The use of polystyrene for embankment construction

by R L Sanders and R L Seedhouse
(Babtie Shaw & Morton Ltd)
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THE USE OF POLYSTYRENE FOR EMBANKMENT CONSTRUCTION

by R L Sanders and R L Seedhouse
(Babtie Shaw & Morton Ltd)

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EXECUTIVE SUMMARY

The report provides design and construction guidelines on the use of polystyrene as an earthwork fill. The introduction reviews the history of the use of polystyrene as a fill material and describes its potential applications and benefits. Examples of situations in which the use of polystyrene fill may be beneficial include:

- Areas of very weak or compressible soils;
- Areas of unstable ground, such as relic landslides, and landslide repairs;
- Restricted sites requiring the use of retained embankments;
- Sites with difficult or restricted access for plant and vehicles (polystyrene may be moved and placed by hand);
- Construction over or adjacent to existing structures, services or embankments that may be adversely affected by increased loading or ground movements;
- Transition zones between bridges and normal fill embankments.

The manufacturing process is outlined and detailed information is given on the properties, and methods of testing, of the various grades of polystyrene available. Recommendations on design criteria and principles are presented. Particular attention is given to the methods available to provide protection against potential hazards. Polystyrene fill materials are vulnerable to solution by a range of chemicals, primarily petroleum products and organic solvents. The use of polyethylene membranes is recommended to provide the primary protection against hydrocarbons and organic solvents which may attack polystyrene. It is also a combustible material and must be protected from sources of ignition by a cover of non-combustible material, such as inert earth fill or concrete. Guidance on detailing of polystyrene fill for the preparation of construction drawings is given. Draft specification clauses are included for the polystyrene fill and for the protective sheeting recommended for use within the report. The report concludes by providing advice on the construction of polystyrene fills.
1. INTRODUCTION
Experience in several countries has indicated that expanded and extruded polystyrene may be used successfully as lightweight fill in highway embankments in situations where conventional construction would be impractical or uneconomic.

This report reviews current practice in the use of polystyrene as fill material, and the properties of the currently available materials. The report presents recommendations for the design, specification and construction of embankments incorporating polystyrene fill material.

2. APPLICATIONS OF POLYSTYRENE FILL
2.1 History of Development
The use of polystyrene in road construction commenced in 1965 in Norway, when trials commenced with the use of expanded and extruded polystyrene as an insulating layer in pavement construction. From these trials it was evident that polystyrene could be used in greater thicknesses as a load-bearing bulk fill in embankment construction. Expanded polystyrene was first used for embankment construction in 1972 at Flom, near Oslo, Norway for the reconstruction of a 1.5m high embankment underlain by peat and soft clay, which had been affected by substantial continuing settlements for 30 years.

In the following eight years, up to 1980, around 25 embankments incorporating expanded polystyrene fill were constructed in Norway with a total 35000m$^3$ of polystyrene materials being placed. Long-term monitoring of selected fills has been carried out to investigate the performance of the polystyrene fill in service (Aaboe 1987). Polystyrene continues to be used extensively in Norway and Sweden. Norwegian experience with the use of expanded polystyrene fill is reviewed by Aaboe (1987) and by Frydenlund and Aaboe (1988).

Expanded polystyrene fill has been used in France since 1983, when a trial embankment was constructed for a motorway widening project in Provence (Magnan, Bailly and Bondit, 1990), and the approach embankment to a bridge near Montpellier was reconstructed using this material (Lassauce and Antoine, 1985, Mieussens, 1985; Chazal
Polystyrene was first used in the United Kingdom in 1985, on the A47 Great Yarmouth Western Bypass in Norfolk, where the material was used to form the approaches to a bridge over a railway line, on a site underlain by soft clays and peat. The design and performance of this embankment is reviewed by Williams and Snowdon (1990) and McElhinney and Sanders (1991). Subsequently, polystyrene fill has been used at Thanet Way, Kent, the A120 Dovercourt Bypass, Essex, the Havengore Bridge, Foulness, Essex and on other schemes.

The Great Yarmouth embankment employed extruded polystyrene, but subsequent schemes in the United Kingdom have largely used expanded polystyrene materials. Polystyrene foam has also been used for embankment fill in Canada, U.S.A., the Netherlands, Germany, Yugoslavia, Japan and Ireland.

2.2 Potential Uses and Benefits of Polystyrene Fill

Polystyrene is an expensive material in comparison with conventional soil fills, but its extremely low density can result in considerable cost savings in situations where substantial structures, foundations or ground improvements would otherwise be required. In situations where differential settlements or long-term secondary compression of organic soils are anticipated, the use of polystyrene may also result in a substantial reduction in maintenance costs. Examples of situations in which the use of polystyrene fill may be beneficial include:

- Areas of very weak or compressible soils;
- Areas of unstable ground, such as relic landslides, and landslide repairs;
- Restricted sites requiring the use of retained embankments;
- Sites with difficult or restricted access for plant and vehicles (polystyrene may be moved and placed by hand);
- Construction over or adjacent to existing structures, services or embankments that may be adversely affected by increased loading or ground movements;
- Transition zones between bridges and normal fill embankments.
In addition to the direct economic benefits, the use of polystyrene fill may also result in significant reductions in the risks of failure of the earthworks and delay to the construction programme, as the performance of the embankment may be predicted with greater certainty than may be the case with an embankment imposing greater load on the foundation.

2.3 Existing Standards and Design Guidelines

The current British Standards applicable to expanded and extruded polystyrene fill materials are BS3837:Part 1:1986 Specification for boards manufactured from expandable beads, and BS3837:Part 2:1990 Specification for extruded boards, which superseded BS3837:1977. These standards are primarily intended for polystyrene boards used in building, mainly for insulation. Additional requirements may need to be specified for use in embankment construction, particularly for extruded materials.

There are currently no United Kingdom standards for the design and construction of polystyrene fill embankments. However, appropriate guidelines have been produced in Norway (Public Roads Administration, Norway 1980) and France (Laboratoire Des Ponts et Chaussees 1990), the latter being the more comprehensive. Current Norwegian design practice is reviewed by Refsdal (1987).

3. MATERIAL PROPERTIES

3.1 General

Polystyrene products are produced in two forms:-
- expanded polystyrene
- extruded polystyrene

To produce polystyrene foam, styrene monomer beads containing an expanding agent are expanded by dry steam up to 40 times their original volume. The beads are then allowed to mature. To form expanded polystyrene the beads are then placed in a mould and further steam is added to induce final expansion and fusion to the required shape. The amount of expansion allowed prior to drawing off the beads from the first stage of expansion directly affects the final density of the polystyrene block. Extruded polystyrene is formed, as the name suggests, by continuous extrusion of the foamed
material through a mould, a process which 'builds-in' a certain amount of compression into the material. Extruded polystyrene is generally more dense than expanded polystyrene and, as a consequence, is a more expensive material. Because of the difference in the production processes, there are some inherent differences in the other physical and mechanical properties of the two materials, as described in the following Sections. It should be noted that polystyrene products do not develop their full strength until approximately 2 days after final moulding.

Polystyrene fill is supplied as factory produced blocks or boards, as it is not technically feasible to foam the material in position on site due to the two stage process required and careful control over steaming and drawing off beads in the first phase of expansion. Mobile production plants have been considered for overseas projects in remote areas where large quantities of material are required. This would not be an economic option in the United Kingdom. The standard commercially available size for expanded polystyrene blocks for fill use is 2440 x 1220 x 610mm, but 305mm thick blocks can also be supplied and cut blocks of other thicknesses can be produced at increased cost. Extruded polystyrene is generally produced in the form of boards, up to a maximum section size of 610 x 110mm.


Expanded polystyrene is generally produced in SD, HD, EHD and occasionally UHD grades for use as fill. Extruded polystyrene grades E1 to E5 retain skins formed on the outer surface during manufacturing. Grades E6 and E7 have the skins removed by planing. Extruded polystyrene grades E1, E2 and E6 are not used as the minimum strengths are well below those that can be currently manufactured in expanded polystyrene. It should be noted that extruded polystyrene can be manufactured to far exceed the minimum strength of grade E5.

Expanded polystyrene beads formed prior to final moulding cannot be used as 'loose fill' as there would be insufficient intergranular friction to give adequate strength. Placement
and containment of the beads and compaction of the overlying pavement would be extremely difficult.

### Grade

<table>
<thead>
<tr>
<th>Grade</th>
<th>Minimum Compressive Stress/Compressive Strength* (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expanded Polystyrene</strong></td>
<td></td>
</tr>
<tr>
<td>Impact Sound Duty (ISD)</td>
<td>25</td>
</tr>
<tr>
<td>Standard Duty (SD)</td>
<td>70</td>
</tr>
<tr>
<td>High Duty (HD)</td>
<td>110</td>
</tr>
<tr>
<td>Extra High Duty (EHD)</td>
<td>150</td>
</tr>
<tr>
<td>Ultra High Duty (UHD)</td>
<td>190</td>
</tr>
<tr>
<td><strong>Extruded Polystyrene</strong></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>200</td>
</tr>
<tr>
<td>E4</td>
<td>300</td>
</tr>
<tr>
<td>E5</td>
<td>350</td>
</tr>
<tr>
<td>E7</td>
<td>250</td>
</tr>
</tbody>
</table>

*Where the maximum stress in the test occurs prior to 10% strain the result is reported as compressive strength.

### 3.2 Physical Properties

#### 3.2.1 Density

The most important characteristic of polystyrene is its extremely low density. Typical dry densities for expanded polystyrene materials are as follows:

<table>
<thead>
<tr>
<th>Grade</th>
<th>Dry Density (Typical density value) (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 3837:Part 1:1986</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>15</td>
</tr>
<tr>
<td>HD</td>
<td>20</td>
</tr>
<tr>
<td>EHD</td>
<td>25</td>
</tr>
<tr>
<td>UHD</td>
<td>30</td>
</tr>
</tbody>
</table>

The dry density of the commonly available extruded polystyrene products generally varies between 28 and 55 kg/m³, although densities of up to 100 kg/m³ have been produced.
The density of polystyrene materials has a direct influence on the other physical properties, such as compressive strength. However, there is no unique correlation between density and other physical properties for expanded or extruded polystyrene because of detailed variations in the production process between manufacturers, and even between individual batches of material. Consequently, it is not sufficient to specify only the density of material required.

The density of the material in service is likely to be significantly greater than the dry density as a result of the absorption of water (see Section 3.2.4).

3.2.2 Behaviour in Compression
The behaviour of expanded and extruded polystyrene under uniaxial compression shows marked differences as shown below:

![Typical Stress-Strain Curves for Compression](image_url)

Figure 1: Typical Stress-Strain Curves for Compression
Expanded polystyrene behaves as a linear elastic material up to strains of around 1 to 2%, where yield occurs. Thereafter, the material shows typical strain hardening behaviour in strain-controlled tests, with the compressive stress continuing to increase, but at a decreasing rate, with increasing strain. After a strain of around 10%, very little further increase in compressive stress occurs, and it is usual to define the compressive strength to be equal to the stress at 10% strain.

Extruded polystyrene shows linear elastic behaviour over a similar range of strain to expanded polystyrene. After yield occurs, the material shows strain softening behaviour in marked contrast to expanded polystyrene. In strain controlled tests, a peak compressive strength is reached at a strain of around 5%, and this peak stress is generally quoted as the compressive strength. After this point, the compressive stress falls markedly, approaching a constant stress at a strain of around 10%. Extruded polystyrene thus behaves in a brittle manner at failure.

Tests in Norway (Frydenland and Aaboe 1988) indicate that the compressive strength of polystyrene is maintained even after repeated loadings of up to 80% of its compressive strength.

Although polystyrene materials are graded according to the maximum compressive stress or strength, this parameter has little practical engineering significance. For engineering purposes, the stress at which yield occurs is more significant as, if this is exceeded, non-recoverable plastic strains will accumulate under repeated loading. In general, the yield stress may safely be taken to be the compressive stress at 1% strain.

Creep tests at constant loads indicate that the tendency for long-term creep deformations increases with the applied stress. Where the stress is such that the initial compressive strain is around 1%, the rate of creep is small. Tests undertaken at 20°C indicate a rate of creep of around 0.2% per year for this condition. Creep appears to be negligible if the initial strain does not exceed 0.5%. In polystyrene highway embankments, however, the non-constant loading induced by vehicles generally form the major proportion of the maximum compressive stresses within the fill. Laboratory tests have been undertaken to determine creep under cyclic loading (Magnan and Serratrice 1989). The findings indicate that as long as cyclic loads are below the yield stress no creep deformation
occurs. This is confirmed by the results of long term monitoring of polystyrene embankments (Aaboe 1987) which shows little apparent increase in compressive strain with time within polystyrene fill. Thus under normal service conditions in highway embankments, as long as the maintained stresses imposed by pavement loading are low in relation to the strength of the material, the potential for creep is very low.

Typical compressive strengths for polystyrene fill materials are as follows:

<table>
<thead>
<tr>
<th>Grade</th>
<th>Compressive Stress</th>
<th>Compressive Stress/</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 1% Strain</td>
<td>Strength at 10% Strain</td>
</tr>
<tr>
<td></td>
<td>(kN/m²)</td>
<td>(kN/m²)</td>
</tr>
<tr>
<td>Expanded Polystyrene:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>21</td>
<td>70</td>
</tr>
<tr>
<td>HD</td>
<td>45</td>
<td>110</td>
</tr>
<tr>
<td>EHD</td>
<td>70</td>
<td>150</td>
</tr>
<tr>
<td>UHD</td>
<td>100</td>
<td>190</td>
</tr>
<tr>
<td>Extruded Polystyrene:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3 - E7</td>
<td>135 - 370</td>
<td>200 - 700</td>
</tr>
</tbody>
</table>

(Values for extruded polystyrene are indicative of the range of materials currently available in the United Kingdom).

Experience suggests that for designs based on the principles set out in Section 4, long term creep deformations are unlikely to be significant.

Polystyrene undergoes very little lateral deflection under vertical load, with Poisson’s ratio being between 0 and 0.02.

3.2.3 Shear Strength and Frictional Resistance
Polystyrene has a high shear strength in relation to its compressive strength. Typical values for various grades of expanded polystyrene (Shell Plastics 1988) are as follows:-
The frictional resistance between blocks is generally of greater engineering significance in embankment design than the shear strength of the intact material. A coefficient of friction of 0.5 is usually taken for the moulded faces of the blocks, equivalent to an angle of friction of 27°. The angle of friction of cut or broken surfaces is, however, likely to be somewhat higher than this value, because of increased surface roughness. No specific test data is currently available indicating the degree of increased friction.

### 3.2.4 Water Absorption

In comparison with most other fill materials, polystyrene materials have a low potential for water absorption, despite their extremely low density. The individual beads that make up the materials have a closed cellular structure and therefore will not absorb water. The void space available for water uptake is, therefore, limited to the interconnected pore spaces between the beads, which form a small proportion of the total volume. The permeability of the material is low, but water may be drawn into the materials by capillary action to a limited extent.

Typical water absorption values for various grades of expanded polystyrene for short term exposure are as follows (Shell Plastics 1988):

<table>
<thead>
<tr>
<th>Grade</th>
<th>Water Absorption by Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After 7 days</td>
</tr>
<tr>
<td>SD</td>
<td>3.0%</td>
</tr>
<tr>
<td>HD</td>
<td>2.3%</td>
</tr>
<tr>
<td>EHD</td>
<td>2.2%</td>
</tr>
<tr>
<td>UHD</td>
<td>2.0%</td>
</tr>
</tbody>
</table>
Extruded polystyrene absorbs water to a much lesser extent, with water absorption by volume being generally in the range of 0.05% to 0.2%.

Long term monitoring of expanded polystyrene fills in Norway (Aaboe 1987) indicates that for fills permanently below the water table the water absorption may approach 9%. For fills that are periodically submerged in water, water contents of up to 4% have been observed. For fills permanently above the water table, the capillary rise appears to be small, around 200mm, and above this the moisture content rarely exceeds 1% by volume.

Experience has shown that the absorption of water has little influence on the strength or compressibility of the fill, although the effect on density is significant.

3.2.5 Effects of Temperature
The mechanical properties of polystyrene fills are not believed to be greatly affected by the range of temperatures generally experienced by embankment fills in the United Kingdom. In the short term, temperatures of up to 95°C may be tolerated provided that the material is not stressed. In the long term, dimensional stability is maintained at temperatures as high as 75°C to 85°C under moderate loading (up to 20 kN/m²). No detailed test data is available for either expanded or extruded polystyrene indicating the precise effect of elevated temperatures (above 20°C and below 70°C) on material properties.

3.3 Chemical Properties
Polystyrene is chemically resistant to a wide range of substances including, at normal soil temperatures:

- dilute inorganic acids
- alkalis
- salts
- humic acid
- most alcohols
- some vegetable oils
- solvent-free bitumens
- silicone oils
- gypsum and portland cement
- water based paints and adhesives
- glycols

There are a range of substances which may attack the surface of the polystyrene, causing shrinkage on prolonged exposure, but are not able to permeate the mass of the material or dissolve the polystyrene, and thus have little effect on the engineering performance of the material. These substances include:

- some vegetable oils
- most animal fats and oils
- paraffin oils
- diesel fuel
- phenol

There are, nevertheless, a range of substances which may attack polystyrene foam to a significant degree, generally by dissolving the material. These include:

- most hydrocarbons, including methane, petrol and tar oils;
- chlorinated hydrocarbons and chlorofluorocarbons (CFCs);
- other organic solvents, such as ketones, ethers and esters;
- concentrated acids.

Many paints, adhesives, cleaning fluids, and construction products (e.g. curing compounds, bituminous sprays or paints) contain organic solvents.

Although the above substances will damage the polystyrene, they will need to be present in large quantities or in high concentrations in soil, fill or water to have any significant effect on the engineering performance of polystyrene fills.

It can be seen from the above that polystyrene is resistant to most substances naturally occurring in the ground, natural earth fills, and ground water. Norwegian experience of polystyrene fills constructed over peat indicated no problems have resulted from generation of methane. Deleterious substances may, however, be present in significant
quantities in contaminated ground, and may also be introduced by accidental spillage or leakage from vehicles, or during construction operations.

Detailed information on the chemical resistance of expanded polystyrene has been published by Shell Plastics (1988).

3.4 Biological Properties
Polystyrene is not susceptible to bacterial or fungal attack, and therefore will not undergo biological degradation. Polystyrene has no nutritional value for animals.

3.5 Combustibility
Polystyrene is a combustible material and will burn readily when ignited in the presence of large volumes of oxygen. To sustain a fire, an oxygen supply of 150 times the volume of burning material is required. The calorific value of expanded polystyrene is 40MJ/kg, equating to 600MJ/m³ for SD grade and 1200MJ/m³ for UHD grade material. In comparison, the heat released by combustion of dry wood is of the order of 7000 to 8000MJ/m³. However, the rate at which heat is released by combustion of polystyrene is much more rapid, than in the case of wood, and a fire will therefore propagate rapidly once started. Polystyrene burns with a luminous sooty flame, and produces dense black smoke containing asphyxiants such as carbon monoxide.

Polystyrene will ignite on contact with an open flame, but can be supplied with a flame retardant additive which reduces the risk of ignition. The additive restricts the early stages of development of the fire such that, if the source of ignition is removed, after a short period of time, the fire will be extinguished. However, the flame retardant additive will not prevent combustion once a fire has taken hold. The additive adds to the material costs.

3.6 Ultra-violet Light
Exposure to ultra-violet light causes discolouration and embrittlement of the surface of the polystyrene. This is of no significance to finished embankment fills but during long periods in storage or during construction, if continuous abrasion or erosion occurs, a progressive wasting of blocks can result. This combination of factors is unlikely to occur.
3.7 Testing


Test methods 1 to 5 for rigid cellular materials are given in BS4370:Part 1:1988 and includes the following:-

1. Measurement of dimensions.
2. Determination of apparent density.
3. Compression test.
5. Dimensional stability test.

BS4370:Part 2:1973 contains test methods 6 to 10 for rigid cellular materials and includes the following:-

6. Determination of shear strength and shear modulus.
10. Determination of the volume percentage of closed cells.

Other tests carried out on polystyrene materials include BS4735:1974 (burning characteristics) and BS6203:1991 and BS6336:1982 (fire characteristics).

These latter tests may be required depending on the required use of the polystyrene fill.

Testing of the polystyrene should be undertaken at random by taking samples cut from a large block of polystyrene. The samples should be tested before the blocks from the respective batch are incorporated into the scheme. In addition to the testing requirement, a Quality Assurance form should accompany all batches to site.

Of all the tested methods listed under BS4370:Parts 1 and 2, there are essentially three main properties to test prior to the installation of the polystyrene fill into a scheme.
i. Measurement of Dimensions
During construction, stability of a polystyrene fill depends to a certain extent upon the consistency of the block dimensions. The measurement of the polystyrene blocks to ensure compliance with dimensional tolerances is therefore an essential requirement.

ii. Compressive Strength
Compressive strength/stress tests are required to ensure that the material has sufficient strength to withstand the imposed loads.

iii. Density
The value of density for polystyrene blocks is relatively simple to assess. Method 1 of BS4370:Part 1:1988 can be used to determine the consistency of the supplied material and thus the possible variations in compressive strength can be assessed.

4. DESIGN CRITERIA
4.1 Design Parameters
4.1.1 Design Parameters for Polystyrene Fill Materials
It is recommended that the design values for the properties of polystyrene fill materials are determined as follows:-

i. Design Strength
For most highway applications, the design strength should be taken to be the compressive stress at 1% strain (see Section 3) for all normal loading conditions; this value will be subject to any additional limits on the internal deformation of the fill.

ii. Design Density
The value of density used in design calculations must allow for the absorption of water under service conditions, except for consideration of buoyancy for which the dry density only should be used. The dry densities of various grades of polystyrene and the likely percentage water absorption for various service conditions are discussed in Sections 3.2.1 and 3.2.4 respectively. In practice, the
weight of polystyrene fill is generally of minor significance, and it is sufficient to assume the following densities for all grades of material:-

**Expanded Polystyrene:-**

- Fills permanently below water = 100kg/m³
- Fills submerged for short periods only = 50kg/m³
- Fills permanently above water = 40kg/m³
- Density for buoyancy calculation = 20kg/m³ (minimum)

**Extruded Polystyrene:-**

Dry density should be used for all conditions.

### iii. Coefficient of Friction

It is recommended that the coefficient of friction between polystyrene blocks is taken to be 0.5, equivalent to an angle of friction of 27°.

### iv. Shear Strength

The shear strength of polystyrene blocks may be taken as the lower value of the range stated in Section 3.2.3 for the appropriate material grade. Any structure should be constructed so as to ensure there are no deep continuous joints thus maintaining material contact of the blocks. In stability calculations the shear strength for the polystyrene blocks should be used except for horizontal slip surfaces where the shear strength along boundaries should be used.

### 4.1.2 External Controls on Embankment Design

The following main parameters and constraints will need to be defined or determined by suitable investigations, prior to commencement of design:-

#### i. Ground Conditions

A ground investigation will be required to a similar standard to that required for normal density fill construction. Sufficient information regarding the ground profiles, soil strength, deformability and permeability, and ground water conditions should be obtained to permit reliable analysis of embankment stability and settlements, and permit the design of any ground improvements, foundation works, etc. that may be associated with the proposed embankment. Where
landfill or contaminated land is expected, determination of the presence of, in particular, organic solvents and gas should be undertaken.

ii. Flood Levels

Maximum design flood levels must be determined for the site of the proposed embankment, for a return period similar to the design life of the structure. Design flood levels should allow for any effect of the proposed structure on flood conditions. Where appropriate, a lower flood level may be defined for use in analysis of temporary conditions during construction.

iii. Loads

The loads applied to the embankment must be defined, including (as appropriate):
- vertical vehicle loads
- braking and impact loads
- wind loading
- loads from structures constructed on the fill
- exceptional loading requirements, such as heavy construction plant or surcharge loads.

It is recommended that design highway or railway vehicle loads, and wind loads, are determined in accordance with BS5400:Part 2:1978. For trunk road embankments abnormal vehicle loads should be considered using the appropriate number of units of 'HB' loading, as defined in BS5400:Part 2:1978, in accordance with the current Department of Transport requirements for bridge design (or as otherwise required by the client). Further research into the need to meet bridge, as opposed to pavement, design loads could result in significant savings.

Braking and impact loads are generally only of concern where they act across the width of the embankment, or adjacent to bridge abutments. Wind loading is not normally a problem for completed polystyrene fills, but may need to be considered for temporary conditions during construction.

iv. Serviceability Requirements

Limits on total and differential settlements of the finished surface should be defined.
v. Adjacent Structures and Services

The locations and details of any structures or services which may be affected by the proposed embankment should be determined. Where appropriate, tolerable limits for the following should be defined:

- settlement (total and differential)
- horizontal movement (total and differential)
- induced loading

In addition, requirements for access for future maintenance should be considered.

vi. Existing Highways and Railways

Adjoining highways and railway lines may also impose constraints on the design. In particular, any limits on induced settlements of existing highways or railways should be defined. Polystyrene fill may result in a reduced effect on existing structures and enable settlements to be kept within tolerable limits. The polystyrene will not produce significant toe weighting to other embankments.

vii. Dimensional Constraints

It is desirable that the highway alignment should be fixed prior to commencement of detailed design of polystyrene embankments, as it is generally more difficult to incorporate changes in pavement levels or position than is the case for normal fill structures. The detailed design of polystyrene should not be finalised until the highway alignment has been fixed as the polystyrene structure involves working with fixed dimensions.

The dimensions of adjoining structures, the maximum width of the embankment at ground level and the maximum depth of drainage and service trenches, safety fence and lighting column foundations, etc. should also be defined as far as practicable.

4.2 Overall Stability and Settlements

The following need to be considered in determining the overall stability of the proposed polystyrene fill embankment:
i. **Weight of Fill Cover and Pavement**

The minimum thickness of fill cover over polystyrene fill will be determined by the requirements for:

- protection of the polystyrene (see Section 5.2)
- imposed traffic loads (see Section 4.5)
- requirements for accommodating services, etc. (see Section 6.5)
- landscaping (see Section 6.6)

It should be noted that below side slopes, and in other areas where the thickness of polystyrene varies, the surface of the polystyrene will be stepped (see Section 6.3), and allowance should be made for the additional fill cover that will therefore be required in these steps. Additional fill material will also be required to create cross-falls on road, pavements and verges.

ii. **Flotation**

The potential for flotation of the completed embankment should be checked for the maximum design flood level, i.e. it should be confirmed that the weight of the polystyrene and its normal fill and pavement cover exceeds the uplift force resulting from water pressure on the base of the polystyrene.

The possibility of flotation during the construction stage (i.e. before completion of fill cover) should also be considered. Less severe flood conditions may usually be assumed for this case, and dewatering of excavations may be considered as appropriate.

iii. **Bearing Capacity and Settlement of Foundations**

Consideration of the weight of normal fill and pavement cover and the potential for flotation will determine the maximum thickness of polystyrene that may be employed, and hence the minimum embankment weight. It should be noted that in practice the thickness of polystyrene fill will be constrained to multiples of standard block thicknesses.

Where water levels permit, polystyrene embankments may be designed with compensated foundations such that there is no net loading of the foundation strata.
This is achieved by excavating the ground beneath the embankment and back filling the excavation with polystyrene fill, such that the net reduction in weight below original ground level equals the weight of the embankment above original ground level. Thus, the potential for long term foundation settlements and foundation failure is completely avoided (n.b. some elastic movements may nevertheless occur during construction, and the stability of the excavation may need to be checked).

In many cases, flood water levels will preclude a compensated foundation using polystyrene fill and a layer of normal density fill may be required between the base of the polystyrene and ground level. This situation will also apply in transition zones (see Section 6.2). In such cases, the bearing capacity of the foundation and the magnitude and rate of settlement will need to be considered. This may be undertaken by normal soil mechanics procedures as used for normal density embankments. It will also be necessary to consider loadings imposed on adjacent structures, and the settlements induced in such structures, adjacent services, highways or railway lines.

In the design of embankments incorporating a mixture of polystyrene and normal density fills, it is also necessary to consider the effects of settlement on the polystyrene fill. Differential settlement of the polystyrene should be kept to a practical minimum, as large differential movements may lead to problems with the placement of the blocks, tilting of the structure and surface drainage. In extreme cases, the stability of the fill may be affected. It is therefore desirable to keep the thickness of fill above polystyrene to the practical minimum (see (i) above) such that the majority of the denser fill materials are placed prior to placement of the polystyrene. A settlement period may then be allowed after completion of filling to the base level of the polystyrene. Where surcharge loading to accelerate consolidation is required, this should ideally be undertaken as a preloading exercise prior to placement of the polystyrene.

Where necessary ground improvements or soil reinforcement may be used to improve the stability of the embankment or to control settlements. Most ground improvement techniques, (including vertical drains, lime-and stone columns,
bridge approach support piling) are compatible with polystyrene, provided they are undertaken in advance of placement of the polystyrene. Some problems may be experienced with the design of systems which rely on the arching action of the fill material (e.g. piling without a structural slab) to transfer embankment loads to foundation elements. Soil reinforcement may be used to improve the overall stability of the embankment but its usefulness will be restricted by limitations in the available anchorage forces. However, soil reinforcement may be useful in creating a strengthened basal layer to the embankment.

On sloping sites, the potential for sliding of the embankment along its base and the overall effect of the embankment weight on slope stability should be considered. On steeply sloping sites, it may be necessary to anchor the fill to the slope to resist sliding. This is best achieved by introducing flat horizontal members between the polystyrene layers.

iv. Stability Under Horizontal Loads

For most highway embankments incorporating polystyrene fill, the stability of the embankment under horizontal loads is not normally a problem. Horizontal forces resulting from vehicle braking normally act along the long axis of the embankment where there is usually ample restraint to resist these forces, although at bridges, these forces may be transferred to the abutment structure. For highway embankments of normal width and moderate height, wind loads are unlikely to be a problem for the completed embankment, although they should be considered in the design of vertical facings.

Stability under horizontal loading may be a problem where large loads act across the width of the embankment, e.g. impact forces on embankment sides or parapet walls. The overall stability may be simply checked by consideration of sliding on an appropriate basal plane. Internal stability (i.e. internal shearing or punching of the fill) may also need to be considered. Significant variations in level as a result of, for example, poor construction or dimensional tolerance, could result in internal voiding and the consequent loss of shear strength between blocks. The design of the basal layer, usually comprising sand, should therefore
be within strict tolerances to ensure overall stability after completion of the embankment.

4.3 Lateral Pressures on Structures
Expanded and extruded polystyrene materials have a very low Poisson's Ratio, and therefore, will impose low lateral forces on adjoining structures. Monitoring of polystyrene structures undertaken by the Norwegian Road Research Laboratory (Aaboe 1987) indicates that, provided a suitable air gap is allowed between polystyrene fill and an adjoining wall at the time of construction, no lateral pressures will be applied to the wall by the polystyrene in the long term. Tests on polystyrene fills placed in contact with a bridge abutment (Frydenlund and Aaboe, 1988) indicate that, for restrained fills, the lateral load applied to the adjoining wall is between 0.1 and 0.2 times the vertical surcharge load to the polystyrene. These loads are insignificant in relation to other loads likely to be imposed on the structure. In Norway, it is normal practice (Aaboe 1987) to adopt a very conservative assumption and apply a uniform horizontal pressure of 10kN/m² against adjoining abutments and walls.

Polystyrene fills, by themselves, generally have a very limited capacity to resist horizontal loads, which derives solely from friction between the blocks. Consequently, any lateral pressures applied to the polystyrene may be transmitted to any adjoining structure or, where the fill is unrestrained, may displace the polystyrene. Therefore, any fills or slopes adjoining the polystyrene should be designed to be self-supporting.

Retaining walls will need to be designed to resist lateral pressures exerted by the normal fill and pavement cover over the polystyrene. The structures may also need to resist horizontal forces (e.g. braking loads) applied to the fill surface but transmitted by the fill to the adjoining structure.

4.4 Internal Stability
4.4.1 Internal Stability of Polystyrene Fill
The following needs to be considered to confirm the internal stability of polystyrene fills:-
i. **Vertical Compressive Stresses**

The compressive stresses induced by the weight of normal fill and pavement cover, normal vehicle loads and any other non-vehicular imposed loads must be determined, and appropriate grades of polystyrene should be selected such that the compressive stress does not exceed the design strength (see Section 4.1.1) of the polystyrene.

Compressive stresses induced by abnormal vehicle loads may exceed the design strength but should not exceed 80% of the minimum compressive stress/compressive strength at 10% strain for the grade of polystyrene selected (see Section 3.1). Where frequent abnormal vehicle loads are expected on embankments incorporating polystyrene fill, consideration should be given to the design strength being defined by the compressive stress imposed by the abnormal vehicle loading.

For concentrated loads, such as wheel loads, it is usually sufficient to assume that the loads are distributed uniformly over a finite area, the size of which increases with depth. For polystyrene, and a cover of soil, aggregates and flexible pavement materials, it is usual to assume an 'angle of spread' of the load of 1 (horizontal) to 2 (vertical) as shown below:

![Diagram of load distribution](image)

**Figure 2: Load Distribution**

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For multiple loads, the assumed stressed zones for adjacent zones will overlap at some point below the surface, below which the vertical stress may be taken as equal to the combined load distributed evenly over the combined stressed zone at a given level.

Where a concrete slab is introduced (see Section 5.2) above the polystyrene, a greater degree of 'load spreading' may be assumed through the slab. For lightly reinforced concrete, an 'angle of spread' of 1 to 1 is usually assumed. The distribution of concentrated loads may be further enhanced by increasing the reinforcement of the slab, in which case the load distribution must be determined by structural analysis.

The compressive stress induced by the weight of fill and pavement cover may be assumed to be constant with depth through the polystyrene.

In general in highway embankments, higher grade (EHD and above) polystyrene materials will only be required for the first few layers below the pavement. For lower layers, and fill below verges and side slopes, lower grade materials are usually sufficient.

ii. Sliding Between Blocks
In situations where the polystyrene blocks are not physically restrained (e.g. by adjoining fill), it will be necessary to consider the potential for sliding of the polystyrene blocks under horizontal loads. Double sided timber fasteners have been used in some countries in an attempt to enhance friction between blocks, but these are considered to be of dubious effectiveness and hinder easy placement and/or damage the fill. Where high lateral loads must be resisted, structural expedients (such as concrete slabs, walls or anchors) are considered to be more effective and reliable.

4.4.2 Internal Stability of Normal Density Fill Elements
The internal stability of normal fill elements of the design should be confirmed by appropriate soil mechanics methods. In particular, it will be necessary to confirm that
the soil cover to the side slopes will remain stable throughout the design life of the structure. It should be noted that the surface of the polystyrene, with its protective cover of polyethylene sheeting (see Section 5) may act as a potential sliding surface.

The stability of the soil cover will impose a practical limit on the side slopes of embankments. Although the polystyrene can be placed to any slope angle up to vertical, in practice it is difficult to retain soil cover on slopes steeper than 1 to 1.5, even if granular materials are used for the soil cover. Soil reinforcement for retaining soil cover has limited value because of the difficulty of anchoring the reinforcing elements to the polystyrene fill. Soil can be retained on steeper slopes by counterbalancing soil cover from one side to the other with a connecting reinforcing membrane to produce a 'saddlebag' over the polystyrene fill. This technique has been successfully employed at Guildford, Surrey.

4.5 Pavement Design

Although subgrade CBR values may be determined for polystyrene fill materials, the behaviour of these materials is not necessarily comparable to that of a soil subgrade. Therefore, the normal methods for determining sub-base and capping layer thicknesses are not directly applicable to polystyrene. For polystyrene fills, it is recommended that the actual pressures transmitted to the polystyrene are considered, and the polystyrene grades and total construction thicknesses selected accordingly. Conventionally, the pavement and sub-base are designed on the basis of a formation CBR of 15%. The thickness of the capping layer material (as defined in the Manual of Contract Documents for Highway Works, Notes for Guidance on the Specification for Highway Works, MCHW 2) therefore increases as the CBR of the subgrade reduces.

During the design of the A47 Great Yarmouth Scheme, laboratory CBRs of 2 to 5% for extruded polystyrene were measured. Expanded polystyrene gives values \(<2\%\) and pavement capping layer design should be based on these values unless particularly high grades of expanded material are tested to see if the CBR values are \(>2\%\).

For trunk roads, a minimum thickness of 1.0m from finished road level to the upper surface of the polystyrene is usually necessary (this includes the sand bedding to the protective impermeable membrane - see Section 5.2). A thinner construction may be
sufficient on less heavily loaded routes. In all cases, however, a minimum thickness of cover will be required to provide protection to the polystyrene (see Section 5.2.2).

In Norwegian and French design guidelines (Public Roads Administration, Norway, 1980, and Laboratoire des Ponts et Chaussees, 1990), a lightly reinforced concrete slab is provided beneath the pavement to assist load transfer to the polystyrene. This enables reduction of the total thickness of cover over the polystyrene or, for the same cover thickness, a lower grade of polystyrene may be used below the pavement. The overall construction costs are not greatly affected by inclusion of a concrete slab and its inclusion adds to the complexity of the design. Therefore in the United Kingdom, except for two schemes, the concrete slab has been omitted, and experience suggests that this does not have any detrimental effect on the performance of the pavement. Nevertheless, there may be practical or economic advantages to be gained from introducing a structural slab in some cases.

In Norway, some problems have been encountered with differential icing between pavements constructed on polystyrene fill and normal construction, particularly in late autumn. This appears to be the result of the low thermal capacity of polystyrene compared with earth fills of similar volume, and the insulating properties of the material which restrict heat flow from the underlying ground. This problem may be overcome by providing a sufficient thickness of pavement materials. Based on Norwegian practice, (Refsdal 1987), it is suggested that a minimum pavement thickness of 800mm should be adopted.

5. PROTECTION OF POLYSTYRENE

5.1 Potential Hazards

Expanded and extruded polystyrene are vulnerable to damage resulting from a number of potential causes and suitable protective measures must be incorporated into the design. The various potential hazards are discussed below:

i. Petrol and Chemical Attack

As described in Section 3.3, polystyrene fill materials are vulnerable to solution by a range of chemicals, primarily petroleum products and organic solvents. Such substances may be released by accidental spillage from vehicles and may also be
present in contaminated ground. An impermeable and chemically resistant barrier must therefore be provided to prevent such substances from coming into contact with the polystyrene. On contaminated ground, a vapour barrier may also be required.

ii. **Heat and Flame**

Polystyrene is a combustible material and must therefore be protected from sources of ignition by a cover of non-combustible material, such as inert earth fill or concrete.

Polystyrene may be produced with a flame-retardant additive which provides protection against minor sources of ignition, but is of lesser benefit if a major fire occurs at its surface.

iii. **Ultra Violet Light**

Exposure to ultra violet light can lead to deterioration of polystyrene materials if they are exposed for long periods. In finished embankments, the polystyrene is usually covered by opaque materials and therefore such deterioration will not occur. However, some deterioration may occur during storage prior to use and during construction, if the material is exposed for long periods.

iv. **Accidental Impact**

Polystyrene blocks are easily damaged by accidental impacts or other direct concentrated loading. A hard facing or fill cover is therefore required to absorb or spread impact forces.

v. **Rodents**

Rodents and other burrowing animals are potentially capable of tunnelling into polystyrene blocks but burrowing will be limited to the creation of shelter and nesting sites. Polystyrene fill materials will tolerate a substantial amount of burrowing without significantly affecting the stability of the structure unlike natural fill materials.
In practice, burrowing animals are likely to confine their activities to any soil cover over the polystyrene, and the polyethylene membranes commonly used for chemical protection (see Section 5.2) will discourage tunnelling into the polystyrene. There are no known reported instances of rodent infestations of polystyrene fill in embankments.

vi. Malicious Damage
Polystyrene fills are potentially vulnerable to malicious damage, but a soil cover or hard facing will conceal and discourage casual vandalism. Malicious damage is only likely to be a significant hazard during the construction stage. Nevertheless, in areas of high vandalism risk, the designer should consider whether there is a risk of damage to other elements of the scheme which may expose the polystyrene fill or result in consequential damage to it.

5.2 Materials for Protection
5.2.1 General Requirements
It can be seen from the preceding Section that there is a need for suitable protective measures to isolate the polystyrene from potential causes of damage. The protection is required to perform the following functions:

- act as an inert insulating layer to protect against heat and flame (and ideally to restrict air supply to the polystyrene;
- absorb or spread impact forces;
- provide an impermeable barrier to exclude petrol, organic solvents and other deleterious substances;
- exclude ultra violet light;
- reduce vulnerability to malicious damage

Most of the above functions can be fulfilled by covering the polystyrene with a layer of inert fill material or pavement materials. A concrete slab may also be used. On vertical fill faces, a reinforced concrete or masonry facing will provide the same functions. Where embankments are particularly vulnerable to vehicle impact (e.g. approaches to
bridges over highways) additional protection from impact in the form of safety barriers may be advisable.

Most fill and pavement materials are permeable to petrol and other fluids (indeed a free draining layer at the base of the fill or pavement cover is advantageous - see Section 5.2.2). Concrete has a lower permeability and offers some short term protection from minor petrol spillage, but does not provide long term protection against major petrol and chemical spillage. A suitable impermeable membrane is therefore required in addition to fill, concrete or masonry barriers. On landfill or contaminated sites, an impermeable membrane may also be required beneath the polystyrene incorporating a vapour barrier. The material forming the membrane must have extremely good chemical resistance to substances deleterious to polystyrene. Most membranes will require protection from fire and mechanical damage, and the fill, concrete or masonry cover is still required on exposed surfaces.

To summarise, effective protection to the polystyrene comprises two elements:-

i. a cover of inert fill material, a concrete slab, or a concrete or brickwork facing;

ii. an impermeable and chemically resistant membrane.

The following Sections review the materials and methods used for these purposes.

5.2.2 Fill Cover
A cover of aggregate or earth fill is generally required to form the pavement, and to cover verges and side slopes for aesthetic reasons, and provides effective protection against heat, fire, accidental damage and ultra violet light. The cover will also conceal the polystyrene and give some protection against malicious damage.

Apart from potentially combustible materials such as unburnt colliery spoil and peat, any chemically stable natural earth fill (including topsoil), crushed rock or inert artificial materials (such as Lytag or Leca) may be used to form the fill cover, provided that it satisfies the other design criteria (e.g. slope stability, crushing strength) as appropriate. However, free draining granular materials are preferred as these may be compacted more
easily over an impermeable base, will assist drainage of fluids (including petrol) from the surface of the fill, and may be constructed to steeper side slopes than most cohesive fills. It is advisable to exclude materials containing large angular particles (greater than 50mm in size) within 100mm of the impermeable membrane or the polystyrene to avoid the possibility of damage to the membrane or polystyrene.

There are currently no rigorous methods for determining the thickness of fill cover required for protection. The Norwegian design guidelines (Public Road Administration, Norway 1980) recommend a minimum thickness of 250mm, and experience suggests that this is sufficient under Norwegian conditions. However, some doubt must be expressed as to the sufficiency of this during a major incident. The French design guide recommends a minimum thickness of 500mm. A minimum thickness of 600mm has been specified on schemes in the United Kingdom, providing a considerably greater degree of protection. In the Design Manual for Roads and Bridges (DMRB 4.1.1), HA 44/91, it is recommended that a minimum thickness of 1m, including topsoil, will be required. The greater thickness has the further advantage of providing a much deeper growing medium for planting and landscaping purposes (see Section 6.6).

In view of the above, it is recommended that a minimum thickness of 1m is adopted for fill cover. It may nevertheless be necessary to increase this thickness below verges to accommodate drainage and services (see Section 6.5) and to provide a sufficient construction thickness to spread wheel loads (see Sections 4.4.1 and 4.5).

5.2.3 Concrete Slabs
In current Norwegian (Public Roads Administration, Norway 1980) and French (Laboratoire des Ponts et Chaussees 1990) practice, a reinforced concrete slab is provided over the surface of the polystyrene beneath the highway pavement and, in some cases, beneath the verges. The primary purpose of this slab is to assist the distribution of wheel loads, but it will also assist the protection of the polystyrene from fire and mechanical damage in an area where the risk of damage is usually greatest. Generally, a lightly reinforced slab between 100 and 150mm thick is utilised.

Most embankments constructed using polystyrene in the United Kingdom have omitted the concrete slab (as at Great Yarmouth, Williams and Snowdon 1990; McElhinney and
Sanders 1991). Experience suggests that there is no particular difficulty in constructing the overlying pavement or fill cover without causing damage to the polystyrene or the impermeable membrane. As stated in Section 5.2.1, concrete is permeable to petrol, and therefore an impermeable membrane will be required whether or not a concrete slab is provided. It should also be noted that a concrete slab is likely to be significantly more expensive than an equivalent thickness of fill cover.

It is concluded that the provision of a concrete slab has no particular advantage over a fill cover, in terms of the provision of protection of the polystyrene, which justifies its additional cost. Nevertheless, there may be structural advantages in terms of improved distribution of wheel loads (see Section 4.5).

5.2.4 Vertical Facings
Where polystyrene fills are constructed to a vertical face, a concrete or masonry facing will be required to provide protection from fire and mechanical damage, and for aesthetic reasons.

Vertical facings should, ideally, be designed as free-standing walls, and will need to have sufficient structural strength to resist horizontal loading, including:-
- wind loading;
- impact forces on the wall face and on parapets;
- lateral pressures exerted by fill cover to the upper surface of the polystyrene.

In some situations (e.g. embankments on steep hillsides) it may be possible to install horizontal anchors through the polystyrene fill to resist lateral forces, and thereby reduce the thickness of the required facings. On steeply sloping sites, such anchors may in any case be required to resist sliding of the embankment.

The thickness of vertical facings will generally be determined by structural considerations. The minimum thickness required for fire protection may be determined from building design codes, with a 4 hour fire rating being desirable. For example, for solid dense concrete blockwork (load bearing, class I aggregate) a wall thickness of 150mm will be required to give a 4 hour fire rating.
5.2.5 Impermeable Membranes

A variety of impermeable polymer membranes are commercially available for uses such as landfill liners, canal/dam lining and effluent treatment lagoons. However, many are not resistant to organic solvents i.e. petrol, diesel and are therefore unsuitable for use as protection to polystyrene. There are, nevertheless, a limited range of materials that are impermeable and chemically resistant to hydrocarbons, organic solvents and acids, the most important of these being high-density polyethylene and polyester. Polyethylene materials are covered by BS 3412:1976 in which HDPE is defined as material with a minimum density of 0.940 Mg/m³ and ASTM D883 where HDPE is defined as material with a minimum density of 0.941 Mg/m³.

HDPE membranes are a type of thermoplastic semicrystalline geomembrane. The advantages of this type of membrane include excellent chemical resistance, the ability to form effective seams by thermal and/or extrusion methods and a large range in thickness. The disadvantages include a sensitivity to seam cracking, the need for high quality seam workmanship and high thermal expansion/contraction.

HDPE membranes demonstrate a high resistance to many chemicals including hydrocarbons and organic solvents which may attack polystyrene.

The specification for membranes should contain requirements for the following properties: Thickness, Density, Strength (tensile properties and elongation), Toughness (resistance to tear and puncture), Durability (chemical resistance) and Seamability (homogeneous fusion of liner sheets). A typical specification for protective membranes is included in the Appendix: Part B.

HDPE membranes are available with either smooth or roughened texture. The development of roughened membranes has led to improved friction between the membrane and soils, geotextiles and other geosynthetics. Increased protection against accidental damage during construction is provided from the implementation of thicker HDPE membranes (2.0 - 3.0mm thickness) but thinner membranes are required to provide sufficient flexibility to be used on stepped surfaces (e.g. below embankment side slopes).
A 2.5mm thick smooth or roughened membrane is recommended for use below the pavement and verges, where the risk of mechanical damage and chemical attack is greatest. On vertical faces, and below side slopes, a 0.5mm thick smooth or roughened membrane may be used without significantly compromising the degree of protection. -

HDPE membranes are considered to be the most suitable of the alternatives available, and are strongly recommended for use as a protection.

It should be noted that low density polyethylene materials (i.e. VLDPE - very low density polyethylene) are generally not resistant to organic solvents i.e. petrol and are therefore not suitable for protection to polystyrene fill. However, linear low density polyethylene (LLDPE) membranes can exhibit chemical resistance properties approaching those of HDPE membranes but with a higher degree of deformability. The large variation of LLDPE membranes available is such that in particular, detailed chemical resistance or mechanical properties, would need to be specified.

Polyester membranes have also been used to form impermeable membranes over polystyrene e.g. A47 Great Yarmouth Western Bypass (McElhinney and Sanders 1991). These materials have good chemical resistance to hydrocarbons and organic solvents, but are not resistant to concentrated alkalis. The light polyester membranes have also proved difficult to lay and join in practice. Consequently, the use of polyester membranes is not recommended.

Polyurethane, sprayed in situ, was initially used for protection in Norway, and has subsequently been used in France (Magnan, Bailly and Bondil (1990)). However, successful spraying of the polyurethane proved difficult and is susceptible to adverse weather conditions. Close control and inspection is also necessary to ensure complete coverage of the surfaces to be protected. Polyurethane also produces toxic gases if set alight. Consequently, the use of this material is not recommended.

It has been the practice in some countries to provide an impermeable membrane below the pavement and verges only. However, in a large spill, it is unlikely that the discharge fluids will be confined to these areas of the highway embankment. It is therefore recommended that impermeable membranes are provided below the side slopes, to
vertical faces behind walls, and any other surfaces that may come into contact with fluids as they drain away from the point of discharge.

The French design guidelines recommend the use of a clay fill cover to side slopes as an alternative membrane. However, the effectiveness of this method is dubious as, during dry weather, shrinkage of the clay may occur leading to formation of cracks, allowing ingress of fluids. In addition, a clay cover is inherently less stable in the long-term than one formed from granular materials.

On landfilled or contaminated sites, it may also be necessary to provide an impermeable membrane below the polystyrene, which may also need to incorporate a vapour barrier (e.g. aluminium foil) to prevent migration of methane or other deleterious gases into the fill.

5.2.6 Property Requirements for High Density Polyethylene (HDPE) Membranes

i. Density
High Density Polyethylene (HDPE) generally comprises approximately 97-98% polymer, and 2-3% of carbon black, anti-oxidants and heat stabilisers.

Various test methods can be used to determine the density of the HDPE including ASTM 1505 and DIN 53479. An international standard test method, ISO 1183, exists and is recommended for the measurement of density.

ii. Thickness
HDPE membranes are produced both with a smooth finish and a rough textured finish. The smooth HDPE membranes are generally available from thicknesses of 0.5mm to 3.5mm at 0.5mm intervals. However, other thicknesses are also available (i.e. 0.75mm and 1.25mm). The roughened HDPE membranes are presently available in thicknesses from 0.5mm to 2.5mm predominantly in 0.5mm intervals.

Manufacturers/suppliers indicate that the thickness tolerance of the membrane will be ± 10% of the nominal thickness of the membrane.
Testing of the membrane thickness can be carried out in accordance with the appropriate ASTM D 1593 and DIN 53370 test methods.

The difference in cost between the smooth and textured membranes is significant, the textured membrane being more expensive and therefore the cost implication of specifying textured membranes must be borne in mind at the design stage. The choice of membrane will depend on the required angle of friction between the membrane and the earthworks.

There are generally two ways of producing roughened membranes. The roughened texture can be created either simultaneously as the membrane is extruded or it can be added by spraying HDPE onto a previously extruded membrane. It should be noted that in the latter case, the material retains the elasticity properties of the smooth sheets but delamination of the sprayed HDPE is conceivable. Elongation at break is substantially reduced on roughened sheets where roughening is formed during extrusion. The effect of these changes needs to be considered in design.

iii. Angle of Friction
The development of textured membranes has led to an increased angle of friction being available. The result of tests undertaken as part of the studies into the use of HDPE for the A47 Great Yarmouth Western Bypass demonstrated that the friction angle for clay on a smooth liner can be as low as 9–10° whilst slightly higher values of 18–19° were recorded for sand/gravel. Roughened sheets can increase the angle of friction to between 34–38°.

iv. Strength
HDPE membranes usually exhibit good tensile and elongation properties. Important properties include the percentage elongation at yield and at break together with corresponding tensile strength at yield and at break. Manufacturers/suppliers specifications indicate that the amount for elongation at yield and at break are identical for all thicknesses of membrane. The tensile strength at yield and at break is very much dependent on the thickness of the membrane. The tensile properties can be determined using one of the ASTM D 638 and DIN 53455 test methods.
The specifications indicate that for the smooth finish membranes, the elongation at yield is approximately 13% whilst the elongation at break is of the order of 700%. This contrasts with some rough finish membranes which demonstrate a similar elongation at yield of approximately 13% whilst elongation at break is dramatically less at approximately 100%.

Manufacturers/suppliers specifications indicate that upon soil burial, the values given for tensile strength and elongation may change by ± 10%.

v. **Toughness**

It is primarily the property of puncture resistance which is of importance in the context of protection for polystyrene fill. This property is particularly important during the construction stage where possible damage from the construction equipment may occur. Damage to the liner could allow the passage of chemicals into the polystyrene fill and subsequent deterioration of the polystyrene. The value of puncture resistance is obviously dependent on the thickness of the membrane being used. Puncture resistance can be assessed by the American test method FTMS 101 C 2031.

vi. **Durability**

The durability of HDPE membranes usually depends on the effects of ultra violet light and heat resistance, chemical resistance and stress crack resistance. The effects of ultra violet light, heat and stress crack resistance do not need to be considered in this application of HDPE membranes although the materials should not be stored for long periods on site prior to their incorporation into the scheme in order to avoid damage from ultra violet light.

vii. **Seamability**

The seam along which two membrane sheets are joined must be sealed along its length to prevent the seepage of any chemicals through to the polystyrene fill. These seams should also be able to withstand physical stresses imposed during the construction phase and throughout the operating lifetime of the structure.
A heat fusion welding system is generally used as polyethylene can be joined by the fusion of the polymers. Seam workmanship is critical and strict Quality Assurance controls should be specified.

There are a number of thermal sealing methods which can be used to join HDPE membranes. All methods involve melting one of the membrane surfaces into a liquid state. The effects of temperature, time and pressure are therefore important during the sealing process. Excessive melting can weaken the geomembrane and insufficient melting can result in a weak seam. The thicker membranes are more easily joined as the thinner membranes are more susceptible to overheating which can lead to poor bonding and the formation of undulations in the material. With increased thicknesses of membrane, the quantity of heat required will change as will the speed of fusion.

Hot air, at temperatures usually in excess of 260°C, can be used with an automated pressure device. A method involving a hot wedge/knife consists of an electrically heated blade which melts the geomembrane before roller pressure is applied. It is important to prevent heat passing to the polystyrene blocks during and immediately after sealing.

The dual-hot-wedge method forms two parallel seams with an unbonded central space between them. This allows rapid testing of the seal by pressurising the system with air to determine if any leaks are present. Extrusion (fusion) welding involves molten polymer being extruded between the two geomembrane surfaces to be sealed. The dual-hot-wedge method is preferred as it allows rapid testing of the seals.

6. DETAILEDING OF POLYSTYRENE EMBANKMENTS
6.1 Abutments and Retained Fill
Polystyrene fill material may be placed directly against bridge abutments and vertical facing walls, although it is advisable to allow an air gap on vertical facing wall to avoid lateral pressures being applied to the wall (see Section 4.3). The air gap should be closed off at the top (e.g. by a flexible membrane) to prevent ingress of loose fill material. An air gap width between 20 and 30mm has been used on two projects in Norway (Fryenland pers.comm.). The protective impermeable membrane (see Section 5.2.5) should be carried down the vertical face of the polystyrene to guard against infiltration of fluids.
between the structure and the fill. Drainage outlets will also be required at the base of the wall.

Polystyrene blocks may be trimmed to fit the exact shape of the adjoining structure, although this may be difficult for complex or sharply curved surfaces, and therefore the form of the adjoining structure should be made as simple as possible. Alternatively, the polystyrene may be placed to the approximate shape of the structure and any void infilled with sand. This option is less advantageous as it will increase the fill weight, and may lead to lateral pressures being applied to the wall.

6.2 Transition Zones
Where polystyrene fill construction adjoins a normal fill embankment, transitional arrangements will be required to accommodate differential settlements between the two types of construction.

For simple embankment designs, where no additional geotechnical measures are proposed to improve stability or control settlements, a transition may be achieved simply by progressively reducing the thickness of the polystyrene over the transition zone. The length of transition zone is determined by the anticipated magnitude of differential settlement and the maximum angular deflection that may be tolerated for the finished surface of the embankment.

Where ground improvements or other measures (e.g. surcharging) are required, the design of the transition zone is potentially more complex. From a practical viewpoint, it would be advisable to adopt uniform ground treatment for both the normal fill and polystyrene fill sections, so that the simple approach described above may be adopted.

However, for economic reasons, it is usually desirable to reduce or eliminate ground treatment beneath the polystyrene fill sections of the embankment, resulting in variations in the stiffness of the embankment foundation, or in consolidation rate, across the transition zone. The variation in settlement will therefore be much more complex, and detailed analysis will be required to determine the settlement profile across the transition zone, and the variations in settlement profile with time. It should be recognised that the performance of many ground improvement methods is difficult to predict with certainty.
The consequences of this uncertainty must be considered in the design of the transition zone.

In designing the transition zone, consideration should be given to the stability of the normal fill slope at the interface with the polystyrene. In order to reduce stresses and deflections in the polystyrene fill, it is recommended that the normal density fill element of the transition embankment is placed at the base of the embankment (apart from the minimum cover required for protection, etc.) - see Figure 3.

Figure 3: Typical detail of transition zone (long section).

6.3 Polystyrene Fill Layers
Polystyrene is supplied in the form of blocks or boards and for economy of production, such blocks and boards are produced in a limited range of standard sizes (see Section 3.1). Although it is possible to cut the blocks and boards to any shape, the operation of cutting and the inevitable wastage of material adds significantly to the construction costs, and therefore it is desirable to minimise the amount of site cutting. Furthermore, it is usual to restrict trimming of blocks to straight cuts perpendicular to the largest face of the block, as this is easiest and involves the least wastage of material.
In consequence of the above, polystyrene fills are formed of successive layers of uniform thickness, with each layer having edges perpendicular to the plane of the previous layer. Where the thickness of fill varies, as is the case below side slopes, this is achieved by stepping of successive layers (Figure 4). This stepped arrangement has a practical advantage in that it assists retention of soil cover on side slopes.

![Diagram](image)

Figure 4: Typical construction of a polystyrene fill embankment.

In the United Kingdom, the standard layer thickness is 610mm, but 305mm thick expanded polystyrene blocks are available when required. The more expensive extruded materials may be used in thinner layers, with these materials being supplied in a range of thicknesses up to 110mm.

Polystyrene fill layers should be planar, but may be laid to a single gradient, to follow approximately the finished level of the embankment, if desired. Curved surfaces, crowns and valleys, and complex arrangements of falls should be avoided as these will make it difficult to place successive layers so as to form a tightly packed and stable mass (for low height fills, it may be practicable to accommodate gentle vertical curves or simple crowns).
In plan, polystyrene fill layers may be trimmed to any desired outline, but it is recommended that simple straight edges separated by the minimum number of angles are adopted, to facilitate site cutting and placement of the protective membranes. Gentle curves may also be accommodated without too much difficulty, but sharp curves and intricate shapes should be avoided.

For detailed design drawings, it is usually sufficient to indicate the limits of each layer, referenced to a convenient setting out line and set of base levels. Detailed block layout plans are not normally necessary but may assist construction. The position of individual blocks can be determined during laying, using the simple rules described in Section 7.2.

6.4 Drainage of Polystyrene Fills

Adequate drainage of the upper surface of polystyrene fills is essential, as accumulation of water will prevent adequate compaction of the overlying fill and pavement materials. Good drainage will also assist protection from petrol and chemical spillage by assisting dispersal of fluids away from the polystyrene and its protective membrane.

It is, therefore, recommended that, on large horizontal surfaces, the protective membranes are laid on a sand bed prepared with falls towards the edges of the embankment. The sand bed has the further advantage of increasing friction between the protective membrane and the polystyrene fill.

Where polystyrene fill is placed against slopes (e.g. in landslide repairs), drainage may also be required along the interface between the polystyrene and the ground to relieve water pressures, resulting from seepage from the ground.

Temporary dewatering may be required in some situations to enable the placement of polystyrene below normal ground water levels. Such dewatering should be maintained until sufficient weight of cover has been placed to resist flotation.

6.5 Accommodation of Services, Street Furniture, etc.

Careful detailing is required to ensure that services, sewerage, and the foundations of lighting columns, safety fences and road signs can be accommodated within the
embankment without damaging the polystyrene fill or compromising the protection to it.

It is usual practice to increase the depth of fill cover below highway verges to about 1.5 to 1.7m, and to place drainage and services within this fill cover. Provided that reasonable care is taken, trenches can be excavated in the fill cover without undue risk of damage to the polystyrene fill. The thicker polyethylene membranes used for protection to the polystyrene have sufficient strength and toughness to resist impact damage from an excavator bucket, should trenches be taken too deep.

Concrete bases are recommended for safety fences, lighting columns and signs. Driven posts should not be used, as there is a risk of puncturing the protective membranes, and such damage is likely to be undetected.

It is recommended that sumps for drainage gullies are accommodated in the verge, rather than below the carriageway edges as is usual practice.

Service ducts passing beneath the carriageway, should as far as practicable be accommodated within the capping layer, above the polystyrene. Where this is not possible trenches may be formed within the surface of the polystyrene fill and lined with the protective membrane. In such cases, the services should be installed in this trench prior to placement of the capping layer. The services may be sealed over with a protective membrane with resealing being relatively simple should further access be necessary.

Service penetrations through the polystyrene fill are not recommended but, where these are unavoidable, careful detailing is necessary to ensure that these do not form routes by which petrol or solvents may enter the fill. For this reason, high density polyethylene sleeves or ducts may be required in some locations. As a minimum requirement, the protective sheeting must be sealed to the pipe, duct or sleeve. Where temporary penetrations for geotechnical instruments are required, the access tubes or cables should be cut down to the surface of the polystyrene and the penetration sealed off with a patch of protective membrane when the instruments are no longer required.
6.6 Landscaping

Landscaping of the finished fill surface presents few problems provided that the required final surface profile is adequately defined during the design stage, as adjustments are difficult to accommodate once construction is under way.

The minimum soil cover required for protection of the polystyrene (see Section 5.2.2) will usually be sufficient to provide an adequate growing medium for large shrubs and small trees. For large trees, it may be necessary to form pockets in the polystyrene to accommodate an additional thickness of soil. Horticultural considerations may impose additional requirements on the specification of the soil cover, such as an increased depth of topsoil. These requirements may impose practical limits on the angles of side slopes, as it is generally difficult to retain thick top soil layers on steep slopes.

Complex shapes should be avoided because of the increased difficulty in forming the polystyrene fill and its protective membranes to such shapes.

Polystyrene and the membranes commonly used for protection are non-toxic to plants, and will not degrade under normal soil conditions or in contact with fertilisers.

7. Construction of Polystyrene Fills

7.1 Storage and Handling

The handling of expanded and extruded polystyrene materials on site presents few difficulties. The commonly supplied sizes of blocks can be lifted easily by hand, and large volumes may be moved rapidly by, for example, a small mobile crane. This ease of handling can be a considerable advantage where access to the site for vehicles is difficult (e.g. steeply sloping sites). Some care is, however, necessary to avoid damage to the blocks by impact or abrasion.

Polystyrene materials are vulnerable to damage from a number of causes if left unprotected (see Section 5.1), and it is therefore desirable that the material is placed in its final position in the works as soon as practicable to reduce the potential for damage. Where site storage of materials is necessary, care is required to prevent deterioration. Stockpiles should be sited on a clean, dry, and level base, located away from heavily used access routes, fuel storage and handling areas, and potential sources of ignition.
The blocks must be carefully stacked in a regular and stable manner, and should be covered by sheeting to exclude ultra violet light. It is also necessary to anchor stockpiles against wind. Good site security is also important as the stockpiled material will be vulnerable to theft and malicious damage, and in high risk areas, consideration should be given to placing material in secure covered storage.

7.2 Placement
Successful construction of polystyrene fills is dependent to a large degree on the preparation of the surface on which the polystyrene blocks are to be laid. It is essential that this surface is smooth and planar, and this is best achieved by placing a bedding layer of sand and levelling this by hand. The surface of this bedding layer should be left loose, such that the first layer of blocks may be "bedded in" to the sand to give a firm stable base to the fill. It may be necessary to relevel the sand to achieve a level upper surface to the first layer of polystyrene. It should be stressed that additional care taken in preparation of the sand bed and laying of the first layer of polystyrene will be worthwhile, as this will greatly facilitate placement of the subsequent layers of blocks.

In each layer, the polystyrene blocks should be laid so as to overlap the joints in the layer below and, where practicable, the orientation of the long axes of the blocks should be at right angles to that in the layer below (Figure 4). Because of slight variations in block size, some selection or rearrangement of blocks may be required to achieve a sufficiently smooth surface on which to place the next layer. Where necessary, blocks may be cut to size to suit the required fill outline, using a hot wire, straight saw blade or a chainsaw. Fixing or joining of polystyrene blocks is not normally required for long term stability, as friction and contact forces on the block surfaces are usually sufficient to retain blocks in place in the finished embankment. The Norwegian and French design guides recommend the use of double sided steel fasteners, as used for timber fixing, to fix blocks together, but as the penetration of fasteners into the blocks is limited, these are considered to be of dubious value. If fixing of blocks is required to ensure temporary stability during construction, it is recommended that this achieved by driving lengths of mild steel reinforcing bar through the blocks into the layer beneath (the length of bar should be approximately one and half times the layer thickness). The presence of fixers does not allow for the easy repositioning of the fill and damage to the blocks may therefore occur.
Placement of polystyrene should be programmed such that the material is covered as soon as possible after placement, and the area of polystyrene exposed should be kept as small as practicable. Where it is necessary to leave areas of polystyrene exposed for long periods, the polystyrene should be covered with sheeting to exclude ultra violet light, and blocks should be pinned or weighted as necessary to prevent accidental disturbance of the fill.

Damage to polystyrene fill may be repaired simply by removing and replacing the individual blocks concerned.

7.3 Plant Restrictions

Restrictions on operation of plant over polystyrene are necessary to prevent damage to the material. In general, no plant should be operated over polystyrene fill until at least 150mm thickness of normal fill cover has been placed. Thereafter, it is recommended that the maximum weight of compaction plant is limited to 6000 kg/m width of roll until filling is completed. Vibratory compaction plant should not be used within 500mm vertically and 2m laterally from polystyrene fill. It is recommended that other construction plant shall be limited to a maximum applied pressure of 20 kN/m².

Where the operation of plant directly on polystyrene fill is unavoidable, temporary mats should be provided to distribute plant loads such that the design strength of the fill is not exceeded. Particular care must also be taken to avoid fuel spillage, and it is advisable to provide temporary sheeting over the polystyrene. It is recommended that trafficking of areas of polystyrene embankment is kept to the minimum required for construction in those areas only, until such time as the highway pavement is completed.

Loading of the completed embankment should not exceed the design vehicle load, and it may therefore be necessary to check the loads applied by large items of plant (e.g. large cranes) to confirm compliance with this requirement. Stockpiling of materials on the fill surface should also be undertaken with care, and preferably avoided, as this may also lead to overstressing of the fill, in particular at lower levels in the embankment.

In all construction operations in the vicinity of polystyrene fill, a reasonable degree of care and vigilance is required to avoid damage to the polystyrene or the protective
membranes. Particular care should be taken when excavating into the soil cover over the polystyrene, and it is essential that operations are closely observed and supervised. Any damage to the polystyrene or membranes must be repaired promptly.

### 7.4 Installation of Protective Membranes

The protective membranes should be laid as soon as practicable after laying polystyrene. Individual sheets should be jointed to form a continuous impermeable membrane. For the high density polyethylene sheets, this should be carried out by extrusion welding. Welding should be carried out clear of the polystyrene surface and the joint should be allowed to cool sufficiently before it is placed in contact with the polystyrene. Care should be taken to ensure that a complete seal is formed along each joint. At the joints, the sheets should be lapped, with the lap being positioned so that fluids tend to drain away from the joint.

Minor damage to the membranes may be repaired without the need to replace whole sheets by placing a patch over the damaged area, provided that there is no significant damage to the polystyrene fill beneath. The patch should extend at least 200mm outside the damaged area and should be joined to the membrane by extrusion welding.

A minimum of 50mm sand bedding is recommended between the polystyrene and the protective membrane under the pavement to provide an even surface for laying the membrane and a passage of escape for any trapped water vapour.
REFERENCES


BS4735:1974. Laboratory method for test for "Assessment of the horizontal burning characteristics of specimens no larger than 150mm x 50mm x 13mm (nominal) of cellular plastics and cellular rubber materials when subjected to a small flame". British Standards Institution, London.


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APPENDIX: SUGGESTED SPECIFICATION FOR POLYSTYRENE FILL AND PROTECTIVE MEMBRANES

A. Polystyrene Fill


2. In addition to the requirements of BS3837:Part 1:1986 or BS3837:Part 2:1990, the material shall have the following properties:

a. Nominal Density and Compressive Stress


<table>
<thead>
<tr>
<th>Grade</th>
<th>Nominal Density kg/m³</th>
<th>Minimum Compressive Stress at 1% strain kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>HD</td>
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<td>45</td>
</tr>
<tr>
<td>EHD</td>
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<td>100</td>
</tr>
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<td>E3</td>
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<td>135</td>
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<td>370</td>
</tr>
<tr>
<td>E7</td>
<td>28</td>
<td>210</td>
</tr>
</tbody>
</table>

Note: The values of compressive stress at 10% strain typically range from 70 to 190 kN/m² for expanded polystyrene and from 200 to 700 kN/m² for extruded polystyrene.

b. Water Absorption

A maximum water absorption value of 6% by volume when tested in accordance with ISO 2896.
3. The polystyrene shall be in the form of moulded rectangular blocks cut and trimmed as necessary to comply with the dimensional tolerances of BS3837: Part 1:1986 or BS3837: Part 2:1990. Where it is necessary to cut a block to the required shape shown on the Drawings, this shall be performed by the use of a hot wire, cold straight edge cutting blade, or chainsaw.

4. The Contractor shall ensure that the polystyrene is transported to site, stored, and placed in such a manner that no deterioration occurs to material from exposure to ultra violet light, sources of heat in excess of 75°C, petrol fluid or vapour, other hydrocarbons, organic solvents, or any other solvent or material which may react with polystyrene. Stockpiles of material shall be placed on a clean, dry, level base and the material shall be stacked in a regular and stable manner. The Contractor shall take all necessary measures to protect the material from mechanical damage.

5. The lowermost layer of polystyrene blocks shall be laid on a bed of fine aggregate, grading C to BS882:1983, of not less than 50mm thickness. The surface on which the lowermost layer of polystyrene blocks is to be laid shall be prepared such that at any point it shall not deviate from the levels shown on the Drawings by more than ± 10mm and shall not deviate by more than ± 3mm from a 3m straightedge.

6. The blocks shall be placed in layers of 610mm or 305mm nominal thickness. The blocks shall be placed in a staggered pattern such that the vertical edges of the blocks shall not be aligned in adjacent layers, except where shown on the Drawings. The blocks shall be laid such that the direction of the long axes of the blocks is perpendicular to that of the blocks in the layer below. The blocks shall be tightly packed and laid such that the difference in level between adjacent blocks, measured at the joint, shall not exceed 3mm.

7. The Contractor shall ensure that adequate measures are taken to prevent movement of the placed material due to wind, vibration or any other effect during construction. Where the polystyrene blocks require fixing in order to comply with this requirement, or where instructed by the Engineer, the blocks shall be fixed to the layer below or to the soil using R10 reinforcing bars of 1.0m length driven vertically.
8. Polystyrene shall not be compacted.

9. No construction plant, other than compaction plant, shall be driven or placed upon the polystyrene until a minimum of 200mm of acceptable fill material or capping layer has been placed over the polystyrene, except for temporary access in accordance with paragraph 11 below. Vibratory compaction plant shall not be used to compact fill material within 500mm vertically and 2m laterally from the polystyrene fill. Compaction plant shall be limited to a maximum weight of 6000 kg/m width until such time as the placement of capping layer or pavement materials is completed to the finished road levels shown on the Drawings.

10. The requirements outlined in paragraph 9 shall also apply for a distance of 2 m from the outside vertical edge of the polystyrene fill.

11. Temporary access over the polystyrene by plant and vehicles, shall only be carried out using protective sheeting over the polystyrene and temporary boarding or tracking such that the pressures applied to the polystyrene shall not exceed 20 kN/m².

12. Materials shall not be stockpiled on the polystyrene fill, or on the finished surface of the embankment above the polystyrene fill, unless otherwise approved by the Engineer.

13. The loads applied to the embankment surface by vehicles or plant operating over the completed embankment shall not exceed the maximum laden weight or the maximum axle load permitted for use on the public highway, or equivalent, except where otherwise approved by the Engineer.
B. Protective Membranes

1. Protective membranes shall be provided to protect the polystyrene fill at the locations shown on the Drawings.

2. Protective membranes shall be high density polyethylene sheeting complying with the requirements of BS3412:1976. The polymer shall be modified to conform to Class W for weather resistance. Membranes shall be of the thicknesses shown on the Drawings. The membranes shall be chemically resistant to petrol and other hydrocarbons, organic solvents and concentrated acids. Typical specifications are given in paragraphs 6 and 7 below.

3. Individual sheets shall be joined to form a continuous sheet, except where shown otherwise on the Drawings or permitted by paragraph 4. The joints shall be formed by the use of an extrusion welding appliance or alternative approved by the Engineer. The contractor shall perform such jointing prior to placement of the membrane in contact with the polystyrene, and placement of the jointed sheets shall not occur until the temperature of the sheet at the joints falls below 75°C. A minimum overlap of 200mm shall be provided at each joint and the overlap made such that, when placed, no fluid can be made such that no leakage of petrol or other hydrocarbons, organic solvents or concentrated acids may occur through the joint.

4. The Contractor shall take all due care, when carrying out operations in the vicinity of the protective membranes, to prevent damage to the membranes. Should a tear occur within the membrane, or a hole be pierced through it, the Contractor shall either replace the sheet in which this occurs, or seal the tear or hole by jointing a piece of membrane of identical thickness and properties to the damaged sheet, extending a minimum of 150mm beyond the tear or hole. The joint shall be formed in accordance with sub-clause B of this clause.

5. Where shown on the Drawings, protective membranes shall be laid on a layer of fine aggregate grading C to BS882:1983. The thickness of this layer, and the levels and gradients of the surface of the layer, shall be as shown on the Drawings.
6. The 2.5mm thick HDPE membrane for use below the pavement and verges shall have the following properties:-

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<thead>
<tr>
<th>Smooth Membrane</th>
<th>Test Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, mm, minimum average</td>
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<tr>
<td>Thickness, mm, lowest individual</td>
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</tr>
<tr>
<td>Minimum density Mg/m³</td>
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</tr>
<tr>
<td>Minimum strength at break N/mm²</td>
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<tr>
<td>Minimum elongation at break %</td>
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<tr>
<td>Puncture Resistance N</td>
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<tr>
<td>Tear Resistance N</td>
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<table>
<thead>
<tr>
<th>Roughened Membrane</th>
<th>Test Methods</th>
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</thead>
<tbody>
<tr>
<td>*Thickness, mm, minimum average</td>
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<td>*Thickness, mm, lowest individual</td>
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</tr>
<tr>
<td>Minimum density Mg/m³</td>
<td>0.94</td>
</tr>
<tr>
<td>Minimum strength at break N/mm²</td>
<td>14</td>
</tr>
<tr>
<td>Minimum elongation at break %</td>
<td>100</td>
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<tr>
<td>Puncture Resistance N</td>
<td>480</td>
</tr>
<tr>
<td>Tear Resistance N</td>
<td>330</td>
</tr>
</tbody>
</table>

* The thickness referred to is the core thickness.

7. The 0.5mm membrane for use on the vertical faces and below side slopes shall have the following properties:-

<table>
<thead>
<tr>
<th>Smooth Membrane</th>
<th>Test Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, mm, minimum average</td>
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<td>Thickness, mm, lowest individual</td>
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<td>Puncture Resistance N</td>
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<td>Tear Resistance N</td>
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