysis procedure to design EPS-block geofoam for stand-alone embankments over soft ground. The primary advantage of the recommended deformation-based design procedure is the calculation of stresses and strains within the EPS mass allows the selection of the type of EPS blocks to be optimized by selecting blocks with a lower density for lower portions of the embankment and higher density blocks for the upper part of the embankment.

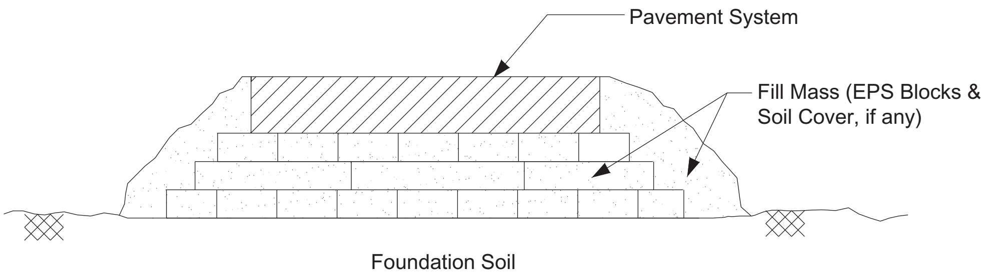

Figure 1. Major components of an EPS-block geofoam embankment.

Using EPS blocks with the lowest possible density yields a cost efficient EPS block geofoam embankment.

The design of an EPS-block geofoam roadway embankment over soft soil requires an understanding of the interaction between the three major components of the embankment, i.e. foundation soil, fill mass, and pavement system. These components are shown in Figure 1. Therefore, the overall design process is divided into three phases that consider interaction between these three major embankment components. The external (global) stability phase considers how the combined fill mass and overlying pavement system interacts with the existing foundation soil and considers stability of the overall embankment. External stability consideration in the proposed design procedure include consideration of Serviceability Limit State (SLS) issues, such as total and differential settlement caused by the soft foundation soil and Ultimate Limit State (ULS) issues, such as bearing capacity, slope stability, seismic stability, hydrostatic uplift (flotation), translation due to water (hydrostatic sliding), and translation due to wind. The internal stability phase considers stability within the embankment fill mass and the primary consideration is the 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 can lead to excessive settlement of the pavement surface. Internal stability in the proposed design procedure includes consideration of SLS issues such as the proper selection and specification of EPS properties so the geofoam mass can provide adequate load bearing capacity to the overlying pavement system without excessive settlement and ULS issues such as translation due to water (hydrostatic sliding) and wind, and seismic stability. The pavement system phase considers the subgrade support provided by the underlying EPS blocks and the primary consideration is the proper selection of pavement material types and thicknesses based on the underlying EPS-block geofoam properties.

The load bearing analysis is part of the internal stability design phase. The basis of the load bearing analysis procedure is initially presented followed by a summary of the design procedure.

2 BASIS OF THE LOAD BEARING ANALYSIS DESIGN PROCEDURE

2.1 *Design goals*

The primary internal stability issue for EPS-block geofoam embankments is the load bearing capacity of the EPS geofoam. A load bearing capacity analysis consists of selecting an EPS type with adequate properties to support the overlying pavement system and traffic loads without excessive EPS compression that could lead to excessive settlement of the pavement surface as shown in Figure 2. To ensure adequate performance of the EPS blocks, three design goals must be achieved. First, the initial (immediate) deformations under dead or gravity loads from the overlying pavement system must be within acceptable limits. Second, the long-term (for the design life of the fill) creep deformations under the same gravity

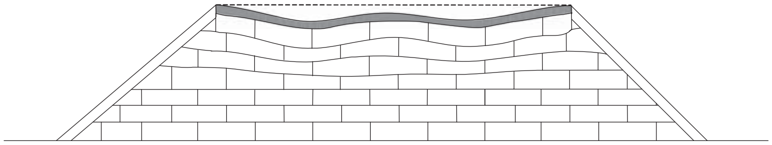

Figure 2. Load bearing failure of the EPS blocks resulting in excessive deformation.

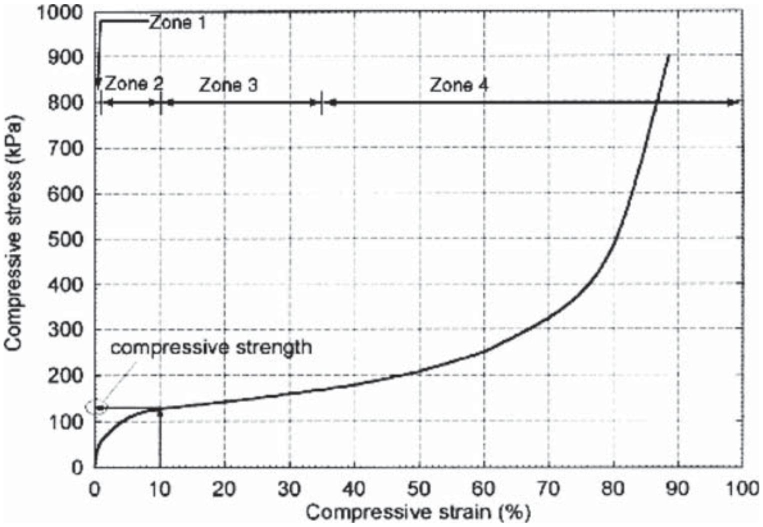

Figure 3. Stress-strain behavior of 21 kg/m^3 (1.3 lbf/ft^3) EPS block under rapid, strain controlled, unconfined axial compression (Horvath 1995).

loads must be within acceptable limits. Third, non-elastic or irreversible deformations under repetitive traffic loads must be within acceptable limits. Therefore, to accomplish these three design goals, an understanding of the compressive, time-dependent (creep), and cyclic stress-strain behavior of EPS-block geofoam is required. An overview of each of these three behaviors is subsequently provided.

2.1.1 *Compressive stress-strain behavior*

Figure 3 shows the typical uniaxial compression stress-strain response of an EPS-block specimen. The test was performed on a block-molded EPS specimen with a density of 21 kg/m^3 (1.3 lbf/ft^3). However, the stress-strain response for other densities are qualitatively similar (Horvath 1995). As shown by Figure 3, EPS does not typically exhibit failure like other solid materials used in construction (metals, concretes, wood) by a physical rupture of the material when uniformly loaded. Additionally, EPS does not behave like soil or other particulate materials where inter-particle slippage occurs and a steady state or residual strength develops at large strains. The behavior of EPS is continuously work (strain) hardening in nature because the EPS essentially crushes one dimensionally back to its original solid polystyrene state.

The stress-strain behavior of EPS shown in Figure 3 can be divided into the following four zones: (1) an initial linear response zone, (2) a yielding zone, (3) a linear and work hardening zone, and (4) a non linear but still work hardening zone (Horvath 1995). Horvath (1995) indicates that the limit of the initial linear response of Zone 1 extends to strains between 1 and 1.5 percent with the larger strain at the end of the linear region occurring with an increase in EPS density. Therefore, for design it can be conservatively concluded that the stress-strain behavior of EPS-block geofoam is both linear and elastic up to a compressive

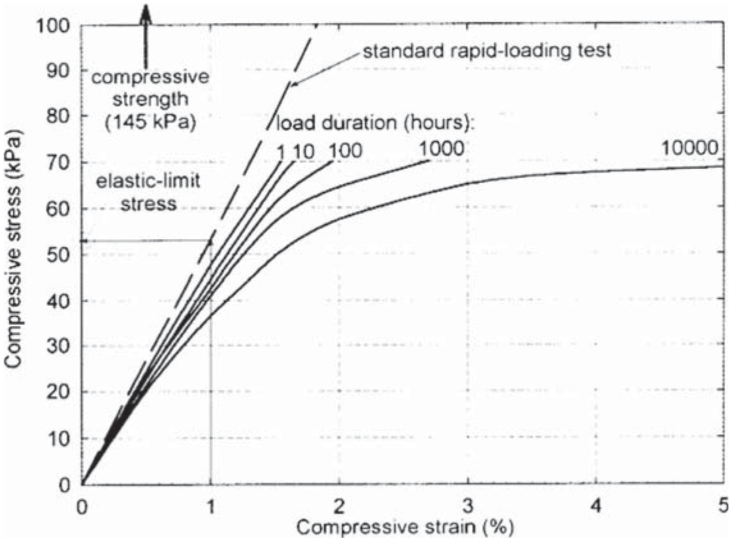

Figure 4. Isochronous stress-strain curves for 23.5 kg/m³ (1.47 lbf/ft³) block-molded EPS based on unconfined axial compression creep tests (Horvath 1995).

strain of approximately 1 percent. The compressive stress at 1 percent strain, as measured in a standard rapid-loading compression test, is defined as the elastic limit stress, σ_e. Consequently, the design goal of limiting initial deformations under dead loads from the overlying pavement system can be achieved by limiting loads to less than the elastic limit stress of the EPS block. The slope of the initial linear portion of the stress-strain relationship (see Zone 1 of Figure 3) is defined as the initial tangent Young's modulus, E_{ti}.

Although the compressive strength is not explicitly used in the load bearing design procedure that will be described herein because the compressive strength is typically defined as the compressive resistance at 10 percent deformation (American Society for Testing and Materials 1999) and this strength occurs in the Zone 1 and 2 transition area, the compressive strength is used during manufacturing quality assurance and control (MQA/MQC).

2.1.2 *Time-dependent stress-strain behavior (creep)*

A reliable mathematical model to estimate long-term vertical strain of EPS blocks under sustained loads is currently not available (Arellano et al. 2001; Stark et al. 2004a). Therefore, the current state of practice for considering creep strains in the design of EPS block embankments is to base the design on laboratory creep tests on small specimens trimmed from the same EPS block that will be used in construction or to base the design on published observations of the creep behavior of EPS.

Figure 4 provides isochronous stress-strain relationships based on the results of creep tests. As shown in Figure 4, EPS will exhibit large creep deformations almost immediately if stresses are near the compressive strength. Therefore, to produce acceptable strain levels in lightweight fill applications, stress levels must be kept low relative to the compressive strength. Also, the isochronous relationships tend to be predominantly linear up to strains of about 1 to 1.5 percent. Lower density EPS tends to creep more than higher density EPS at the same relative stress level.

Horvath (1995) summarized the published observations about the creep behavior of EPS geofoam in terms of the immediate strain rate produced by an applied stress. If the applied stress produces an immediate strain of 0.5 percent or less, the creep strains will be negligible even when projected for 50 years or more. If the applied stress produces an immediate strain between 0.5 percent and 1 percent, the geofoam creep strains will be tolerable (less than

1 percent) in lightweight fill applications even when projected for 50 years or more. If the applied stress produces an immediate strain greater than 1 percent, creep strains can rapidly increase and become excessive for lightweight fill geofoam applications.

Based on these general observations, the compressive stress at a vertical strain of 1 percent, i.e. the elastic-limit stress, appears to correspond to a threshold stress level for the development of significant creep effects. Therefore, the design goal of limiting long-term creep deformations within acceptable limits may be achieved by limiting field applied stresses to less than the elastic limit stress until more reliable creep models are developed. If the applied stress is less than the elastic limit stress, creep strains within the EPS mass under sustained loads are expected to be within acceptable limits of 0.5 to 1 percent strain over 50 to 100 years.

2.1.3 *Cyclic stress-strain behavior*

Figure 5 provides a typical stress-strain plot of an EPS-block geofoam specimen subjected to cyclic loading. As the stress level extends beyond the elastic limit stress, there is both plastic deformation as well as a decrease in the magnitude of the average tangent, Young's modulus. Therefore, the design goal of limiting non-elastic or irreversible deformations under repetitive traffic loads also may be achieved by limiting maximum applied stresses to less than the elastic limit stress. This conclusion concerning behavior under cyclic loads is 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 cyclic loading behavior of full-size EPS blocks.

2.2 *Recommended load bearing design approach*

The recommended load bearing design approach included the NCHRP design guideline for stand-alone embankments and the one presented herein is an explicit deformation-based design method. It is based on the recognition that the compressive strength of EPS does not quantify the deformation characteristics of EPS-block geofoam. As previously shown, based on a review of the general compressive, time-dependent (creep), and cyclic stress-strain behavior of EPS-block geofoam specimens, the three load bearing design goals can all be achieved by limiting dead and live loads to within the elastic limit stress of the EPS blocks.

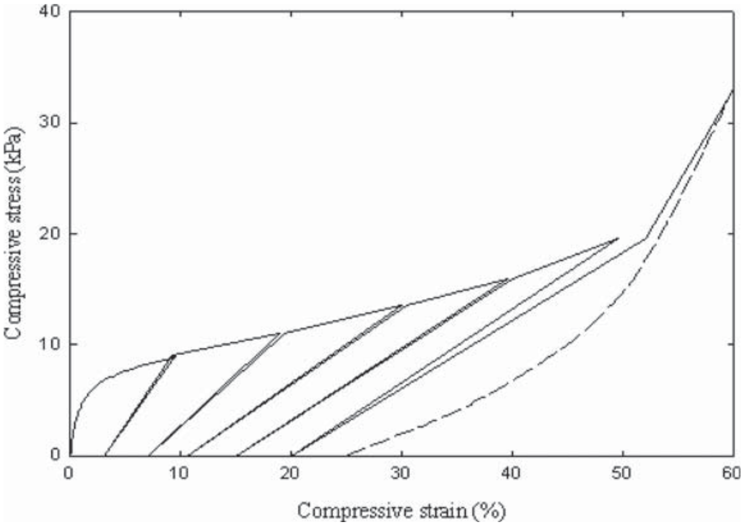

Figure 5. Cyclic load behavior for 13 kg/m^3 (0.81 lbf/ft^3) block-molded EPS (Horvath 1995).

Therefore, a designation system based on elastic limit stress is included in the NCHRP recommended material and construction standard. Table 1 provides the required elastic limit stress values for various EPS densities. EPS densities are provided because it is a useful physical property for MQA/MQC. The basis for the values indicated in Table 1 is presented in the NCHRP report and an overview is provided by Arellano and Stark (2001; Stark et al. 2004a). The use of *EPS40* directly below the pavement system is not recommended because it possesses the lowest density.

One advantage of a deformation-based design procedure is that the calculation of applied stresses at various locations within the EPS mass allows for location specific selection of EPS blocks with elastic limit stress values that exceed the anticipated applied stresses. Therefore, the density of the EPS blocks within the embankment can be optimized and specified for various portions of the embankment. Therefore, with a deformation-based design it is possible to select an EPS density that provides adequate load-bearing capacity within tolerable settlements without requiring an inefficient density. Because the applied vertical stress within an embankment decreases with depth under the pavement and side slopes, it is possible to use multiple densities of EPS blocks in an embankment. For example, lower density blocks can be used at greater depths and/or under the side slopes and higher density blocks used directly under the pavement system.

One advantage of a deformation-based design procedure is that the calculation of applied stresses at various locations within the EPS mass allows for the explicit selection of EPS blocks with elastic limit stress values that exceed the anticipated applied stresses. Therefore, the density of the EPS blocks can be optimized and thus specified for various portions of the embankment. Therefore, with a deformation-based design it is possible to select an EPS

Table 1. EPS-block geofoam elastic limit stress and initial tangent Young's modulus requirements.

Material designation	Dry density/unit weight of each block as a whole, kg/m^3 (lbf/ft^3)	Dry density/unit weight of a test specimen, kg/m^3 (lbf/ft^3)	Elastic limit stress, kPa (lbs/in^2)
EPS40	16 (1.0)	15 (0.90)	40 (5.8)
EPS50	20 (1.25)	18 (1.15)	50 (7.2)
EPS70	24 (1.5)	22 (1.35)	70 (10.1)
EPS100	32 (2.0)	29 (1.80)	100 (14.5)

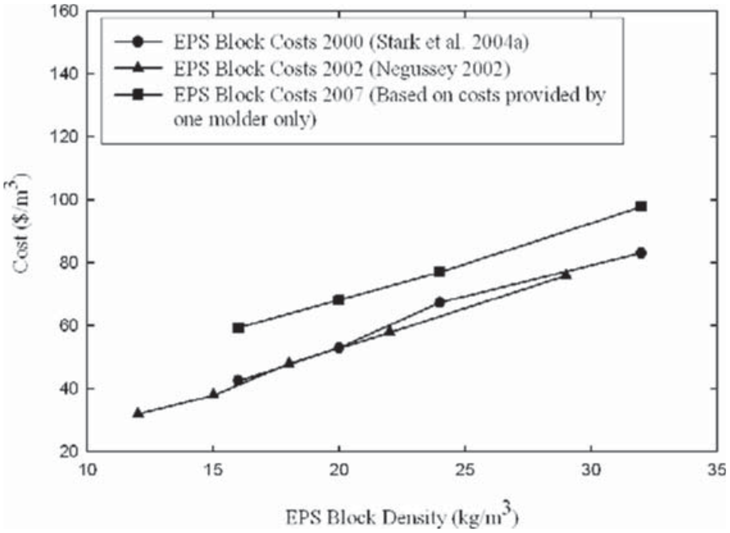

Figure 6. EPS-block geofoam prices.

density that provides adequate load-bearing capacity within tolerable settlements without requiring an inefficient density. Because the applied vertical stress within an embankment decreases with depth under the pavement and side slopes, it is possible to use multiple densities of EPS blocks in an embankment. For example, lower density blocks can be used at greater depths and/or under the side slopes than higher density blocks that have to be used directly under the pavement system.

The reason for minimizing the use of excessively high density EPS block is that the cost of EPS block is linked to the block density as shown by Figure 6. Therefore, there is a cost incentive to rationally select one or more EPS densities within a proposed embankment, with blocks of different density placed according to the applied vertical stresses. Therefore, an advantage of the recommended deformation-based design procedure is that the calculation of stresses and strains within the EPS mass allows the selection of the type of EPS blocks to be optimized by selecting blocks with the lowest density that will yield a minimum elastic limit stress that exceeds the anticipated applied stresses. As shown by Figure 6, the selection of EPS blocks with the lowest possible density yields a cost efficient EPS-block geofoam embankment.

3 DESIGN PROCEDURE

3.1 *Overview*

The procedure for evaluating the load bearing capacity of EPS blocks as part of internal stability that was incorporated in the NCHRP 24–11(01) design guideline can be separated into two parts. The objective of Part 1 is to determine the traffic and gravity load stresses applied by the pavement system to the top of the EPS blocks to select the type of EPS that should be used directly beneath the pavement system. Part 1 consists of the following eight steps: (1) Estimate traffic loads, (2) Add impact allowance to traffic loads, (3) Estimate traffic stresses at the top of the EPS blocks, (4) Estimate gravity stresses at the top of the EPS blocks, (5) Calculate total stresses at top of the EPS blocks, (6) Determine minimum required elastic limit stress for the EPS blocks directly beneath the pavement system, (7) Select appropriate EPS block type to satisfy the required EPS elastic limit stress for underneath the pavement system, e.g., *EPS50*, *EPS70*, or *EPS100*, and (8) Select preliminary pavement system type and determine if a load distribution layer is required.

The objective of Part 2 is to determine the traffic and gravity load stresses applied at various depths within the EPS block fill mass to select the appropriate EPS for use at these various depths within the embankment. Part 2 consists of the following five steps: (9) Estimate traffic stresses at various depths within the EPS block fill mass, (10) Estimate gravity stresses at various depths within the EPS blocks, (11) Calculate total stresses at various depths within the EPS blocks, (12) Determine minimum required elastic limit stress at various depths within the fill mass, and (13) Select appropriate EPS block to satisfy the required EPS elastic limit stress at various depths in the embankment.

The details for each step of the load bearing design procedure can be found in the NCHRP reports (Stark et al. 2004a; Stark et al. 2004b). A brief synopsis of the key aspects of the load bearing design procedure is provided here.

3.2 *Selection of EPS type directly below the pavement system*

In Step 1, the largest live or traffic load expected on the roadway above the embankment is estimated. In Step 2, an allowance for impact forces from dynamic, vibratory, and impact effects of traffic may be considered. The Japanese Public Works Research Institute (1992) recommends an impact coefficient of 0.3. Therefore, an impact coefficient of 0.3 can be applied to the live load for traffic that is determined in Step 1 and the total load applied is the dead plus live loads.

The objective of Step 3 is to estimate the dissipation of vertical stress through the pavement system so that an estimate of the traffic stresses at the top of the EPS fill mass can be obtained. Various pavement systems, with and without a load distribution layer between the pavement system and the EPS blocks, should be evaluated to determine which pavement system alternative is most cost effective. The live load stresses at the surface of the EPS fill mass can be reduced by including a load distribution layer between the pavement system and EPS blocks. In addition to reducing stresses through stress distribution, the load distribution layer may also provide lateral confinement of the overlying unbound pavement layers. This additional lateral confinement compared to the confinement provided by the EPS blocks may allow the use of a minimum pavement system thickness. Therefore, the use of a load distribution layer may also decrease gravity load stresses from the pavement system. The type of load distribution layer that has been predominantly used in practice since the earliest EPS-block geofoam lightweight fills in Norway in the 1970s is a 100 to 150 mm (4 to 6 in.) thick reinforced Portland cement concrete (PCC) slab. The primary disadvantage of a PCC load distribution layer is that PCC slabs generally represent a significant relative cost. Alternative load distribution layers for reinforcement that can be considered in pavement design include a geogrid, geocell with soil or PCC fill, and soil cement.

Step 4 consists of determining the stresses resulting from the gravity load of the pavement system and any road hardware placed on top of the roadway. Step 5 consists of calculating the total stress at the surface of the of EPS blocks directly underlying the pavement system. This total stress, σ_{total}, is the sum of the live load obtained in Step 3 and the gravity stress obtained in Step 4. Step 6 consists of determining the minimum required elastic limit stress for the top layer of blocks. The minimum required elastic limit stress for the top layer of EPS blocks that will be located directly beneath the pavement system can be calculated by multiplying σ_{total} from Step 5 by a factor of safety as shown by Equation (1).

$$\sigma_e \geq \sigma_{total} * FS \tag{1}$$

where σ_e is the minimum required elastic limit stress of EPS and FS is a factor of safety.

The main component of σ_{total} is the traffic stress and not the gravity stress from the pavement. Because traffic is a main component of σ_{total} and traffic is a transient load like wind loading, a factor of safety of 1.2 is recommended for the load bearing analysis. This is the same value of factor of safety recommended for other transient or temporary loadings such as wind, hydrostatic, and seismic used for external stability analyses.

Step 7 consists of selecting an EPS type from Table 1 that exhibits an elastic limit stress greater than or equal to the required σ_e determined in Step 6. The EPS selected will be the EPS block type that will be used directly beneath the pavement system. The required depth for the selected EPS type will be dependent on the stresses within the EPS fill mass that will be determined at various depths as part of Steps 9 through 13. However, the EPS type selected in Step 7 should extend to a minimum depth of 610 mm (24 in.). This minimum depth is recommended because it is typically the critical depth assumed in pavement design for selection of an average resilient modulus for design of the pavement system (Huang 1993). The use of *EPS40* is not recommended directly beneath paved areas.

If an EPS with an elastic limit stress greater than 100 kPa (14.5 lbs/in^2), i.e. *EPS100* is required, consideration can be given to contacting local molders to determine if EPS-block geofoam with an elastic limit stress greater than 100 kPa can be molded for the project. If EPS blocks with a higher elastic limit stress than what is currently available locally is required, consideration can be given to modifying the pavement system design to further distribute live loads and decrease stresses at the top of the EPS blocks or within the EPS block fill mass.

Step 8 consists of performing a cost analysis to select an optimal pavement system that can be used over the type of EPS blocks determined in Step 7. Various types of pavement systems may be considered in the cost analysis such as asphalt concrete, Portland cement concrete, and a composite pavement system. The cost analysis can also be used to determine if a PCC separation layer between the pavement and EPS is cost effective. The optimal pavement system that is selected based on this cost analysis will be used in Steps 9 through 13.

3.3 *Selection of EPS type at various depths within the EPS block fill mass*

Step 9 consists of estimating traffic stresses at various depths within the EPS blocks. This step estimates the dissipation of traffic induced stresses with depth through the EPS blocks of the embankment. The 1 (horizontal) to 2 (vertical) approximate or Boussinesq stress distribution theory can be used to estimate traffic induced stresses at various depths within the EPS fill mass. Based on an analysis performed during the NCHRP study and the results of a full-scale model test that was performed at the Norwegian Road Research Laboratory (Aabøe 1993; Aabøe 2000) to investigate the time-dependent performance of EPS-block geofoam, a 1 (horizontal) to 2 (vertical) distribution of vertical stresses through EPS blocks was found to be in agreement with the measured vertical stresses, which showed a stress distribution of 1 (horizontal) to 1.8 (vertical). At depths where the traffic vertical stresses overlap based on the 1 (horizontal) to 2 (vertical) method, the approximate stress distribution of closely spaced loaded areas provided by Sowers (1979) can be used to estimate the total stress resulting from the individual overlapping traffic stresses.

In Step 10, the stresses resulting from the gravity load of the pavement system, any road hardware placed on top of the roadway, and the EPS blocks are estimated. The procedure used to obtain the stress distribution at the center of earth embankments (U.S. Army Corps of Engineers 1994) can be used to obtain an estimate of the increase in vertical stress at the centerline of the geofoam embankment at various depths due to the increase in gravity stress of the pavement system. This procedure is also described in the NCHRP report (Stark et al. 2004a).

Step 11 consists of calculating the total stresses at various depths within the EPS fill mass. This total stress is the sum of the live load traffic stress obtained in Step 9 and the gravity stress obtained in Step 10. Step 12 consists of determining the minimum required EPS block elastic limit stress at various depths. Equation (1) can also be used in Step 12 to determine the minimum required elastic limit stress except that σ_{total} is the value determined in Step 11. Step 13 consists of selecting an EPS type from Table 1 that exhibits an elastic limit stress greater than or equal to the required σ_e determined in Step 12.

In summary, the basic procedure for designing against load bearing failure is to calculate the maximum vertical stresses at various levels within the EPS mass (typically the pavement system/EPS interface is most critical) and select the EPS that exhibits an elastic limit stress that is greater than the calculated or required elastic limit stress at the depth being considered.

4 CONCLUSIONS

The primary internal stability issue for EPS-block geofoam embankments is the load bearing capacity of the EPS geofoam fill mass. Load bearing capacity analysis is Step 14 of the procedure to design EPS-block geofoam stand-alone embankments over soft ground that is included in the NCHRP design guideline. The recommended load bearing design approach is based on specifying EPS blocks that exhibit an elastic limit stress greater than the estimated total applied stresses to ensure that the three design goals of load bearing capacity design are achieved. These goals are limiting the initial (immediate) deformations under dead or gravity loads from the overlying pavement system, limiting the long-term creep deformations under the same gravity loads, and limiting non-elastic or irreversible deformations under repetitive traffic loads to within acceptable limits.

The basic procedure for designing against load bearing failure is to calculate the maximum vertical stresses at various levels within the EPS mass (typically the pavement system/EPS interface is most critical) and select the EPS that exhibits an elastic limit stress that is greater than the calculated or required elastic limit stress at the depth being considered. An overview of the load bearing capacity procedure was provided.

The primary advantage of the explicit deformation-based design method is that the calculation of stresses and strains within the EPS mass allows the selection of the type of EPS blocks to be optimized by selecting blocks with the lowest density that will yield the required elastic limit stress. The selection of EPS block with the lowest possible density will yield a cost efficient EPS-block geofoam embankment.

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