Construction and Building Materials 157 (2017) 438–448

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

# Expanded polystyrene geofoam in pavement construction

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## HIGHLIGHTS

- Expanded polystyrene (EPS) has offered solutions to many construction problems.
- Manufacturing process, physical and mechanical properties of EPS are reviewed.
- Applications of EPS as lightweight fill in pavement construction with case studies.
- Design and construction issues and areas for research for the application of EPS.
- Limitations and quality assurance for the use of EPS in pavements are explored.

## ARTICLE INFO

*Article history:*
Received 25 June 2017
Received in revised form 16 September 2017
Accepted 19 September 2017
Available online 26 September 2017

*Keywords:*
Expanded polystyrene
Geofoam
Lightweight construction materials
Pavement construction
Expanded polystyrene properties
Expanded polystyrene construction issues

## ABSTRACT

Expanded polystyrene (EPS) has offered solutions to many civil engineering problems associated with pavement construction. Issues, such as the construction of pavements on low bearing capacity subgrade soils (such as peats and clays), or in regions with severe winters, and the construction of pavements over underground services, have all been overcome with the use of EPS geofoam. This material is used for many pavement applications. These include the use of EPS geofoam as a lightweight fill, as a thermal insulator, a vibration dampener, and for the protection of underground services. Unfortunately, there are a number of barriers that are stopping the use of EPS geofoam from becoming standard worldwide. More has to be done to develop and proliferate technical knowledge to avoid the inefficient, and even the incorrect use of EPS geofoam. There is also room for research in the development of new and innovative applications for the use of EPS geofoam, and for the development of updated standards and test procedures. To facilitate research in these areas, this review paper discusses the design considerations, limitations, and quality assurance procedures for the use of EPS in pavement applications, while paying special attention to the areas of weakness for which recommendations are made. Furthermore, this review paper details historic case studies in which EPS was used, as well as discusses the mechanical properties of EPS, and, finally, its manufacturing process.

## Contents

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https://doi.org/10.1016/j.conbuildmat.2017.09.113
0950-0618/

## 1. Introduction

Expanded polystyrene (EPS) is a polymeric geosynthetic material with a cellular closed cell structure. Its manufacture involves the heating of expandable beads of polystyrene with steam, and the placement of these heated expanded polystyrene beads into moulds to create prismatic blocks of EPS [1]. These blocks are manufactured for use in a variety of civil engineering applications. One of its primary applications is in pavement construction to counter the issue of low bearing capacity subgrade soils, an application that has been very successful, and, consequently, has been widely adopted and utilised for more than four decades [2]. Other applications of EPS include thermal insulation, compressible inclusion, slope stability, bridge abutment construction, stadium seating construction, and even noise/vibration dampening [3–5].

There are a number of attributes that make expanded polystyrene a suitable material for pavement construction. Firstly, EPS is an ultra lightweight material that has a density of approximately 1/100th of other conventional fill materials (see Table 1). This means that EPS can be used in a lightweight fill application, where it is used in the place of low bearing capacity foundation soils or heavy fill materials, to prevent the associated issue of unacceptable rates of settlement. Also, EPS has a small Poisson's ratio, and a high self-sustaining character, resulting in reduced lateral pressure when used as a backfill material for structures like retaining walls. Other benefits include the savings that can be made in cost and time during construction. Significant cost savings can also be made from the decreased maintenance costs due to the low settlement associated with EPS geofoam, since the volume of soft soil that needs to be removed can be reduced (some scenarios), and since the costly task of utility relocation can be avoided entirely (construction can be done over utilities). In addition, savings in construction times can be made since construction can continue during adverse weather conditions, since the time needed for underlying soils to consolidate is eliminated, and since the installation is rapid [6–8].

**Table 1**
Range in densities of typical lightweight fills [19].

| Lightweight Fill Type | Range in Density |
|---|---|
| Geofoam (EPS) | 12–35 |
| Foamed concrete | 335–770 |
| Wood fibre | 550–960 |
| Shredded tyres | 600–900 |
| Expanded Shale and Clay | 600–1040 |
| Fly-ash | 1120–1440 |
| Boiler Slag | 1000–1750 |
| Air Cooled Slag | 1100–1500 |

The first application of EPS geofoam in pavement construction took place in Germany in the 1950s during an investigation that assessed the suitability of EPS geofoam as a pavement insulator. In this investigation, Styropor boards were used in place of conventional frost protection. Despite its success in this application, the use of EPS geofoam in pavement insulation was restricted specifically to highlands and mountainous areas where severe winters would demand the implementation of frost protection measures [9]. Later, EPS geofoam was adopted as a lightweight fill material in road construction following the findings of an investigation conducted by the Norwegian Public Roads Authority [10]. Their research highlighted the ability of expanded polystyrene to withstand the repetitive stresses that are typically induced by a road structure, and, as a result, recommended it for use as a lightweight fill material. In line with these findings, the Norwegian Public Roads Authority adopted this material as a lightweight fill in 1972 during the construction of a road embankment in Norway (the Flom Bridge) [11]. It was a landmark project where EPS geofoam was used to successfully eliminate the unacceptable settlement of the road structure, which was constructed atop low bearing capacity subgrade soils.

Later, EPS geofoam were utilized successfully all around the world in geotechnical applications, in countries such as Norway, the Netherlands, the US, Malaysia and Japan [12]. Interestingly, the use of EPS geofoam has become widespread in Japan, where it initially was introduced as a lightweight fill material in 1985 [13], only for it to account for half the total geofoam use worldwide by 1995 [7]. Other types of materials such as foamed recycled glass and recycled plastic granules have also been recommended as lightweight road construction materials [43,44].

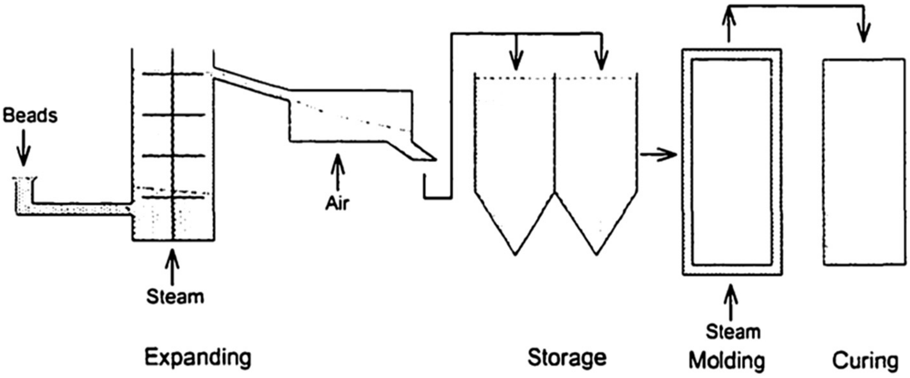

**Fig. 1.** EPS geofoam manufacturing process [12].

**Table 2**
EPS geofoam densities [20].

| ASTM C 578 Type | Density kg/m$^3$ | ASTM D 6817 Type |
|---|---|---|
| I | 15 | EPS15 |
| II | 22 | EPS22 |
| VIII | 18 | EPS19 |
| IX | 29 | EPS29 |
| XI | 12 | EPS12 |

**Table 3**
Nominal densities of rigid cellular polystyrene – moulded (RC/PS-M) [21].

| Class | Nominal Density kg/m$^3$ |
|---|---|
| L | 11 |
| SL | 13.5 |
| SL | 16 |
| M | 19 |
| H | 24 |
| VH | 28 |

## 2. Material properties

### 2.1. Manufacture of EPS geofoam

The manufacture of expanded polystyrene involves two processes, pre-expansion, and moulding. The pre-expansion process involves the placement of polystyrene beads into a container that is then heated by steam at a temperature between 80 °C and 110 °C. The original polystyrene beads expand into spheres commonly referred to as 'pre-puff', which are approximately 50 times larger than the original polystyrene beads. These new spheres are then used for the second stage of EPS geofoam manufacture (moulding). Before proceeding, the pre-puff is cooled so that it can stabilise in a process that usually takes several hours. Afterwards, the pre-puff is placed into a mould that is heated by steam so that the pre-puff may soften and expand further. Later the EPS blocks are released from the mould and are left for several days to 'season'. The seasoning must be completed to allow for the outgassing of the blowing agent used in the manufacture, and to allow for the swelling and the dimensional changes that are associated with the cooling process to complete [1]. The entire process is depicted in Fig. 1 [7].

Two processes that are executed after block manufacture are cutting and trimming, which are done at the factory prior to transportation. Trimming involves the slicing of thin pieces of material off one or more faces of the EPS geofoam blocks to ensure that they meet particular dimensional tolerances; the EPS geofoam blocks should not exceed a ±0.5 tolerance in terms of flatness, squareness, length, width, or thickness [14]. This process is necessary since there are a number of problems associated with improper moulding. EPS blocks that are not moulded correctly can have distorted shapes that can pose significant issues if unattended. These distorted blocks will not experience full contact on their full-face areas when they are laid, which is an issue since calculations assume full contact between all horizontal block surfaces; the consequence being that the actual stresses will be underestimated, and that localised stress concentrations will arise. This can potentially lead to serviceability failure in the mode of excessive total and differential settlement [15]. Another issue from improper moulding is concavity. If it is excessive, water may pool on the EPS blocks, and may be absorbed by the blocks. This will result in an increase in the unit weight of the blocks inducing pressure that may cause settlement and pavement reconditioning [16]. Cutting, on the other hand, involves cutting a full length of EPS block in two or more portions. This is done so that blocks can meet the size requirement to be laid in a particular layout arrangement. Cutting has become increasingly more common nowadays (as recent as the 90s) as moulds have increased in length relative to older moulds [15].

### 2.2. Density

Expanded polystyrene is a material with a very low density. It has a density that is as little as 1/100th of conventional fill materials (see Table 1), making it an excellent fill material [17]. Interest-

**Table 4**
Minimum compressive resistance requirements, and, in turn, flexural strength capacities of various EPS types as per ASTM D6817 [8].

| Physical Property | ASTM D 6817 Type | | | | | |
|---|---|---|---|---|---|---|
| | EPS12 | EPS15 | EPS19 | EPS22 | EPS29 | EPS39 |
| Compressive Resistance at 1% Strain (kPa) | 15 | 25 | 40 | 50 | 75 | 103 |
| Compressive Resistance at 5% Strain (kPa) | 35 | 55 | 90 | 115 | 170 | 241 |
| Compressive Resistance at 10% Strain (kPa) | 40 | 70 | 110 | 135 | 200 | 276 |
| Flexural Strength (kPa) | 69 | 172 | 207 | 240 | 345 | 414 |

ingly, the engineering properties of expanded polystyrene are directly related to density. This includes compressive strength, Young's Modulus, and creep behaviour. As a result, it is important to use an EPS block that has a suitable density [18]. For this reason, EPS blocks of densities that range between 16 and 32 $kg/m^3$ are typically used in pavement construction, even though densities of 100 $kg/m^3$ can be achieved [7].

Expanded polystyrene is typically manufactured to standard densities, which vary from country to country, and according to the standards in place. Some of the typical densities available around the world are displayed in Tables 2 & 3 [16].

### 2.3. Compressive strength

Compression is the predominant mode of loading for EPS in geotechnical applications; therefore, the compressive strength is an incredibly important parameter [22]. Interestingly, the compressive strength of EPS is given by the compressive stress at a strain of 10%, as stipulated by the ATSM standards (see Table 4 for typical values). This is the case since expanded polystyrene does not fail in the typical rupture fashion when placed under compressive load; rather it crushes one-dimensionally into solid polystyrene [4]. Horvath also confirms that the compressive strength of EPS provides no insight into creep behaviour. Consequently, he suggests that designers should design within the elastic range of EPS so as to keep the long-term compressive strain within an acceptable range. This is defined at the 1% compressive strain in a rapid loading test. In this range, creep effects are negligible [23].

### 2.4. Young's Modulus and Poisson's ratio

The Young's Modulus of expanded polystyrene is related to the density of the block used, much like the compressive strength and creep behaviour. Currently, it is calculated determined by uniaxial compression tests on 50 mm samples according to ASTM D 1621, EN 826, and ISO 844 [20]. However, currently, there is little agreement amongst researchers in respect of the values for the Young's Modulus for EPS blocks of varying densities. This may be due to the lack of a standard test procedure [12].

Poisson's ratio relates the lateral and longitudinal strains experienced by a material when subjected to a vertical load. It is a function of density; increasing linearly with the density of the block when stress-strain behaviour is linear, but decreasing rapidly for greater strains [16]. For EPS geofoam, when behaviour is in the elastic range, Poisson's ratio is approximately equal to 0.12 [8].

Research conducted in Japan by EDO-EPS has provided an equation that can be used to calculate Poisson's ratio [23]. It can be seen below in Eq. (1):

$$\nu = 0.0056\rho + 0.0024 \tag{1}$$

where
$\nu$ = Poisson's ratio of EPS
$\rho$ = Density of EPS ($kg/m^3$)

### 2.5. Shear strength

The shear strength of expanded polystyrene can be broken into two different types; these are the internal and external shear strengths. The former relates to the sliding resistance of an EPS block, whilst the latter, the external shear strength, relates to the sliding resistance at the interface between the EPS blocks, and also the sliding resistance at the interface between the EPS blocks and other materials [16].

Through investigations conducted by BASF, it was discovered that there is a direct relationship between the internal shear strength and density. A greater density EPS block will have increased shear strength. Also, the internal shear strength of an EPS geofoam specimen can be determined by the rapid loading of the specimen. In this rapid loading test, the specimen is loaded until the maximum shear stress is reached [22].

The first sub-category of external shear strength, which is the shear strength at the EPS/EPS interface, can be calculated with the following modified Mohr-Coulomb equation, as shown in Eq. (2) [22]. From the equation, it can be observed that the shear strength at this interface is dependent on the stress generated by the weight of the EPS blocks and the pavement system. Also, it is important to note that when excessive horizontal loading is anticipated, it may be necessary to install mechanical connectors to ensure that the blocks do not shift laterally [24].

$$\tau_e = \sigma_n \tan(\varphi) \tag{2}$$

where
$\tau_e$ = external shear resistance at the EPS/EPS interface (kPa)
$\sigma_n$ = normal stress at the EPS/EPS interface (kPa)
$\varphi$ = EPS/EPS interface friction angle (degrees)

It is recommended that the designer uses the ASTM D5321 test procedure for the determination of friction angle [22]. The friction angle can typically range from between 27° and 32° [23].

The second sub-category of external shear strength, the shear strength at the interface between the EPS geofoam and other materials, can also be calculated using the modified Mohr-Coulomb theory equation provided earlier in Eq. (2). The only difference is the frictional angle that is used. This is the case since the frictional angle varies for different materials. However, it is acceptable for the designer to assume 30° for the frictional angle for a geofoam/sand interface [25]. Furthermore, it has been determined that the interface angle is 55° for an EPS/geomembrane interface, and 25° for an EPS/geotextile interface [22].

### 2.6. Creep and durability

The continual load applied to the EPS geofoam blocks in the pavement structure, post construction, is the source of creep behaviour and is of primary concern to the designer. This continual load, which comes from the dead load of the pavement structure, causes the closing of the gaps between the EPS geofoam blocks, potentially resulting in the beginning of the time-dependent creep of the pavement structure. Interestingly, the severity of this creep is directly related to the magnitude of the continuously applied load [20]. Furthermore, it has been observed that once the long-term continuous loading exceeds the 2% compressive strain limit, creep deformation behaviour will be induced. To avoid this, the designer should make the design according to the linear portion of the compressive stress/compressive strain curve [26].

**Table 5**
Chemical resistance of EPS geofoam [8].

| EPS is resistant to: | Chemicals that may damage EPS: |
|---|---|
| Alkalis | Hydrocarbons |
| Dilute inorganic acids | Chlorinated hydrocarbons |
| Gypsum plaster | Organic solvents |
| Most alcohols | Ketones |
| Portland cement | Ethers |
| Silicone oil | Esters |
| Solvent-free bitumen | Diesel and gasoline |
| | Concentrated acids |
| | Vegetable oils |
| | Paraffin |
| | Animal fats and oils |

The durability of expanded polystyrene has already been well established. Tests performed on Norway on samples exhumed from historic EPS geofoam projects (up to 24 years old) showed no signs of material deterioration. The compressive strength tests conducted on these samples showed that there was no overall reduction in compressive strength, and that the recorded creep measurements were deemed minor. The study also suggested that the 100-year lifetime of EPS blocks in civil engineering applications would hold true provided that buoyancy forces are accounted for, the EPS blocks are protected from agents that can dissolve them (protected from petrol/diesel fuels, etc.), and that the applied dead loads are not greater than 30–50% of the material's strength [27]. The only deterioration that was observed was from the absorption of water over the long-term; an occurrence that is undesirable since water absorption leads to decreased thermal efficiency and increased stiffness of the EPS geofoam [23].

It is important to note that prolonged exposure to UV radiation can affect the durability of EPS geofoam product. If in the presence of UV light for a period of several months, or up to several years, the EPS blocks will discolour and become chalky and brittle. This can easily be overcome by reducing the exposure of the material to UV radiation to a period no greater than a month, or by covering the EPS if prolonged exposure is anticipated [7].

One problem that has been associated with the use of EPS geofoam products is the issue of insects tunnelling through buried EPS blocks. Some burrowing insects have been observed to tunnel through the EPS blocks despite the foam having no nutritional value [7]. However, the issue has not been deemed significant, as there has been no known instance of infestation. Consequently, the ASTM D6817 standards and the NCHRP guidelines do not stipulate the use of an insecticide. Ultimately, the decision to use an insecticide is in the hands of the designer [28].

### 2.7. Thermal resistance, chemical resistance, and moisture absorption

Expanded Polystyrene consists of only 2% polystyrene, the other 98% being air. Since the entrapped air is a poor thermal conductor, expanded polystyrene is an excellent insulation material. Its R-value, which is a measure of the thermal resistivity of a material, is within the range of 0.5–0.8 cubic-metre degree Celsius per Watt ($m^3$ °C/W). This is several times greater than the R-value of soil, which is typically only a meagre 0.1 $m^3$ °C/W. In addition, it has also been reported that the R-value of expanded polystyrene increases with density, reaching a maximum at a density of 35 $kg/m^3$ [12], and that the thermal resistance decreases with water absorption [29].

A number of chemicals can dissolve EPS geofoam, and for pavement construction applications, fuels from motor vehicles are the principle concern. Fuels, such as diesel and petrol, can dissolve the EPS blocks when spills occur. However, this issue can easily be overcome by placing a geomembrane, or other suitable material over the EPS for protection [1]. The chemicals that EPS blocks are, and are not resistant to, are listed below in Table 5.

Expanded polystyrene can absorb some water despite its closed cell structure, which is attributable to many different factors. These factors include the thickness of the EPS geofoam, the density of the EPS geofoam, the phase of the water (liquid/vapour), the presence of water only in the vapour phase, the presence of water only in the liquid phase, and, finally, time [1].

### 2.8. Environmental considerations

Expanded Polystyrene has become more popular than other foams of similar engineering properties for a number of reasons. These reasons include the fact that the manufacture of EPS geofoam has not been linked to the depletion of the earth's ozone since its manufacture does not involve the use of CFC, HCFC, or similar blowing agents, and, unlike other foams, the manufacture of EPS does not result in the release of formaldehyde, an environmentally unfriendly gas [1]. Furthermore, expanded polystyrene is considered to be non-harmful. Consequently, it has been adopted as a material for the manufacture of eating utensils, food containers, and beverage cups [7].

## 3. Design considerations

This section addresses the considerations that the designer must appreciate when designing pavement structures with EPS. This section also discusses some of the important geotechnical parameters that must be calculated for the design of pavements using EPS. For a more detailed design procedure, the designer should see the NCHRP Report 529.

### 3.1. Flexural strength and bearing capacity

The flexural strengths and compressive strains of the various EPS products available in the US are given in the table below in Table 6. These values come from ASTM D6817 code and do not require calculation.

The bearing capacity of the EPS geofoam is an important parameter that must be calculated when designing pavement structures, as the EPS geofoam can fail in bearing, potentially causing excessive vertical settlements in the pavement system, and even damage to adjacent properties. The ultimate bearing capacity of EPS can be calculated using Eq. (3), which is presented below:

$$q_{ult} = cN_c + \gamma D_f N_q + \gamma B_W N_\gamma \tag{3}$$

where

$c$ = Mohr-Coulomb shear strength parameter termed cohesion, $kN/m^2$,
$N_c$, $N_\gamma$, $N_q$ = Terzaghi's bearing capacity factors,
$\gamma$ = Unit weight of soil, $kN/m^3$,
$B_W$ = Bottom width of embankment, m, and
$D_f$ = Depth of embedment, m

Eq. (3) can be further simplified into Eq. (4). This is possible as the EPS geofoam blocks are generally placed atop soft saturated cohesive soils. This means that, the internal the cohesion (c) can be equated to the undrained shear strength ($s_u$). Also, this simplification is possible when the length of an embankment is assumed

**Table 6**
ASTM D6817 physical property requirements of EPS geofoam [7].

| Physical Property | ASTM D6817 Type | | | | | |
|---|---|---|---|---|---|---|
| | EPS12 | EPS15 | EPS19 | EPS22 | EPS29 | EPS39 |
| Compressive Resistance at 1% Strain (kPa) | 15 | 25 | 40 | 50 | 75 | 103 |
| Compressive Resistance at 5% Strain (kPa) | 35 | 55 | 90 | 115 | 170 | 241 |
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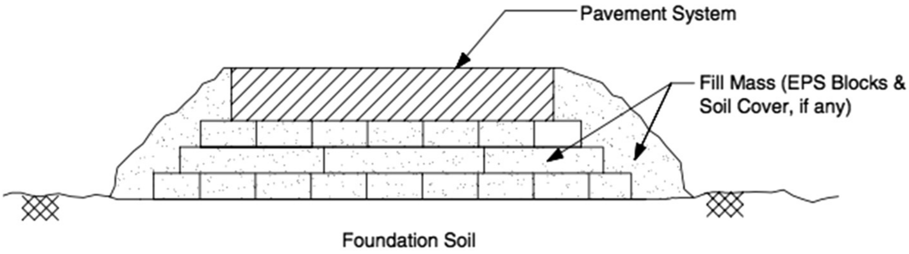

**Fig. 2.** Major components of an EPS block embankment [22].

to be significantly larger than the width of the embankment. This particular assumption makes further transpositions possible, such that Eq. (4) can be derived.

$$q_{ult} = s_u N_c \tag{4}$$

where

$N_c$ = Terzaghi's bearing capacity factors
$N_c = 5\ (1 + 0.2B_w/L)$
$q_{ult}$ = Ultimate bearing capacity of the soil (kPa)
$s_u$ = Undrained shear strength (kPa)

Eq. (4) can be further simplified if the EPS embankment is regarded as a continuous footing. This would mean the $B_w/L$ ratio would equal 0. Ultimately, we will be left with Eq. (5), which is presented below:

$$q_{ult} = s_u \times 5 \tag{5}$$

### 3.2. Buoyancy and seismic loading

The potential effects of groundwater on the EPS blocks must be considered during design, since EPS geofoam is extremely lightweight and has a closed cell structure, making it susceptible to buoyancy when in the presence of water. Interestingly, this buoyancy is not reduced significantly by the absorption of water by the EPS blocks over time. To counter this issue, sufficient dead load stresses must be applied on the EPS blocks to counteract the potential uplift forces [30].

Seismic loading must be considered during the design of pavement systems to avoid geotechnical problems, such as seismic settling and seismic liquefaction. This is of significance since seismic loadings can affect both the internal and external stability of road embankments. Interestingly, the considerations made for seismic loading during the design of EPS embankments, are much the same as the considerations made for seismic loadings induced on embankments constructed from other earth materials. It has also been discovered that the risk of seismic loading depends on the site, and the nature and the thickness of the natural soil atop the bedrock, rather than the material in use (EPS geofoam) [22].

### 3.3. Settlement

Settlement is another important factor that must be considered during the design of pavement structures using EPS geofoam. The settlement that occurs as a result of immediate settlement, primary consolidation of the fill material, secondary consolidation of the fill material, and the long-term creep of the fill material, must be accounted for during design. Generally, settlement that occurs as a result of the lateral deformation of subgrade soils at the edge of an embankment is typically not considered, because, provided the factor of safety for external instability is greater than 1.4, it is negligible in comparison to the other previously mentioned modes of settlement. Lateral creep deformation, however, needs to be accounted for during design if the embankment is to be constructed atop underground utilities [22].

### 3.4. Pavement composition considerations

An EPS geofoam embankment consists primarily of three components that can be observed in Fig. 2. These include the foundation soil, proposed fill mass, and the pavement system. The foundation soil is placed prior to the fill mass, and can be subject to ground improvement techniques. The proposed fill mass consists of EPS blocks, and, sometimes, it also consists of a layer of soil cover that sits between the bottom of the EPS blocks and the foundation soil. This soil may also be placed at the sides of the embankment depending on whether the embankment is trapezoidal or vertical. Finally, the pavement system is constructed atop the EPS mass [22].

A Load Distribution Slab can be constructed as part of the subgrade to reduce the stresses induced by vehicles to acceptable levels, or to reduce the thickness of the embankment, and, consequently, the cost of the pavement structure. It is typically used in the construction of high-volume traffic highways, and the construction of highways typically trafficked by heavy vehicles. Its use is dictated by certain factors; these include cost, which typically accounts for 20–30% of the project cost; the risks associated with sliding during seismic events; the ponding of water on the slab inside the pavement system; and the increased risk of differential icing and solar heating [17].

There are several recommendations that should be followed during the design of a pavement with regards to its composition [22]. Firstly, a minimum of two layers of EPS blocks should be provided so that blocks do not move during service, a scenario in which the pavement could fail, and, secondly, the overall minimum depth of the EPS fill mass should be 1.2 m so that the risk of differential icing is minimized.

## 4. Design applications

Expanded polystyrene is suitable for a number of different applications in pavement construction. These applications include the use of EPS for lightweight fill, vibration dampening, thermal insulation, and even for underground service protection. The relevant properties that allow EPS geofoam to be utilized in each of these applications are the primary focus here.

### 4.1. Lightweight fill design

When designing infrastructure on low bearing capacity subgrade soils, engineers have to utilise innovative materials and construction techniques to ensure that these low bearing capacity soils are not overloaded. In these situations, engineers can take advantage of the ultra-lightweight character of EPS by using it in place of other heavier fill materials. This results in a reduction in the overall weight of the pavement structure, a reduction that can

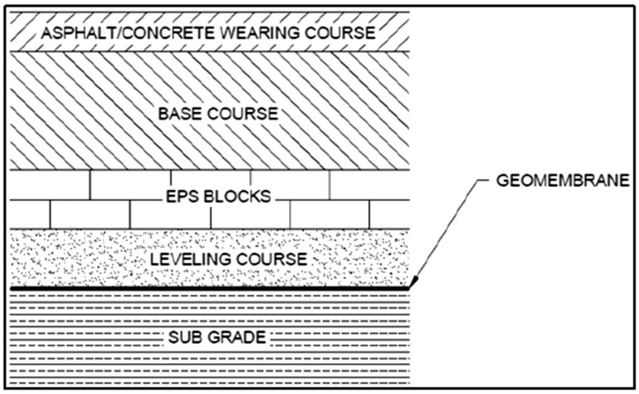

**Fig. 4.** EPS subgrade in pavement system [12].

serve as a major solution to the settlement issue association with pavement structures that are constructed in poor soil conditions [2,8].

The use of expanded polystyrene as a lightweight fill is not limited to pavement construction. It is also applicable for:

- Approach fill for bridge abutments
- Bridge underfill
- Slope stabilisation
- Construction of 'compensating foundation' on compressible soils
- Rail embankment construction, and other types of embankment construction
- Retaining or buried wall backfill

### *4.2. Noise/vibration dampening*

A considerable amount of research has been conducted on the application of expanded polystyrene in vibration dampening. Studies have focused on the vibration dampening ability of expanded polystyrene in filled trenches and wave barriers. Despite this research, expanded polystyrene has not been used practically in this application yet. More research must be done before practical applications can go ahead [31]. In addition, currently, there are no engineering design methods available for the design of EPS filled wave barriers despite a number of published studies [32].

Many investigations have verified the suitability of expanded polystyrene in vibration dampening. Itoh et al. [33] investigated the ability of EPS geofoam barriers in the reduction of ground wave vibration. They reported that materials with low impedance, like EPS geofoam, are very effective at reducing the amplitude of waves. In another study, completed by Murillo et al. [34], it was observed that the depth, the width, and the location of an EPS geofoam barrier had a significant influence on vibration attenuation. Alzawi and El Naggar [32] also investigated the vibration damping ability of an EPS geofoam in-filled barrier with respect to its location, geometry, and soil properties. They reported that the barriers performed better in stiff soils, and that deeper trenches are required for significant vibration dampening when the trench barrier is moved closer to the source of the vibration.

A recent study by Liyanapathirana et al. [31] investigated the suitability of EPS geofoam in-filled wave barriers for ground vibration dampening. The process involved placing a geofoam in-filled wave barrier between an existing pile and a new driven pile (source of vibration) so that the effect of EPS foam in vibration attenuation could be assessed.

The findings showed that:

- The depth, width, and length of the wave barrier are important factors that dictate the efficiency of the wave barrier in all the soils studied (Ariake Clay, Bangkok Clay, Singapore Marine Clay). It was found that changes in the length and depth would increase the dampening ability of the wave barrier, whilst changes in the width would either dampen or amplify the ground vibrations.
- When the wave barrier is closest to the driven pile, or the existing pile, the vibration dampening of the EPS wave barrier is at its lowest. It is highest when it is in the middle.
- The results clearly showed that when $E_{geofoam}/E_{soil}$ is less than 0.1, the attenuation ability of EPS increases significantly.
- There is a significant wave scattering effect between the geofoam barrier and the existing pile when the barrier is moved closer to the existing pile. Consequently, it was concluded that more research has to be done in respect of this wave scattering effect before EPS foam barriers are used in practice.

### *4.3. Protection to underground services*

Materials with a compressible inclusion can be used for a variety of applications; one of these applications is for the protection of underground pipes, culverts, and tunnels. This application takes advantage of the ability of expanded polystyrene to be significantly more compressible than the other materials it is in contact with. This allows the expanded polystyrene to deform more readily than the other components that lay beneath it [35], which means that any underlying services, typically in the form of pipes or culverts, will experience reduced vertical and horizontal loads. This application is not new and has been used in Norway since 1988 [36].

Currently, there are four methods in which EPS can be utilized to protect underground services from excessive loads. These methods include the construction of lightweight embankments, imperfect trenches, slot cover trench systems, and, finally, beam cover systems [37]. The last two methods are not discussed as they are currently still under research. Only the lightweight embankment

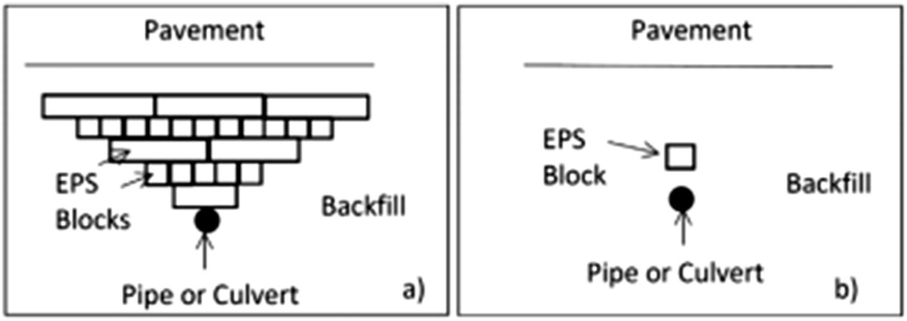

**Fig. 3.** a) Lightweight cover/embankment over pipe or culvert b) imperfect trench method [37].

and imperfect trench methods are discussed here; these two methods are depicted in Fig. 3.

The first method, the lightweight embankment system, is similar to the construction of EPS embankments. The principle difference here is that the EPS blocks are used to reduce the overall stresses that are acting on the underground services. This is done to protect pipes and culverts from potential damage that is usually caused by the stresses that are typically induced by vertical ground displacement, and by the various types of settlement. The other method, the imperfect trench method, involves the placement of an EPS block above the underground service [37]. In this application, the EPS geofoam block acts as compressible inclusion. It creates a positive arching over the pipeline/culvert, and, as a result, compresses, ultimately, mobilizing the shear strength in the soil to reduce the vertical earth pressure on the pipeline or culvert [36].

### 4.4. Thermal insulation

As mentioned earlier, the thermal insulation properties of expanded polystyrene were established long ago when EPS geofoam was first trialled in Germany (in the 1950s) as a pavement insulator. In this application, EPS geofoam blocks were used in place of conventional frost protection with great success [9]. It was observed that EPS geofoam was a suitable thermal insulator, and, consequently, was adopted for use for the thermal insulation of pavements in countries with severe winters and deeply penetrating ground frosts [26].

In these same cold climates, EPS can be used in pavement construction as insulation to end the issue of the seasonal freezing and thawing of soils. This involves the placement of a layer of EPS geofoam blocks in the pavement system as a subgrade, as depicted in Fig. 4, so that the temperature changes in the soil during the severe winters can be limited [17]. This is paramount since the soil can heave (swell upwards), potentially causing substantial damage to the pavement structures.

## 5. Limitations

There are a number of considerations that must be considered when designing with expanded polystyrene. The designer must appreciate the limitations of expanded polystyrene, and the potential pitfalls associated with its design and applications so that failure can be avoided. This section addresses these limitations and potential pitfalls and provides recommendations accordingly.

### 5.1. Inadequate design or improper construction practice

As a result of the lack of financial support for the ongoing research, education, and standard development for the use of expanded polystyrene in pavement construction, designers have been left in a situation where they have to proactively seek current and correct technical information. This is an unfortunate situation as the designer may receive incomplete or possibly inaccurate technical information. This can lead to inefficient or incorrect design, and, possibly, to the failure of the EPS geofoam in the project application. This has been the case in the US where there has been a trend of failures for some widely used EPS geofoam applications. Consequently, Horvath addressed this issue in one of his papers [38], in which he identified a number of reasons for this trend of EPS failures in the United States. They all relate to improper design and construction practices, including:

- Designs being completed according to incomplete or incorrect information. This can be as a result of a lack of a reliable standard. The implication of this is the potential for an EPS material of insufficient strength to be selected for the design.
- Damage caused to EPS blocks during construction. This can be through the modes of mishandling, incorrect storage, overstressing by construction equipment, and even flotation as a result of improper placement due to the action of air and water.
- Lack of oversight by a government or industry body. Many developed nations (e.g. Japan) with widespread EPS use have been almost failure free thanks to the oversight by government/industry bodies.

### 5.2. Flammability

As a material, expanded polystyrene is inherently flammable. It is still flammable even after the outgassing of the flammable blowing agent after the block moulding stage. This parameter, however, can be quantified using a parameter known as the oxygen index (OI), which can be defined as the minimum percentage of oxygen required for maintaining the combustion of an ignited material. EPS geofoam has an OI index of 18%, which is less than the 21% required to maintain combustion in atmospheric air, and as a result, is deemed a flammable material [15].

Despite this, it should be noted that properly aged EPS geofoam blocks are not inherently dangerous. There are no special precautions that are to be implemented during shipping, storage, or installation, aside from the typical protocols of storing and handling the material in a way that it is protected from heat and flames. Additionally, it is recommended that storage areas are designated non-smoking areas with proper signage [15].

However to address this issue, manufacturers have produced a flame retardant EPS geofoam product that has an OI of 24%. Although the material is no longer flammable, it can still melt at 150 °C [17]. Unsurprisingly the use of this fire-retardant EPS is not a universal practice, as designers may opt out of its use due to the increased cost of the material, and as a result of questions that have been raised concerning its environmental safety [15].

### 5.3. Differential icing

The difference in the thermal properties of a pavement system over EPS geofoam, and a pavement system over natural soil vary considerably, and, as a result, differential icing can occur. Differential icing is defined as the formation of ice on a section of pavement constructed on a non-earthen material whilst the pavement system above the natural earth material is ice-free [25]. This is an issue since there is an increased chance of car accidents, as drivers will not anticipate the icy conditions of an adjacent stretch when they are driving on an ice-free stretch of road.

However, over the years, a number of suggestions have been made to overcome these issues. These include the placing of a sufficient thickness of soil between the EPS mass and the top of the pavement, and the use of a sub-base material that has sufficient 'fines' and a high heat capacity. A material with fines is desired since they can retain water [17].

## 6. Construction considerations

### 6.1. Site preparation

Proper site preparation is paramount for the correct installation of EPS blocks. To ensure internal stability, and to avoid the onset of stress concentrations and the rocking of EPS blocks, the site should be as level as possible. This is essential since the laying of the EPS layers becomes increasingly more problematic with each subsequent layer when the site is not level [17]. Other site preparation procedures that should be adhered to include:

- Keeping the area upon which the EPS blocks are to be laid free from accumulated water or ice.
- Ensuring the site has sufficient drainage during construction to avoid the potential hydrostatic uplift of the EPS blocks as a result of heavy rainfall.
- Ensuring the sub-grade upon which the EPS blocks are to be laid is free from debris and vegetation.

### *6.2. Compaction*

There are a number of guidelines governing the compaction of the soil atop the EPS fill mass. Firstly, EPS geofoam should not be compacted or driven over by construction machinery. This is to avoid mechanical damage, which is unrepairable. Secondly, compaction of EPS geofoam can only begin when it is covered by at least 200 mm of acceptable fill material, or covered by a 200 mm capping layer. In addition to this, vibratory compaction equipment should not be used for compaction within 500 mm vertically, and 2 m laterally of the EPS fill mass [39].

### *6.3. Handling and UV protection*

Due care must be taken when transporting and handling EPS blocks as they can easily be damaged, and since any incurred damage is permanent. Damage can occur during transportation as a result of EPS blocks being tied down with straps on flatbed trailers. If sufficient protection is not provided where the straps make contact with the EPS, the EPS blocks can crush or be completely broken off at the corners due to the load applied. Damage can also come in the form of puncture holes in the EPS blocks as a result of the various instruments used to grip the blocks. These issues can be overcome by using strap protection, and by using friction grip devices to handle the blocks (or other lifting methods) [15].

As discussed earlier, expanded polystyrene becomes yellow, chalky, and brittle after prolonged exposure to UV radiation. Consequently, the construction contractor should keep the exposure of expanded polystyrene to UV ratio to a minimum. Exposure should not exceed a period greater than a month [28].

### *6.4. Layout and placement*

Expanded polystyrene blocks should be placed in a staggered arrangement, in layers that are perpendicular to each other. This will increase the strength of the pavement, as the sub-grade would be continuous, as opposed to being disjointed [39]. It is also important to use shear connectors as they prevent the possibility of the blocks sliding, which can lead to slope failure under seismic loading. Without shear connectors, the blocks can slide, thereby creating gaps between the blocks [3].

## 7. Quality assurance

Quality assurance, in the form of laboratory testing, must be completed to ensure that the quality of EPS blocks used in the intended geo-technical application is acceptable. These procedures must be undertaken irrespective of the size of the EPS geofoam project. The quality assurance procedure typically involves the testing samples of production EPS geofoam to measure their geotechnical parameters [15].

### *7.1. Record keeping*

All the EPS geofoam blocks that are delivered to the site should have self-adhesive labels or barcode labels. These labels should detail the manufacturing history and the supplier's information so that it can be traced back if necessary. It is also important that the parameters that pertain to the construction are detailed; these include parameters, such as density, the mass of the block, and the dimensions of the block, etc. Other information that should be displayed includes the name of the supplier, the date of manufacture, and the period of seasoning [17].

### *7.2. Testing and sampling*

The location of the sample within the EPS block to be tested is the most important aspect of the sampling process. The means of extracting the sample (hot-wires or handsaw, etc.) is not significant as long as the sample is somewhat larger than the intended dimensions for the final specimen. The sampling location is of particular importance since the EPS blocks are not uniform in density after moulding, and since the mechanical properties tend to vary throughout the block. Consequently, a proper sampling procedure must be adhered to so that the weakest sections of the EPS block are sampled and ultimately tested.

Fig. 5 shows the standard locations of the test specimens; these are the possible locations from which the weakest sample of EPS geofoam can be obtained. This practice has been used for decades, and, consequently, has been enlisted into some standards. The samples are later trimmed according to the intended test specimen dimensions, ideally by using a jig and hot wire cutters. Finally, the test specimens are subjected to force displacement, uniaxial compression, and flexure tests to determine the relevant geotechnical parameters needed for design [15].

## 8. Case studies

### *8.1. Flom bridge embankment reconstruction, Oslo, Norway*

Major research conducted in Norway concluded that EPS geofoam could sustain the repetitive stresses typically induced by a pavement structure. Following these findings, the Norwegian

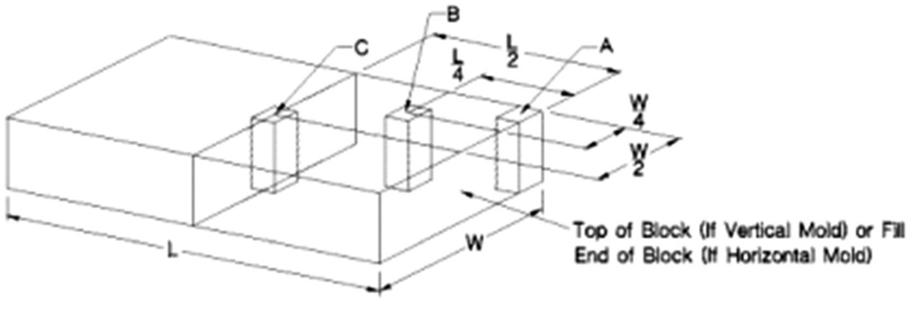

**Fig. 5.** Recommended locations for sampling of EPS blocks for testing [15].

**Fig. 6.** EPS geofoam blocks being used as lightweight fill [27].

Public Roads Authority adopted EPS geofoam as a lightweight fill material in the construction of embankments in 1972. This first took place during the reconstruction of the Flom Bridge embankment, a bridge embankment that, on average, experienced 200 mm of settlement a year prior to its reconstruction. In this project, the settlement was effectively halted when EPS geofoam was used in place of other traditional fill materials [10,27] (Fig. 6).

The tests conducted on 24-year-old EPS geofoam blocks that were exhumed from the Flom Bridge project showed no material deterioration effects. These results were a part of a long-term monitoring plan investigating the long-term performance of EPS geofoam blocks in embankment construction in Norway. The investigation was carried out to observe if any changes to the material properties of the EPS blocks would occur over time. This was done through the testing of the strength, density, and water absorption of the exhumed EPS blocks, and, finally, through the investigation of any creep effects [27].

### 8.2. Interstate 15 reconstruction, Salt Lake City, USA

In 1997, the Utah Department of Transportation undertook a $1.5 billion project for the reconstruction of the Interstate I-15. The project involved the widening of the embankments of a narrow 27-kilometre corridor. The reconstruction of this highway was undertaken in May 1997 and was completed in July 2001, in time for the Winter Olympic Games of 2002 [40].

EPS geofoam was utilised in two different applications for pavement construction in this project. Firstly, it was used as a lightweight fill material, and, secondly, for underground utility protection. Since extensive sections of the highway were constructed atop compressible clays, and clayey silts, which could be found in thicknesses of up to 25 m, EPS geofoam blocks were used as a lightweight fill. Also, these compressible soils would typically begin to consolidate on the virgin compression load when only 2-3 m of an embankment is constructed atop it; a phenomenon that would not be triggered by a super lightweight material like EPS geofoam, hence its use. Also, underground utilities, such as high-pressure gas lines, water mains, and communication pipes, traversed many areas of ramped embankments. To protect these underground services from settlement, EPS geofoam was used to reduce the loads applied on these services [40].

The long-term testing completed on this project reinforced the suitability of EPS geofoam in pavement construction. The observed long-term creep effects and settlement effects were minor. Only a 15 mm settlement affected the pavement structure, and a total creep deformation of 0.2–0.4% was observed 10 years post-construction (on the 3300 South Street site). Furthermore, it was concluded that creep behaviour in the 50-year period would be within the maximum expected values [41].

### 8.3. Matlingeweg Street reconstruction, Rotterdam, The Netherlands

The Matlingeweg Street reconstruction is a notable project, a project that was studied in detail by Duśkov [42]. The construction of this roadway involved the construction of two sections of road, one section of road with only one layer of (500 mm thick) EPS blocks, and the other section of road with two layers of EPS blocks. This was done in an attempt to reduce the stresses applied on the poor bearing capacity subgrade soils beneath the EPS blocks. After only one month of service, significant cracks were observed, large enough that the road system was regarded as having failed. Interestingly it was observed that the cracking had only occurred in the section of placement constructed upon a single layer of EPS geofoam.

A forensic study investigated the cause of failure for the Matlingeweg Street reconstruction project. The study showed that the EPS blocks had shifted vertically as much as 5 mm, and shifted horizontally as much as 20 mm, causing significant gaps between the EPS blocks. Ultimately, it was concluded that the cause of this movement was a result of poor block contact during construction. As a result, Horvath [30] suggested the use of at least two layers of EPS blocks in lightweight fill applications, especially for fills that would be subjected to dynamic and seismic loading (i.e. by traffic loading). Horvath made this recommendation since the ability of an assembly of EPS blocks to act as a mass depends on the block inter-locking from the layout of the blocks, and from the inter-block sliding friction. To achieve this behaviour, it is essential that two layers of EPS blocks be used, with special consideration given to the layout of the blocks [30].

## 9. Conclusion

Expanded polystyrene appears to be a versatile material that can be used in a myriad of geotechnical engineering applications, particularly in pavement construction. This is possible due to the interesting mechanical properties of EPS geofoam. Most notably, its lightweight character, which allows it to be an excellent fill material, its low thermal conductivity, which makes it a suitable pavement insulator in cold climates, its compressibility, which facilitates its application in the protection of underground services, and finally, its vibration dampening qualities that makes it a potential vibration dampener.

For the application of the EPS geofoam in pavement construction, there are a number of areas for improvement, and for potential research. They mostly pertain to the improvement of current applications and the development of new applications for the material in pavement construction, and the preparation of resources to aid designers in their design process. This is essential to further proliferating the use of this material in pavement construction, to developing more innovative solutions to some major pavement construction issues, and towards ensuring that designers are confident and capable of preparing safe designs. These areas of improvement have been summarised below.

- Research on the new experimental methods for EPS geofoam in underground service protection.
    - Four methods have been developed so far, two of which are currently in use, and the other two that are still under research.
- Research on the vibration dampening ability of EPS.
    - The vibration dampening ability of EPS geofoam has not been studied sufficiently. Also, no standards or guidelines have been developed for the design of vibration dampening EPS-in filled trenches.
- Research on new potential applications for EPS.
- The development of updated guidelines and other design materials.
    - This is important to ensure that the designer has adequate information. This will minimise the risk of improper or incorrect design of EPS geofoam in the different project applications.
- Development of updated standards and test procedures.
- Research into the repair of damaged EPS.
    - Any damage inflicted on EPS geofoam is permanent. Research into the repair of damaged EPS blocks should be considered.

## References

[1] J.S. Horvath, Expanded polystyrene (EPS) geofoam: an introduction to material behavior, Geotext. Geomembr. 13 (4) (1994) 263–280.

[2] X. Huang, D. Negussey, EPS Geofoam Design Parameters for Pavement Structures, Geo-Frontiers 2011: Advances in Geotechnical Engineering, 2011, pp. 4544–4554.

[3] J.C. Barrett, A.J. Valsangkar, Effectiveness of connectors in geofoam block construction, Geotext. Geomembr. 27 (3) (2009) 211–216.

[4] J.S. Horvath, Geofoam and geocomb: lessons from the second millennium AD as insight for the future. Paper presented at the Proc., 13th GRI Conf., 1999.

[5] R.M. Koerner, Designing with Geosynthetics, Prentice Hall, Upper Saddle River, New Jersey, 1998.

[6] L.-K. Lin, L.-H. Chen, R.H. Chen, Evaluation of geofoam as a geotechnical construction material, J. Mater. Civ. Eng. 22 (2) (2010) 160–170.

[7] T. Stark, D. Arellano, J. Horvath, D. Leshchinsky, Geofoam applications in the design and construction of highway embankments, 2004, Retrieved from.

[8] T. Stark, S.F. Bartlett, D. Arellano, Expanded Polystyrene (EPS) Geofoam Applications & Technical Data, EPS Industry Alliance, Crofton, 2012.

[9] G. Beinbrech, R. Hillmann, EPS in road construction—current situation in Germany, Geotext. Geomembr. 15 (1) (1997) 39–57.

[10] T.E. Frydenlund, R. Aaboe, Long term performance and durability of EPS as a lightweight filling material. Paper presented at the 3ª Conference International EPS Geofoam 2001, 2001.

[11] S. Alfheim, K. Flåte, G. Refsdal, N. Rygg, K. Aarhus, The first EPS geoblock road embankment–1972. Fra EPS konferansen: "th International Conference on Geofoam Blocks in Construction Applications", Lillestrøm. til, 6, 2011.

[12] A.F. Elragi, Selected engineering properties and applications of EPS geofoam, 2000.

[13] G. Miki, EPS construction method in Japan. Paper presented at the Proceedings of International Symposium on EPS (Expanded Poly-Styrol) Construction Method (EPS Tokyo'96), 1996.

[14] ASTM International (2011), Standard Specification for Rigid Cellular Polystyrene Geofoam. ASTM D6817-11. West Conshohocken, PA, 2011.

[15] J.S. Horvath, Manufacturing quality issues for block-molded expanded polystyrene geofoam. Research Rep. No. CEEN/GE-2011, 2, 2011.

[16] E.L. Santiago, An investigation of expanded polystyrene geofoam mechanical properties. Universidad Politecnica Puerto Rico (Puerto Rico), 2014.

[17] D. Arellano, Guidelines for the Use of Expanded Polystyrene (EPS)-Block Geofoam for the Function of Lightweight Fill in Road Embankment Projects. University of Illinois at Urbana-Champaign, 2005.

[18] A.W. Stuedlein, Instrumentation, Performance, and Numerical Modeling of Large Geofoam Embankment Structures, 2003

[19] V. Elias, J. Welsh, J. Warren, R. Lukas, Ground Improvement Technical Summaries. U.S. Department of Transportation Federal Highway Administration, vol. 1, 2-2, Washington DC, 1999.

[20] X. Huang, Evaluation of EPS geofoam as subbase/subgrade material in pavement structures. Syracuse University, 2006.

[21] Standards Australia 1992, Rigid cellular plastics sheets for thermal insulation – Part 3: Rigid Cellular Polystyrene – Moulded (RC/PS-M), AS 1366.3-1992. Available from: Australian Standards. [Accessed 23 May 2017].

[22] T. Stark, D. Arellano, J. Horvath, D. Leshchinsky, Guideline and Recommended Standard for Geofoam Applications in Highway Embankments, Transportation Research Board, 2004.

[23] J.S. Horvath, Geofoam geosynthetic: past present future, Electron. J. Eng. 1 (1995).

[24] A. Corporation, GeoGripper Plate. American Foam Manufacturers, 2011.

[25] J.S. Horvath, Geomaterials research project-geofoam and geocomb geosynthetics: a bibliography through the second millennium AD. Res. Rpt. No. CGT-2001, 1, 2001.

[26] B. Plastics, Styropor – Highway Construction/Ground Insulation: Rigid Styropor Foam as a Lightweight Construction BASF Material for Highway Foundations, BASF, Ludwigshafen, Germany, 1998.

[27] R. Aabøe, T. Frydenlund, 40 years of experience with the use of EPS geofoam blocks in road construction. Paper presented at the 4 Conference EPS 2011 Norway, 2011.

[28] R.M. Koerner, Designing with Geosynthetics (Vol. 1), Xlibris Corporation, 2012.

[29] D. Negussey, Properties and Applications of Geofoam. Society of the Plastic Industry, 1997.

[30] J.S. Horvath, Lessons learned from failures involving geofoam in roads and embankments. Research Rep. No. CE/GE-99, 1, 1999.

[31] D. Liyanapathirana, S.D. Ekanayake, Application of EPS geofoam in attenuating ground vibrations during vibratory pile driving, Geotext. Geomembr. 44 (1) (2015) 59–69.

[32] A.M.A. Alzawi, H. El Naggar, Vibration isolation using in-filled geofoam trench barriers. The University of Western Ontario, 2011.

[33] K. Itoh, X. Zeng, M. Koda, O. Murata, O. Kusakabe, Centrifuge simulation of wave propagation due to vertical vibration on shallow foundations and vibration attenuation countermeasures, J. Vib. Control 11 (6) (2005) 781–800.

[34] C. Murillo, L. Thorel, B. Caicedo, Ground vibration isolation with geofoam barriers: Centrifuge modeling, Geotext. Geomembr. 27 (6) (2009) 423–434.

[35] J.S. Horvath, The compressible inclusion function of EPS geofoam, Geotext. Geomembr. 15 (1–3) (1997) 77–120.

[36] J. Vaslestad, M.S. Sayd, T.H. Johansen, L. Wiman, Load reduction and arching on buried rigid culverts using EPS Geofoam. Design method and instrumented field tests, 2011.

[37] S.F. Bartlett, B.N. Lingwall, J. Vaslestad, Methods of protecting buried pipelines and culverts in transportation infrastructure using EPS geofoam, Geotext. Geomembr. 43 (5) (2015) 450–461.

[38] J.S. Horvath, Emerging trends in failures involving EPS-block geofoam fills, J. Perform. Constr. Facil. 24 (4) (2010) 365–372.

[39] D. Thompsett, A. Walker, R. Radley, B. Grieveson, Design and construction of expanded polystyrene embankments: practical design methods as used in the United Kingdom, Constr. Build. Mater. 9 (6) (1995) 403–411.

[40] S. Bartlett, D. Negussey, M. Kimble, M. Sheeley, Use of geofoam as super-lightweight fill for I-15 reconstruction. Paper presented at the Transportation Research Board 79th Annual Meeting, Washington, DC, 2000.

[41] S. Bartlett, D. Negussey, C. Farnsworth, A. Stuedlein, Construction and Long-Term Performance of Transportation Infrastructure Constructed Using EPS Geofoam on Soft Soil Sites in Salt Lake Valley, Utah. Paper presented at the 4th International Conference on the use of EPS Geofoam Blocks in Construction Applications, 2011.

[42] M. Duškov, Measurements on a flexible pavement structure with an EPS geofoam sub-base, Geotext. Geomembr. 15 (1–3) (1997) 5–27.

[43] A. Arulrajah, E. Zaghoubi, Y.C. Wong, S. Horpibulsuk, Recycled plastic granules and demolition wastes as construction materials: resilient moduli and strength characteristics, Constr. Build. Mater. 147 (2017) 639–647.

[44] A. Arulrajah, M.M. Disfani, F. Maghoolpilehrood, S. Horpibulsuk, A. Udonchai, M. Imteaz, Y.J. Du, Engineering and environmental properties of foamed recycled glass as a lightweight engineering material, J. Cleaner Prod. 94 (2015) 369–375.