Geofoam blocks in Civil Engineering applications

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Abstract In Norway the use of Geofoam blocks in road construction applications started in 1972. Excessive settlements of a road embankment adjoining a bridge abutment founded on piles to firm ground was then successfully halted by replacing a 1 m layer of road aggregate with blocks of Expanded Polystyrene (EPS). Boards of EPS had previously been successfully tested in road structures over several years in a major research project related to Frost Action in Soils. The use of Geofoam blocks for lightweight fill purposes, reduced earth pressure and several other applications for a variety of Civil Engineering purposes, has since been adopted and further developed in many countries worldwide. In this article the state of the art regarding various applications of Geofoam blocks are shown based on available information supplied by the authors.

Keywords Geofoam blocks, Lightweight, Stability, Bearing capacity, Settlements

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1. Introduction

Geofoam blocks are made of Expanded Polystyrene (EPS) initially produced for packaging and insulation purposes. The material is extremely light and can be produced in many shapes and densities, typical density $\rho = 20$ kg/m^3. Geofoam blocks for civil engineering applications have typically dimensions 0.5 x 1.0 x 2.5 – 3.0 m weighing some 25 – 30 kg. Material strength properties varies relatively linearly with density and a 20 kg/m^3 material may typically have a compressive strength of $\sigma = 100$ kPa at 10% strain. Geofoam blocks are produced in vide range of densities and strength characteristics. The term Geofoam is also used in connection with Extruded Polystyrene (XPS), but this production process limits the products to board formats.

When Geofoam blocks were first used as a lightweight fill material for road construction purposes in Norway in 1972 [1] it had already been demonstrated by a research project on Frost Action in Soils that boards of EPS could sustain the repetitive loads in a road pavement and that material properties did not deteriorate with time. When excessive settlements (~20 cm/year) occurred in a road embankment adjacent to a bridge founded on piles to firm ground, it was decided to replace 1 m of ordinary embankment materials with EPS blocks placed in two layers each with a thickness of 0.5 m. The embankment rested on 3 m of peat overlaying 10 m of soft clay deposits and due to repetitive adjustments of the road level, the embankment load on the subsoil increased resulting in accelerated settlements and risk of embankment failure. By replacing 1 m of embankment aggregate with Geofoam blocks, being nearly 100 times lighter than the replaced embankment material, the settlements were successfully halted.

The use of Geofoam blocks in civil engineering applications has since been adopted as a general practice in many countries and for a multitude of purposes. International conferences have been instrumental in the dissemination of information related to the properties and use of Geofoam blocks. The first conference was held in Oslo, Norway in 1985 attended by 150 participants from 11 countries [2]. With a strong Japanese engagement in using and further developing the method the second conference was held in Tokyo, Japan in 1996 where 300 participants from 15 countries attended [3]. Similarly, with an increased focus on the use of the method in the U.S. the third conference was held in Salt Lake City, Utah in 2001 [4]. The fourth conference was held in Lillestrøm, Norway in 2011 [5]. The present conference is in this respect a further landmark in disseminating information on the use of Geofoam blocks in civil engineering applications.

In addition to international conferences seminars and local arrangements on a national level have also further promoted the use of Geofoam blocks in addition to bilateral agreements between government agencies and private organizations in various countries and by direct contacts on a personal level.

Today projects using Geofoam blocks are known to have been completed in many European countries: Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Netherlands, Norway, Poland, Russia, Serbia, Sweden and the UK, but other European countries may also have adopted the method. In Asia the major user is Japan (Figs. 1 and 2), but China, Malaysia, Thailand, The Philippines, South Korea and Taiwan are also known to have used Geofoam blocks. India has recently shown an interest and several other Asian countries are likely potential users. The first road embankment with Geofoam blocks was recently completed in Turkey [6, 7]. In America the method is adopted in the US and Canada as well as in Argentina, and Columbia. Civil engineering projects involving Geofoam blocks have been reported from Victoria, New South Wales and Queensland in Australia. No African projects are known so far but situations where the use of Geofoam blocks may have an advantageous potential, are likely to exist there too.

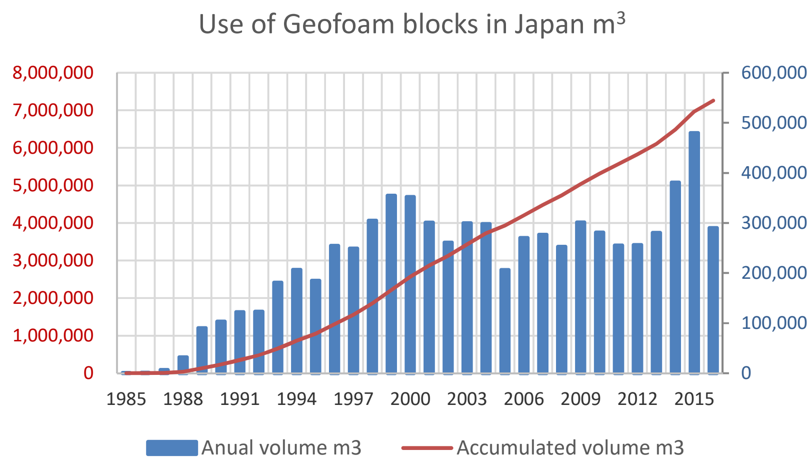

Fig. 1. Volume of Geofoam blocks used for civil engineering purposes in Japan (EDO)

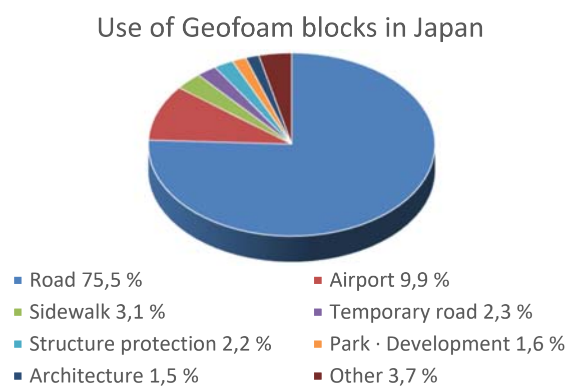

Fig. 2. Use of Geofoam blocks in Japan by purpose (EDO)

2. Applications

2.1 Lightweight fill

The major use of Geofoam blocks has so far been as a lightweight fill material, mainly for road construction purposes [8-17] but also for railroads [18, 19], airfields and other construction projects. The blocks may be applied to reduce the construction load on soft subsoils for both stability and settlement reasons. A typical road cross section with inclined and/or vertical side slopes may be as shown in Fig. 3. Normally the pavement structure above the Geofoam blocks will consist of a sparsely reinforced concrete slab of 10 – 15 cm thickness with a minimum bearing course (some 35 cm) above topped with an asphalt wearing course. In cases where the load on the Geofoam blocks is not critical, a normal pavement structure may be applied but a membrane is then usually added above the Geofoam blocks.

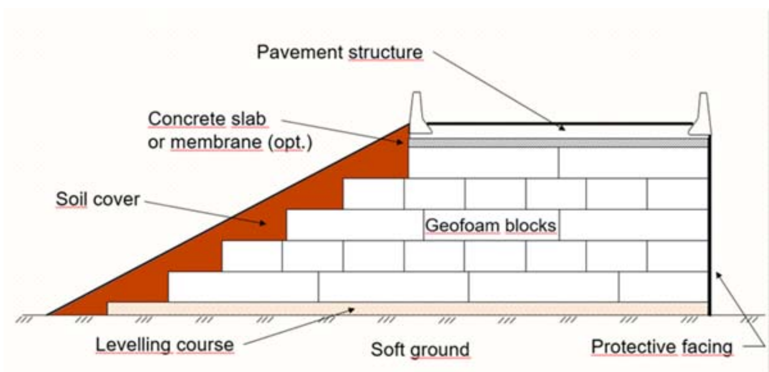

Fig. 3. Cross section of road embankment with Geofoam blocks

As indicated the Geofoam fill may also be terminated with a vertical face on one or both sides. In such cases some form of protective casing should be added to the vertical face. Materials used for such purposes have been aluminum and steel sheets, concrete panels, wooden planks and sprayed concrete. In a landslide area on the Yamagata Expressway in Japan a 16 m high road structure was constructed with vertical walls on both sides, the same design was used to widen the road as shown in Fig. 4 [20, 21]. .

Here 10 cm thick sparsely reinforced concrete slabs were cast for every 3 m height of EPS block fill in order to bind the structure together and even out possible minor level differences when placing the blocks. Also, a form of sliding connections were introduced to allow for possible differential vertical movements.

Fig. 4. Yamagata Expressway, Japan with vertical side walls (EDO)

When widening existing normal roads, it may also be advantageous to use Geofoam in the widened road structure in order to improve stability conditions and avoid differential settlements [22] between the old and the new road structure (Fig. 5).

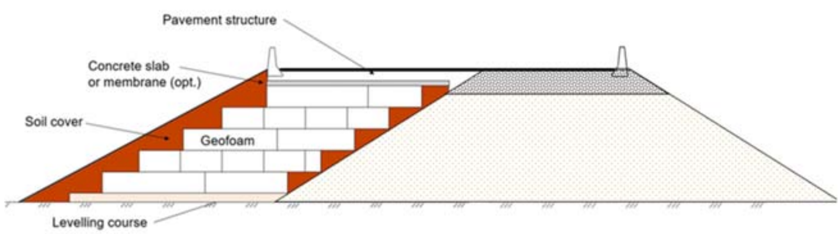

Fig. 5. Road widening application using Geofoam blocks

When widening or constructing roads on steep side slopes, Geofoam blocks with vertical side termination may be a favourable solution (Fig. 6). On slopes, particularly where high fills are involved, the need for proper anchorage should then be analyzed separately. The anchorage should provide support for horizontal forces from soil pressure on the structure and vehicles hitting guard rails or side barriers.

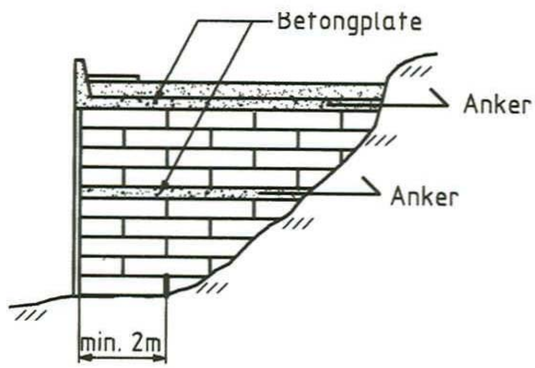

Fig.6. Cross section of high embankment on slope (NPRA)

On the Otari Road in Nagano Prefecture, Japan a 1.2 km road section was constructed (Fig. 7) [21]. The maximum height of the road structure was 17 m and volume of Geofoam blocks used 30.000 m^3 (Fig. 5).

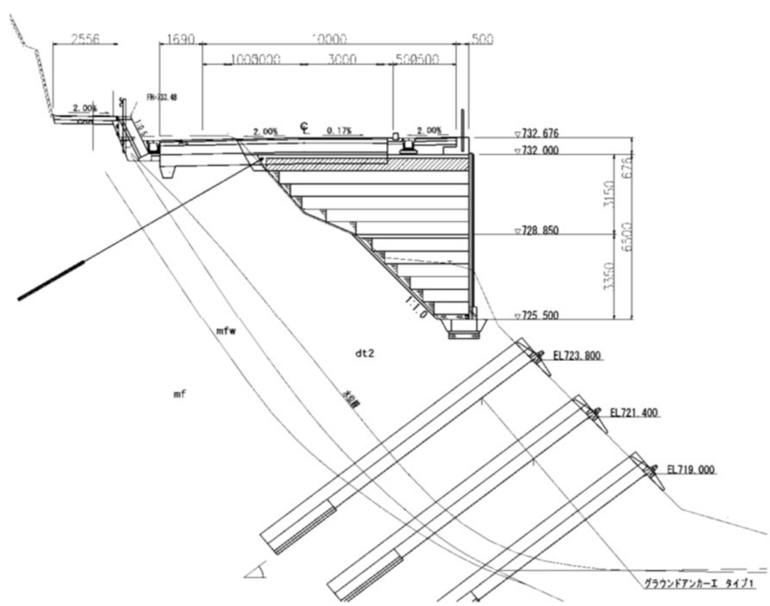

Fig. 7. Design cross section of Otari Road in Nagano Prefecture, Japan (EDO)

With a properly designed ballast layer and load distribution slab (if required) above Geofoam blocks of sufficient strength, the method may also be used for railroads and several such projects have been completed in Norway, the UK, Japan, U.S. and possibly in other countries.

The Utah Transit Authority (UTA) in Salt Lake City has constructed EPS bridge approach fills for its light-rail and commuter rail systems. The dynamic deflection performance of these systems under train loadings has been monitored [19]. Dynamic accelerations were obtained via accelerometer arrays placed on the rail sleepers for these systems. Dynamic deflections estimated from these measurements based on a double integration of the acceleration data suggest that the dynamic deflections are acceptable and comparable to those measured on earthen embankment.

The same applies for airfields whether on taxiways or runways as it is only a question of making an adequate design in order for the structure to sustain the wheel loads from landing or taxying aircrafts. The New Orleans Airport East/West runway rehabilitation project included the removal of existing damaged pavement and the construction of new taxiways. EPS geofoam was used under the new pavements to control settlement on the highly compressible and saturated subsoils and to prevent differential settlements at the intersection of new and existing pavements.

Geofoam blocks may also be used for stability improvement purposes in terrain with potential slide hazards and for slope failure mitigation in areas where slides have occurred (Fig. 8). In order to reduce the driving forces, here a volume of high density natural soil is replaced with Geofoam blocks. Proper drainage is also provided in order to prevent hydrostatic pressure building up within the soil/Geofoam structure. Recent studies were conducted to understand the behavior of slopes under seepage forces and corresponding remedial block configurations tested in a laboratory bench scale models [23-26].

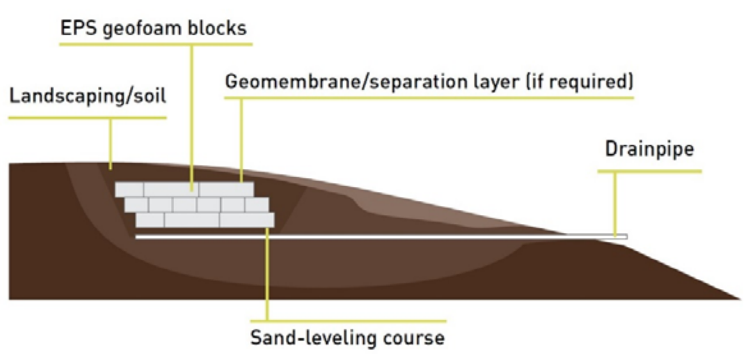

Fig. 8. Schematic drawing of Geofoam block placement in a slide area [27]

Geofoam blocks may also be used as a compensating foundation for buildings in order to reduce the load on underlying compressible soils and minimize building settlement along with solving potential bearing capacity problems. At the building site existing soil is excavated and replaced by Geofoam blocks in order to reduce the net applied load to the soil by the new structure. If the amount of soil excavated equals the total load applied by the new structure, a fully compensated foundation is obtained, i.e. no increased load is applied to the subsoil by the structure.

Similarly, Geofoam blocks may also be used as a lightweight fill material for landscaping purposes. This may be particularly useful when creating undulating terrain features close to existing buildings where normal soil aggregate used for the same purpose could create settlement problems for the building foundations. Some examples of this application include creating roof gardens for urban buildings (Fig. 9). For the same reasons Geofoam blocks may also be used to construct sound barriers to protect roadside residents from noise pollution (Fig. 10).

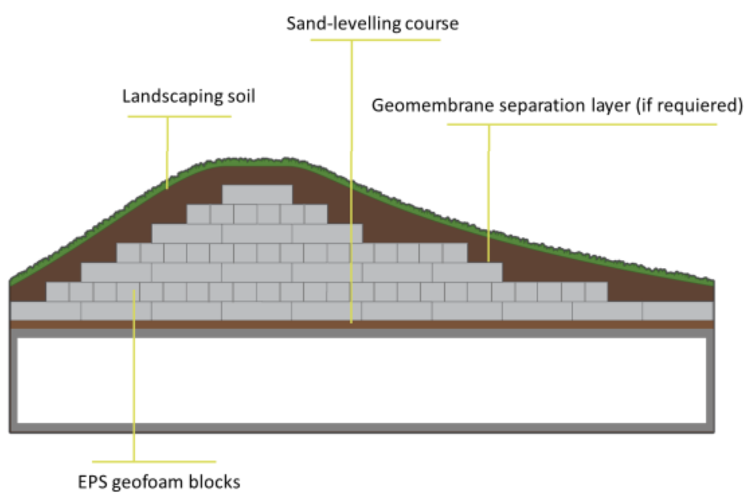

Fig. 9. Schematic drawing of vegetative roof on building [27]

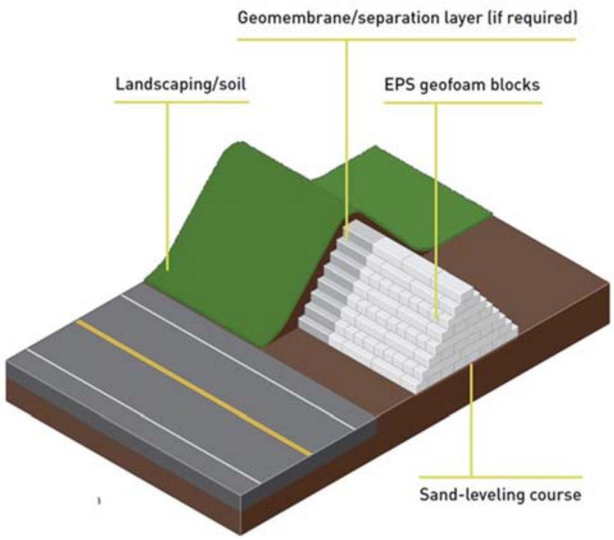

Fig. 10. Geofoam blocks used in noise barrier [27]

When excessive settlements occur in levees and repair must be initiated to cope with expected flood levels, the use of Geofoam blocks may provide a favourable solution. If ordinary fill material is used to raise the embankment height, this will result in further subsidence. By replacing part of the embankment soil with Geofoam blocks, further subsidence may be halted. With the extremely low density of Geofoam, caution must, however, be observed to prevent the Geofoam blocks from becoming buoyant. The buoyancy potential must be considered based on expected flood levels and the volume of Geofoam blocks used and their position relative to the flood level. The uplift tendency may also be countered to some extent by providing anchorage (Fig. 11).

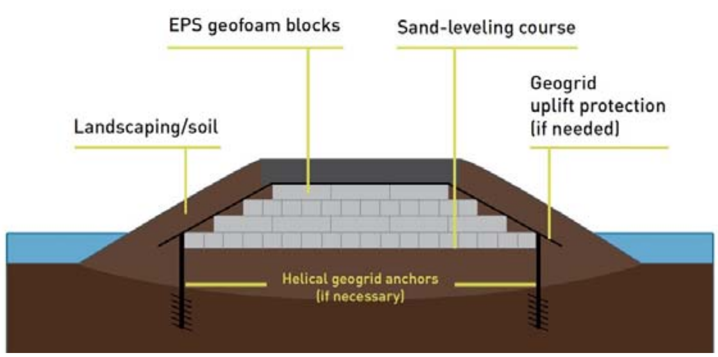

Fig. 11. Cross section showing levee repair using Geofoam blocks [27]

It is of course possible to utilise the buoyancy effect of Geofoam blocks directly for floating piers and similar harbour and marina arrangements. This effect has been taken advantage of for a long time, and in Vancouver, British Columbia, Canada Geofoam blocks are used to support a floating helicopter pad (Fig. 12).

Fig 12. Floating helipad supported by Geofoam blocks in Vancouver, Canada

A similar use of the buoyancy effect has been introduced in the Netherlands where a floating garden built on Geofoam blocks are seen on one of the canals in Amsterdam (Fig. 13)

Fig. 13. Floating garden on one of the canals in Amsterdam, The Netherlands

Some special forms of Geofoam blocks have also been designed to accommodate rising water levels without introducing the full buoyancy forces that a solid Geofoam block would cause [28]. This is obtained by making hollow blocks with slits on the sides allowing water to enter without introducing the full buoyancy force of a solid block (Fig. 14).

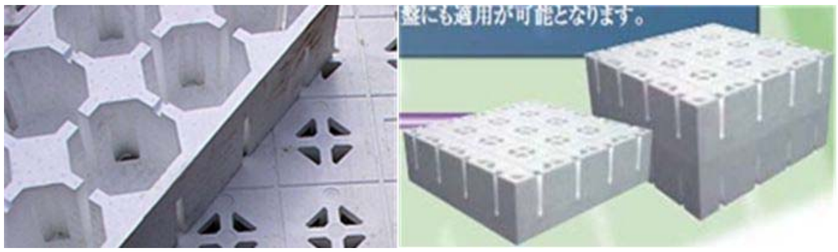

Fig. 14. Design of EPS block with reduced buoyancy effect.

Geofoam blocks may also be used to form tiered seating in locations such as auditoriums, movie theaters, gymnasiums and churches. The high compressive resistance and light weight of Geofoam make it well suited to both new construction and renovation projects. Stacked Geofoam blocks before a protective concrete layer is added and seats, bleachers and other attachments and finishes are installed to complete the project (Fig. 15).

Fig. 15. Stacked Geofoam blocks for seating arrangements (http://blog.achfoam.com/?p=2455)

2.2 Load reduction

Particularly when encountering soft ground conditions with inferior bearing capacity but also in general when subsoil bearing capacity may be a problem due to heavy loads, Geofoam blocks may be used to improve both bearing capacity and settlement conditions. Since the material density of Geofaom blocks is much less than ordinary mineral soils, the load on the subsoil may be substantially reduced by replacing some amount of ordinary soil with EPS. This was the case for the first application of Geofaom blocks in a roadfill in Norway in 1972. By balancing the loads removed by soil excavation with the loads applied to the subsoil by the completed structure, both satisfactory bearing capacity and settlement conditions may be achieved.

Depending on the structure loads and foundation area the compressive strength of the Geofoam blocks must be adjusted accordingly, but the difference in material density of various EPS strength qualities are small compared to the density of the mineral soil to be replaced.

In several projects, particularly in Europa and the US, this principle has also been applied in connection with the design of bridges where bridge abutments have been supported directly on Geofoam blocks. Such an example is shown where the foundations for a temporary Acrow type steel bridge is founded directly on some 5 m high Geofoam fills resting on soft and quick clay in Norway (Fig. 16) [29]. Similar solutions have also been applied for permanent concrete bridges (Fig. 17).

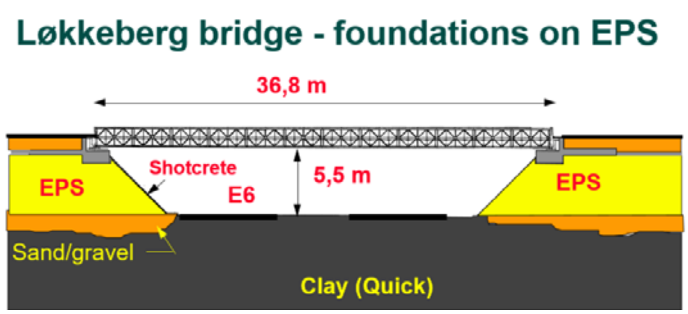

Fig. 16. Bridge abutment founded directly on Geofoam blocks (NPRA)

Furthermore, since fills with geofoam blocks may be terminated with vertical walls, no or only minimal horizontal forces will be transmitted to any structure adjacent to or connecting to the fill. This effect will significantly simplify the design of bridge abutments and retaining walls related to accommodating horizontal forces (Fig. 18).

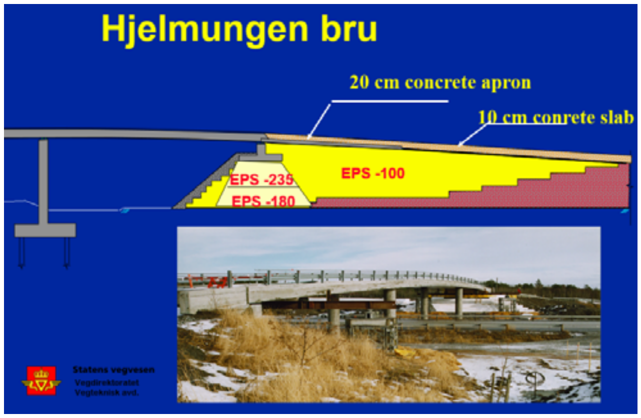

Fig. 17. Abutment for multispan concrete bridge founded directly on Geofoam blocks with varying compressive strength (Norway)

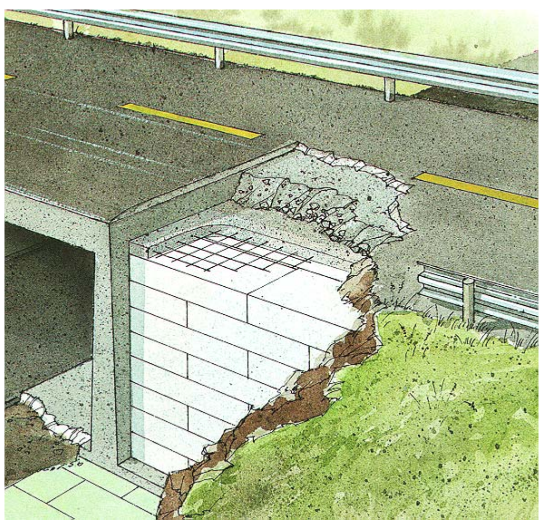

Fig. 18. Backfill of Geofoam blocks against bridge abutment

Another type of load reduction application associated with bridges is a simplified design (Fig. 19). The sheet piles may be driven from the river shores without polluting the water or interfering with fish activities. Scaffolding for casting the bridge deck is connected to the sheet piles or precast bridge deck slabs may be used.

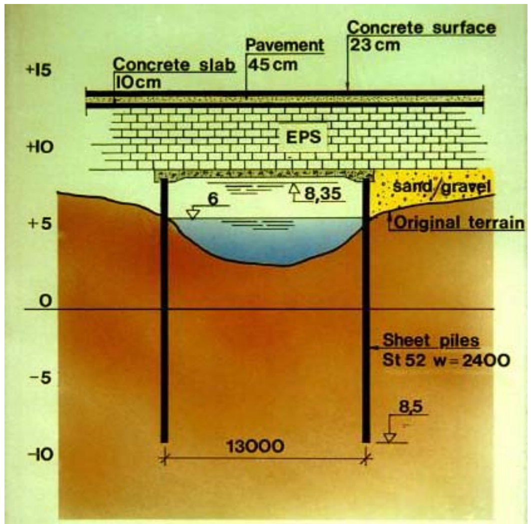

Fig. 19. Simplified bridge design (NPRA)

Geofoam has been used to provide an alternative foundation system for replacing a single span steel girder bridge in Upstate New York [30]. The site is in a wide valley of deep soft sediments. The replaced bridge was supported on a shallow foundation and had settled excessively. The span and width of the replacement bridge was increased to provide more flow capacity and sidewalk. The precast concrete box girder replacement bridge and stub abutment system is heavier than the replaced bridge. Conventional deep pile foundations would have required end bearing at depths greater than 30 m. The alternative foundation system used for the replacement bridge consists of a sheet pile cell that surrounds each abutment foot print. Soil within the sheet pile cell enclosure was excavated and the water level was lowered by sump pumping. The volume of the excavated soil was replaced by EPS geofoam blocks to compensate for the weight of the bridge and foundation system (Fig. 20). The steel reinforcement for a 0.5 m load distribution cap and stub abutment over the geofoam backfill is welded to the top of the sheet pile enclosure. The precast concrete box girders rest on neoprene bearing pads over the stub abutments. While in service, the EPS geofoam blocks become fully submerged during high flood periods. The sheet pile wall friction resistance functions to provide additional capacity to both downward loading and uplift due to buoyancy at low and high flood stages. The completed geofoam supported bridge (Fig. 21) is regularly inspected and continues to receive top rating.

Fig. 20. Geofoam placement within the sheet pile cell

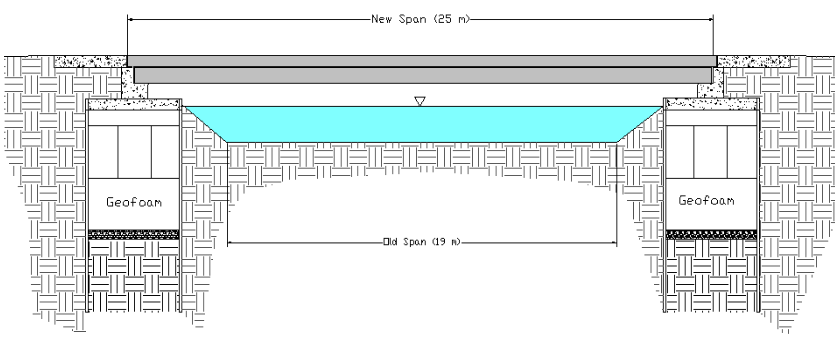

Fig. 21. Schematic section of the geofoam supported bridge

The magnitude and distribution of earth pressure on buried culverts depend on the overburden thickness and the relative stiffness of culvert and soil with varying load distribution along the culvert perimeter. Normally the vertical pressure will be higher than the horizontal pressure. By introducing a compressible layer above the culvert, a more evenly distributed pressure system may be obtained around the culvert. This is a well-known method (often called the induced trench or imperfect ditch method) and various types of compressible materials have been applied for such purposes. EPS is a material well suited for this type of application as the stiffness of the EPS material and layer thickness may be selected to suit a particular project. As the embankment is constructed above the culvert, the EPS layer will deform creating arching effects in the soil above that will redistribute more vertical load to the side of the culvert and hence increase the horizontal pressure. Such effects have been monitored on many culvert projects proving theoretical effects (Fig. 22) [31].

For EPS fills where the blocks are subjected to lateral forces from behind the fill or from traffic and seismic loads, a similar effect by placing deformable EPS blocks against bridge abutments and non-yielding retaining walls, may be utilized to reduce lateral pressure against the wall or abutment [32-35].

For EPS fills with sufficient internal stability terminated in a vertical wall there is no need for a retaining wall as mentioned in section 2.1, only some mechanical protection of the outer blocks. For bridge abutments it has also been demonstrated that leaving a small gap between a stable EPS fill and an abutment wall will prevent transmission of lateral forces on to the abutment from the EPS fill. Monitoring the abutment some 7 years after its completion showed that the EPS fill remained stable and that no measurable movement of EPS blocks had occurred [36].

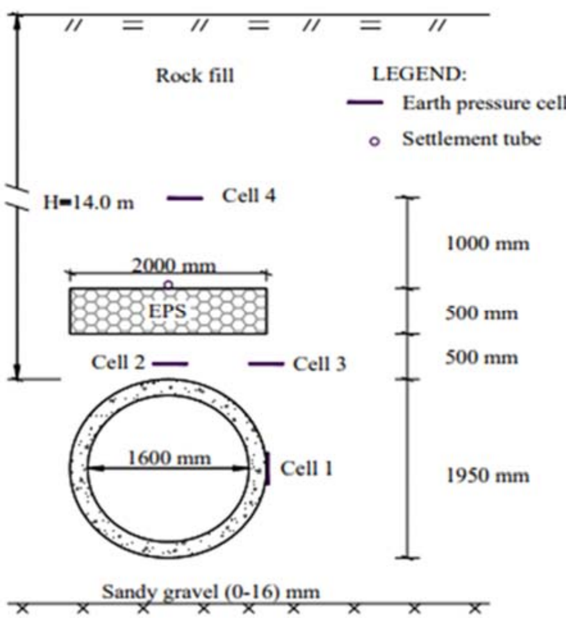

Fig. 22. Example of monitoring pressure distribution on a culvert with a deforming EPS layer above (NPRA)

2.3 Energy absorption

For protecting road users from avalanche hazards in mountainous areas avalanche sheds are sometimes constructed on road sections with frequent avalanche activities. Such sheds will normally have a cover of soil material on the shed roof to absorb some of the impact forces from falling rocks. In order to further reduce the impact loads, Geofoam blocks may be placed on the shed roof with a concrete slab and soil cover on top. When large boulders or rocks hit the structure, the EPS material will deform and absorb a major part of the dynamic energy thus substantially reducing the dynamic loads transferred to the shed (Fig. 23). This idea was first introduced and tested in Japan [37], The method may also be applied for protecting other types of structures form dynamic impacts.

Fig. 23. Geofoam blocks applied for energy absorption on rock fall protection tunnel in Turkey (Curtesy of EPSDER, Turkey)

2.4 Seismic effects on EPS fills

From the start some concerns have been raised regarding the behavior and stability of EPS embankments subjected to seismic loads. This problem has been thoroughly addressed particularly in Japan [38] and the USA [39] both from a theoretical approach as well as in small- and full-scale experiments. This includes both the stability of normal EPS embankments, embankments on slopes and free-standing EPS structures terminated with vertical walls as well as fills adjacent to bridge abutments and retaining walls. Fig. 24. show a test setup of reduced scale shaking table and Fig.25 show a test setup of a Geofoam structure on a large shaking table in Japan. The general picture is that the EPS material has a positive effect on the type of structures analysed during seismic loading and in Japan no special seismic design considerations are required for fills with heights less than 6 m and a height to breadth ratio < 0.8. For higher fills such considerations are recommended. Secondary seismic effects after an earthquake like tsunamis, landslides etc. may, however, damage EPS fills, but no serious damage was reported for EPS structures during the earthquake or the following tsunami effects from the 2011 Tohoku earthquake in Japan. During the 2016 Kumamoto earthquake large ground deformations occurred and an EPS embankment under construction deformed somewhat. The fill was, however, completed without adjustments and the finished road is in normal service.

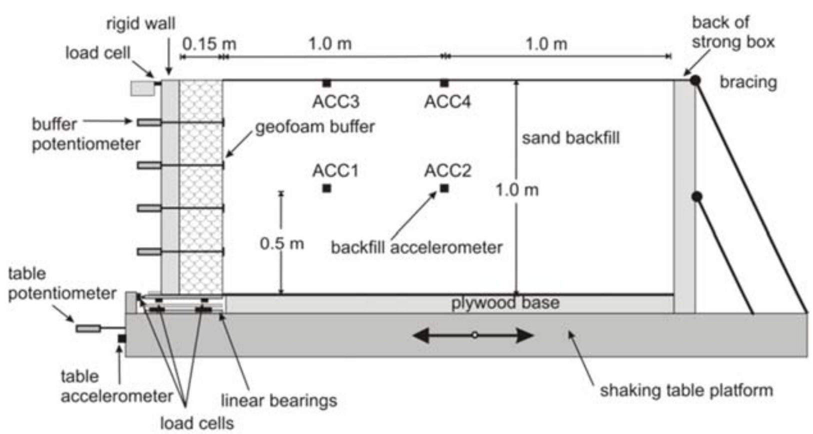

Fig. 24. Setup for shaking table test on Geofoam block structure [32]

Fig. 25 Full scale seismic loading experiment on shaking table (EDO, Japan)

2.5 Speed and ease of construction

For various reasons some construction projects have to be completed within a minimum time span. With the light weight and relatively large volume per block Geofoam blocks may come in handy when construction speed is essential. This has proved the case in several projects [14].

When a high-speed rail service was to be established on the Manchester – Liverpool railway line this involved replacing an old steel bridge from 1899 with a new rail structure [40]. At the same time it was essential to keep the trains running with only a short brake allowed in the railway services for replacing the bridge. The bridge ran across a filled in river channel where various materials had been deposited over a long period of time. The construction method adapted was first to preload the subsoil with a 4.5 m high fill for a period of 9 months starting in 1997. The preload was then removed and a Geofoam fill constructed up to a level just below the steel bridge with the bridge pillars still intact. Then the bridge was demolished, the height of the EPS fill increased to a level somewhat below the new track level and covered with a levelling layer of granular material. A precast concrete trough was then lifted un to the EPS fill. A HDPE liner, ballast material and rails were added on top of the concrete trough and the whole job was completed within 100 hours from the bridge was removed until trains were running again (Fig. 26). The total volume of EPS blocks used with various densities, was 13,000m^3.

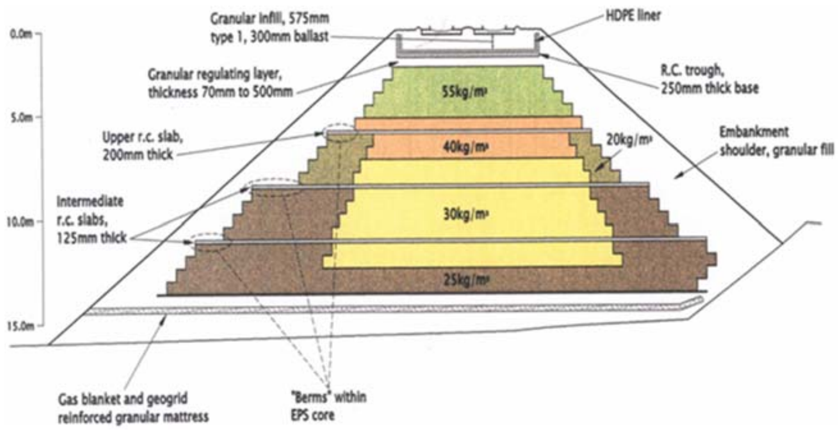

Fig. 26. Main components of EPS fill design for reilway bridge replacement [40]

2.6 New applications

2.6.1 Lightweight Culvert Structure

In Dutch road engineering practice, the arching principle is used to design a settlement-free tunnel construction integrated in an EPS embankment without a pile foundation (Figs. 27, 28). The modular system of corrugated steel sheet elements fulfilled the specific project requirements such as a free space for cyclists and pedestrians, the available cover on the tunnel structure and the construction of the cover layers and pavement structure for the traffic load over the tunnel. In terms of both building costs and construction time reduction, the system offered advantages. The oval tunnel system is based on the load distribution by normal force along the "pressure points" in the steel shell construction. As an alternative to the standard design with compacted sand around the culvert, adequate side support is ensured by a light-weight foamed concrete enclosure combined with stronger EPS blocks. Such a tunnel construction is already in service under the new roundabout of the provincial road N222 near The Hague. There are no technical restrictions regarding either the profile or the traffic load over the considered tunnel system.

Fig. 27. Construction of corrugated steel tunnel in EPS fill

Fig. 28. Finished structure

2.6.2 Seepage Mitigation

Geofoam blocks are used for slope stabilization in Japan and USA [41-44]. The design guideline for using geofoam blocks for slope stabilization and repair projects is based on the recommendation that geofoam slope system incorporate a drainage system for preventing water accumulation above the bottom of the geofoam block configuration [45]. However, the groundwater table may rise due to drainage malfunction. The behavior of geofoam blocks has been studied in Turkey using scaled physical slope experiments [23, 46]. Under the lights of this first study a geofoam block assemblage called embankment type configuration where the backslope applies overburden along the geofoam block assemblage inside the slope (Fig. 29) was proposed [24]. It has been shown that embankment type configuration could prevented both deep-seated failures of marginally stable sandy slopes subjected to seepage and hydrostatic sliding along the base of the geofoam block assemblage [24]. Further studies using geofoam blocks with internal drainage system showed that this would further improve the performance of slopes under seepage [25, 26]. However, the results of these laboratory studies can only be used for providing information about the basis to understand the prototype behavior of geofoam blocks sandy slopes under seepage. It is recommended that the laboratory small scale 1-g model test results must be verified by instrumented prototype model prior implementing the recommended block assemblage in projects [22-26].

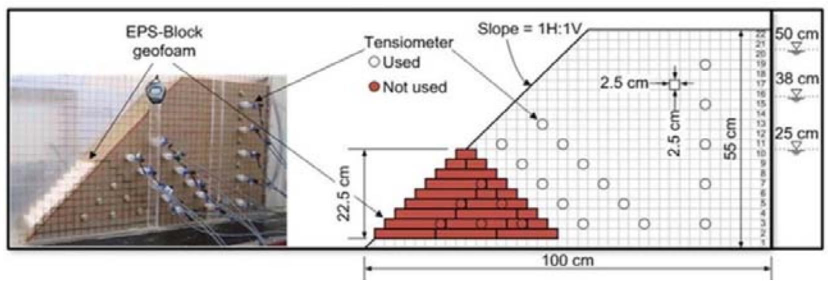

Fig. 29. Embankment type geofoam block configuration [24]

2.6.3 Interface Shear Strength

Internal stability analysis of geofoam highway embankments consists of hydrostatic sliding, transition due to wind and seismic stability [10]. The available shear resistance in between the geofoam blocks needs to be evaluated for seismic stability. If this resistance insufficient, additional resistance can be provided by shear key concept where continuous horizontal geofoam block planes are interrupted by installing half blocks periodically in the geofoam block assemblage [39]. In addition, adhesives can also be used to increase interface shear strength [47, 48]. Alternatively, a concept with interlocked geofoam blocks has been proposed [49] where the geofoam blocks have ledges and notches along their tops and bottoms, respectively. Therefore, when they place on top of each other, horizontal shear planes in between geofoam blocks are interrupted with interlocked configurations [49]. The interlocking mechanism will increase the interface shear strength of traditional geofoam block to geofoam block surface, and as the number of ledges and notches increased the interface shear strength of interlocked blocks approached to the internal shear strength of geofoam blocks [49]. Therefore, this interlocking mechanism can be viable alternative for the geofoam embankments to be constructed in high seismic activity areas. However, due to the scale effect of the laboratory specimens, conducting large scale shear tests were recommended prior to using the interlocked concept in the field [49].

3. Material specifications

When the first road project with EPS blocks was considered, the Norwegian Public Roads Administration (NPRA) decided to define the compressive strength of the EPS material at 5 % strain when testing 50 x 50 x 50 mm cubes in an unconfined compression test apparatus. With the use of EPS blocks for lightweight fill purposes adopted in many countries and the manufacturers showing a higher interest in such uses, more test method have been introduced and a number of research projects have been carried out on this topic including dynamic loading. Different block shapes have also been tasted (cubes and cylinders) with dimension varying from 50 mm to 100 mm and even full-size blocks. The tensile strength behavior of EPS geofoam has also been investigated [50] and found to depend on density. When strong fill materials with high strengths are required Indian investigations [51] show that expanded polystyrene-based geomaterial with fly ash can be used as a substitute for eps geofoam blocks.

This has resulted in both national and international standards being developed. Within the European Union (EU) a standard EN 14933 "Thermal insulation and light weight fill products for civil engineering applications – Factory made products of expanded polystyrene (EPS) – Specification" came into force in 2009 [52]. Here the strength of EPS material is defined at 10 % strain tested on 50 x 50 x 50 mm cubes, but requirements at 2 % and 5% strain are added. Unit density is not set as a requirement in this connection. Discussions are, however, ongoing regarding the size of specimens to be tested with the argument that larger samples will resemble the behavior of full size blocks more closely. In this connection and in order to harmonise requirements in EN 14933 with other CEN standards and Eurocodes the European Manufacturers of Expanded Polystyrene (EUMEPS) has set up a special task force to look into this matter.

The need for international standards is to harmonise material requirements to facilitate free trade and fair competition. The efforts within EU is a start in this direction, but at present most countries outside Europe adhere to local national standards bur some also follow the European standard. Although national standards in general have similar requirements, a common international standard is not expected to materialize sometime soon.

4. Design considerations

With the known properties of EPS material used for load carrying purposes, normal deign procedures may be used for selecting a suitable quality of EPS material for the project in question. For road embankments a compressive strength of σ = 100 kPa corresponding to density of some $\rho = 20$ kg/m^3 will normally be sufficient, but depending on the load situation other material qualities may be required.

For road fills involving Geofoam blocks, reduced loads are in most cases a key issue and in such projects a 10 – 20 cm sparsely reinforced (to prevent curing and temperature cracking) concrete slab is cast directly on top of the upper layer of Geofoam blocks for load distribution purposes. A minimum road base is then placed on top of the concrete slab before an asphalt topping or concrete pavement is added. In countries with below zero winter temperatures the base layer should have a minimum thickness (recommended 35 cm in Norway) in order to prevent black ice formation on the road surface during winter onset.

Since EPS material is soluble in petrol and other oil derivatives, some protective cover should be provided above the Geofoam blocks in case of a major oilspill. The load distributing concrete slab will act as a protective layer but in addition a protective geomembrane sheet (HDPE or similar) is commonly placed to cover the whole Geofoam structure. The membrane should have a thickness of at least 1.0 mm and be inert to petrol and other solving agents. So far no accidents involving damaged Geofoam blocks due to oilspill have been reported and the risk for such incidents occurring is extremely low, but it is a scenario to be prepared for. Even if such an incident should occur, repair actions may easily be taken by replacing the damaged blocks.

In cases where maximum load reduction is not called for, a normal road base may be placed on top of the Geofoam blocks, but again as a precaution a protective geomembrane should be placed on the Geofoam surfaces. Other types of pavement structures may also be applied depending on the loads involved and the strength of the EPS blocks used.

For EPS fills with inclined side slopes, the Geofoam blocks should be covered by a soil layer on the side slopes above the geomembrane. A minimum cover thickness of 25 cm is recommended (Figs. 3 and 5).

For high Geofoam fills a lightly reinforced 10-20 cm thick concrete slab is usually added for every 3.5 – 4 m embankment height. This will bind the structure together and provide improved stability as well as evening out any minor height differences between blocks.

In order to avoid long term creep effects in the EPS structure, it is common practice only to utilise part of the short-term load capacity of the material in design procedures. For normal projects a long-term/short-term load ratio in the range of 0.3 is commonly applied. This procedure is expected to limit creep deformations to 2 % over a period of 50 years. For transient loads a higher ratio may be applied. Also with improved manufacturing processes this may allow for higher ratios in the order of 0.40 – 0.45 to be used for permanent loads.

Although Geofoam blocks have a low unit density of ρ = 20 kg/m^3 (γ_d = 0.2 kN/m^3) when leaving the moulding form at the factory, some allowance should be made in design calculations for possible later changes when placed in the ground. For the first road fill in 1972 the NPRA adopted a design unit density of ρ =100 kg/m^3 (γ_d = 1 kN/m^3). Based on later experience this design rule has later been changed to ρ = 50 kg/m^3 (γ_d = 0.5 kN/m^3) for Geofoam blocks placed in a dry position above the groundwater table while the design load for temporarily or permanently submerged blocks have been maintained at ρ =100 kg/m^3 (γ_d = 1 kN/m^3). Similar design rules apply in other countries.

Submerged EPS blocks may become buoyant depending on the water level and the weight of the pavement structure on top of the blocks. The factor of safety against uplift must therefore be considered. Normally, EPS blocks are placed in a drained condition above the groundwater level. For buoyancy calculations a nominal density of ρ = 20 kg/m^3 (γd= 0.2 kN/m^3) should be applied if this is the material density of the EPS blocks used and the corresponding factor of safety against uplift should be $\gamma_m \geq 1.3$ based on the highest probable water level with a return period of 200 years. The factor of safety is calculated as the total weight of the fill divided by the occurring uplift force.

Since the EPS blocks may be considered as closed bodies where only minute amounts of water will enter when the blocks are suddenly submerged, the resulting buoyancy force per unit volume may be calculated as the difference between the unit density of EPS and the unit density of water, i.e.:

$F_{op} = \gamma_{EPS} - \gamma_w = 0.2 - 9.8 = -9.6$ kN/m^3 (1)

For the specially designed blocks designed for reducing buoyancy forces as mentioned in Section 2, the buoyancy force calculation will be different.

The fill must have sufficient safety against uplift both during the construction stage and later.

In order to provide sufficient internal stability in fills on slopes, a minimum width of 2.0 m is generally required at the foot (Fig. 6). Also sufficient drainage must be provided in order to prevent ponding of water and resulting horizontal forces, particularly on slopes. For high embankments, wind forces must also be considered, both during the construction stage and for the completed structure.

On slopes, particularly where high fills are involved, the need for proper anchorage should be analyzed separately. The anchorage should provide support for horizontal forces from vehicles hitting guard rails or side barriers and soil pressure on the structure.

When EPS is used as fill adjacent to and in contact with bridge abutments, retaining walls etc. the ratio between horizontal and vertical stress on the structure may be considered as σ_h/σ_v= 0.1. This implies that the ordinary fill material adjacent to the EPS fill is terminated with a stable slope so that no soil pressure is exerted on the EPS fill.

5. Construction procedures

When the use of Geofoam blocks started, there was some concern regarding interface friction between blocks and possible block movements both during construction and later due to traffic forces. To eliminate such risks timber binders was used to bind the blocks together. The friction coefficient between adjacent blocks is, however, relatively high ($\mu = 0.7$) and it has been shown that when the fill is completed, the internal friction is sufficient to maintain a stable structure. In areas with seismic activities timber binders will, however, assist in preventing sliding of individual blocks. During construction high speed winds may create suction forces that can lift and shift individual blocks. In such cases timber binders or similar arrangement may be recommended. Gluing the blocks together is also a procedure that is known to have been applied.

EPS is a combustible material and in order to prevent fire accidents, a flame retarding agent [hexa-bromo-cyclo-dodecane (HBCDD), a brominated flame-retardant (BFR)] was for some period added to the EPS material in the production process. This practice has since been abandoned in Europe for environmental reasons as the HBCDD material is shown to accumulate in the ground, particularly near the production plants. When non-flame-retardant Geofoam blocks are used, the construction process and storage pile should be under constant surveillance on the construction site until the whole fill is covered, pavement placed on top and soil on side slopes (if relevant). When the structure is completely covered, fire hazards are eliminated.

5.1 Evenness and tolerances

Before placing the first layer of blocks the ground surface should be prepared to form an even and level surface. A normal requirement may be that deviations in the subsoil stratum from an even surface should be 10 mm or less measured with a 3 m straightedge. Blocks should not be placed on frozen subsoil.

When placing the EPS blocks, a continuous check should be kept to ensure that the evenness of the blocks is satisfactory in each layer. The importance of this factor increases with the height of the fill.

When more than one layer is applied, the EPS blocks in different layers should be placed with the longitudinal direction at right angles to each other and adjacent blocks in the same layer should be shifted about half a block length in relation to adjacent blocks in order to obtain an interlocked, stable structure and avoid continuous vertical joints running through the structure (Fig. 30). This is a very important part of the construction procedure

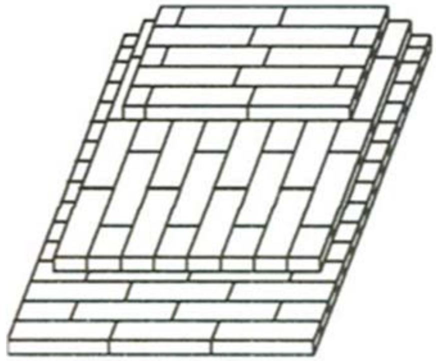

Fig. 30. Interlocking alignment of blocks in different layers.

The different layers in an EPS fill should be parallel to the bearing courses. If the road surface is designed to have a two-way (roof type) cross fall, the EPS fill should still be placed in parallel layers. The specified cross fall may be achieved by adjusting the thickness of the pavement structure accordingly. End adjustments using EPS chips or thin boards (< 10 cm thickness) should not occur.

For fills with normal side slopes of 1:1.5 or 1:2, the side slope of the EPS fill is often terminated with a side slope of 2:1. For very soft subsoils less steep side slopes may be considered in order to reduce loads on the subsoil and prevent excessive settlements. All types of fill material may be used on side slopes. The minimum thickness should be at least 0.25 m. After placing the protective membrane against the EPS side slopes, a geotextile cloth is often also added on top of the membrane before placing the soil cover.

In order to obtain a solid, homogeneous structure variations in block dimensions must be kept within certain limits. The shortest side of any block should at least be 0.5 m if not otherwise specified and the block length at least be 2.5 m. Block sides should be plane and at right angles to each other. Tolerance levels for given dimensions (length, width, height) is normally set to be within ± 1 % and block surfaces should not deviate from a plane surface with more than 5 mm measured with a 3 m straightedge. Differences in heights between adjacent blocks in the same layer should not exceed 5 mm. Particular care should be taken if the blocks are delivered from different producers.

When placed in curves, small vertical gaps between blocks may occur. In such cases it is recommended to fill the gaps with LECA spheres (Light Expanded Clay Aggregate) of some other granular material.

5.2 Guard rails

For road embankments above a certain height guard rails are normally required. For EPS fills guard rails may be anchored in the concrete slab (Fig. 31) above the EPS blocks (if the slab design solution is used).

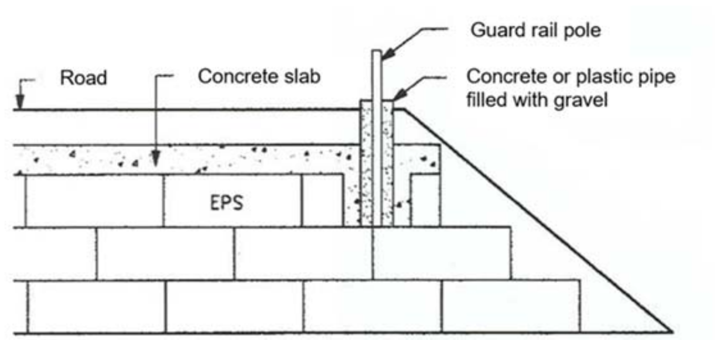

Fig. 31. Anchoring of guard rails

Guard rails may also be anchored by using a special arrangement (Fig. 32). If the concrete slab on top of the EPS is omitted, a similar arrangement may be used by reducing the width of the upper block layer by some 0.5 m replacing the EPS with ordinary fill materials instead.

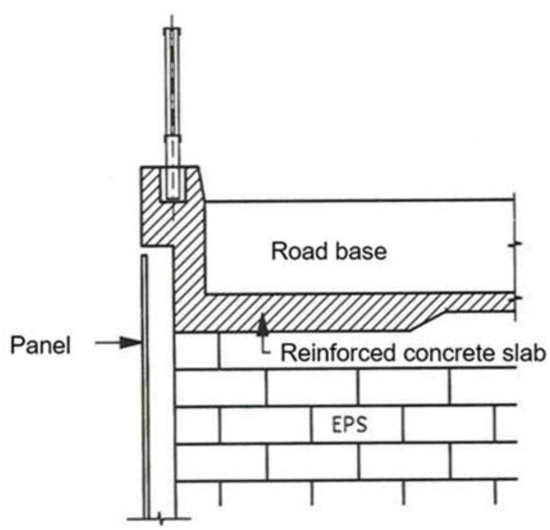

Fig 32. Arrangement of guard rails for EPS fill with a vertical termination.

Where EPS fills are used against bridge abutments, special concrete aprons may be installed in the transition zone between the EPS fill and bridge abutments or culverts to reduce settlement differences. The concrete apron may be 200 mm thick and 3 - 6 m long (in the direction of the road) cast with a high strength mix design. A joint should be provided between the apron and the concrete slab above the EPS blocks if a slab is used

Construction of EPS fills may be performed during winter if the ground has been levelled and no frozen subsoil is present.

5.3 Quality assurance

A producer of EPS blocks should at the latest, when a tender for delivery is opened, produce documents giving details of the quality assurance system applied in the production process. Quality certificates should be submitted for blocks delivered on site and detailed requirements for such documentation may be specified (i,e like in EN 14933). Sampling should be performed by the authorities in charge of construction and the samples tested according to the specified quality control before the blocks are placed in the fill.

Selection of blocks for quality control should be made at random, but evenly distributed among any set of blocks. The frequency, when testing for material strength, may be as shown in Table 1. Sampling of test specimens may be performed as shown in Fig. 33. Block dimensions and evenness may be checked on one in every 25 blocks. Requirements regarding evenness and level of subsoil surface below the EPS may be checked in a cross-section profile for every 10 m of road.

Table 1. Frequency of control for compressive strength.

Size of fill	Number of blocks to be checked
< 500 m3	Minimum 3 blocks
500 - 1000 m3	Minimum 5 blocks
> 1000 m3	Minimum 5 blocks pr. 1000 m3

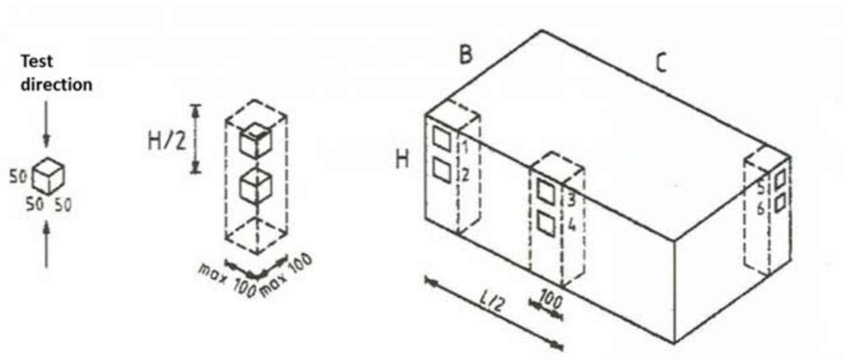

Fig. 33. Possible sample pattern for testing material strength. (dimensions in mm).

For a specified EPS strength quality of σ = 100 kPa the average value for tested blocks should not be less than 100 kPa. The average value for individual blocks (minimum 6 samples) should not be less than 90 kPa and no single test result should be less than 80 kPa. This is a type of acceptance values that may be used.

6. Monitoring programmes

Expanded polystyrene is a very stable compound chemically and no material decay should be expected when placed in the ground and protected according to the present design guidelines. Still, since the first road insulation project with EPS was performed in Norway in 1965 and the first EPS lightweight embankment was constructed in 1972, EPS embankments have been monitored for long term performance [29] along the lines followed for other lightweight fill materials used in road constructions. The monitoring programme has over a period of some 40 years focused on the following material properties:

- Material behaviour
  - Compressive strength
  - Water absorption
  - Decay
- Deformation
  - Total embankment deformation and deformation in EPS layers
  - Creep effects
- Stress distribution
- Reduced lateral pressure
- Bearing capacity

Also laboratory and full scale tests have been performed related to stress distribution and deformations in the EPS material.

Measured values show that the material strength is maintained during the observation period and even a slight increase in strength has been indicated.

Observations of unit density furthermore show that the design unit weight of $\gamma_d = 0.5$ kN/m^3 is not exceeded for embankments with EPS material placed above the groundwater table. The corresponding water content is measured to below 1 % by volume and no change is observed with time.

In blocks, which are periodically submerged, water contents of up to 4 % by volume have been measured. In permanently submerged blocks measured water contents have reached values close to 10 % by volume with some increase over the years. Further increases above 10 % by volume are, however, not to be expected. For submerged fills the average density is therefore of the order of $\rho = 90 - 95$ kg/m^3 after some 20 years in the ground. The water content decreases rapidly in blocks above the water table and show values for drained conditions only some 200 mm above the highest water level.

As expected excavated blocks from permanent and temporary structures show no visual sign of decay. Furthermore no indication of insect attacks have been observed and the EPS material has no nutritional value for either insects or animals. Rodents have, however, in one case been observed to have excavated their own small den for housing purposes. This had, however, not impaired the function of the EPS fill.

In EPS fills subjected to normal loads (weight of concrete slab and bearing course layers) deformations of the order of 1 % of the fill height have been observed after the load has been applied. Even in fills supporting higher loads as shown in fig. 13 and 14, deformations of the same order and with minute creep effects over time have been observed. Deformations and creep effects vary, however, somewhat for the different block layer

Summing up, the overall results form the monitoring programme indicate that the EPS material behaves as expected and that the selected design parameters provide stable and satisfactory structures for long time performance [29].

Similar monitoring and research programmes performed in other countries show results along the same lines.

7. Failures

Of the several EPS projects now completed in many parts of the world, only a few known failures have been reported. Two failures are associated with water fluctuations and buoyancy forces. The other three are caused by fires.

On the 16th of October 1987 Northern Europe experienced exceptionally strong storms with high wind velocities and high rainfall intensities. Norway was also exposed to major floods, and in the Oslo area the first EPS fill built in 1972 floated off as did an adjacent section of motorway constructed some years later. What was wrong? Had the dangers of buoyancy forces not been considered? Yes, such calculations had been performed, but the highest possible flood level predicted at the design stage in 1972 was 0.85 m lower than the flood level that occurred in October 1987. It was therefore rainfall and flood level predictions in 1972 that were misleading.

Also the second failure reported from Thailand involved an unexpected high water level causing a completed road fill to be washed away. It should therefore be duly noted that the dangers of buoyancy forces should be carefully studied when considering the design of an EPS fill. Often soft subsoils are located in lowland areas subjected to flooding. In such cases accurate predictions of the highest possible water level are essential to obtain a safe and lasting road structure.

An incident is also reported from Crayford near London, England in 2016 where 16 cars were damaged in an underground carport when a 24-inch pipe burst and flooded the carport. The EPS boards used under the parking level in this case, became buoyant and the car roofs crashed against the ceiling of the carport. The flooding was of course very unfortunate and unexpected.

Ordinary polystyrene is a combustible material and will burn when set on fire. For this reason some precautions should be taken when constructing EPS fills using normal quality material as describes in section 5. Such precautions may include fencing in any stockpiles at the construction site and provide guards round the clock, or place the blocks directly in the fill when they arrive on site, working round the clock if necessary. However, once the EPS is covered by the pavement material on top, and soil on the slopes, there will not be sufficient oxygen available to sustain a fire.

Two failures due to fires have occurred in Norway, and both were caused by welding activities on bridge abutments adjacent to EPS fills during the construction phase. In the first case 1500 m^3 of EPS were transformed into black smoke in a matter of some 10 minutes. The concrete bridge abutment was also damaged due to the heat developed with concrete spalding from the reinforcing bars (Fig. 34). Since the fire was initiated by sparks from welding activities on the bridge, the contractor responsible for the welding had both to repair the bridge abutment and replace the EPS fill at his own expense. A similar incident occurred in 1995 and again the repair costs had to be covered by the contractor responsible for the welding activities. The fire potential should therefore not be overlooked.

Fig 34. Bridge abutment damaged by EPS blocks put on fire

8. Reuse of EPS

When the first EPS fill in Norway at Flom bridge floated up in 1987 as described in section 7, there was at the same time an incident in downtown Oslo where a sheet pile wall, for a deep excavation next to a road off ramp, was on the verge of collapsing. This required a rapid temporary removal of the off ramp, but since the ramp served a busy traffic intersection, it also needed to be quickly repaired. At the time in question block manufacturer could not supply new blocks as quickly as required. Instead the blocks that was removed from the Flom bridge area, was reused to quickly repair the off ramp in downtown Oslo.

In 2006 two embankments on Euroroad 6 in the southern part of Norway (Løkkeberg Bridge Fig. 16 and Hjelmungen Bridge Fig. 17) was removed partly due to widening but also due to changes in the alignment of E6. These blocks were also examined and checked as part of the monitoring programme and it was decided to reuse more than 5000 m^3 EPS blocks (Fig. 35) on other EPS embankments connected to the E6 project. Some 17 years after the blocks were placed, test data show results well above that of a normal EPS quality (average value of σ =104.6 kPa for ρ = 20 kg/m^3 material).

Fig 35. A Stockpile of EPS from Løkkeberg Bridge, b Reuse of EPS blocks from Løkkeberg Bridge (NPRA)

The Carousel Shopping Mall in Syracuse NY was constructed in 1989 using 28,000 m^3 of EPS geofoam blocks to control perimeter settlements of al large mat foundation. After four years of service expansion of the mall was required and geofoam blocks along 100 m of the foundation wall were removed. All of the exhumed blocks, except ones damaged in the process of recovery, were in good condition and were reused for the expansion construction. The performance of the reused EPS blocks has been satisfactory over more than 20 years.

The major volume of EPS material worldwide is produced for packaging and insulating purposes and this has to some extent become an environmental problem since packaging use is only temporary with a large volume of discarded material accumulating. To counter this effect collecting systems have been established in many countries and the manufacturers are now adding some amount og discarded EPS material into the production of new Geofoam blocks. With a recycling content of some 20 % at present this may cause some greater variation in material quality of the finished product.

9. Conclusions

All knowledge gained form research activities involving both lab tests and full scale monitoring programmes as well as experiences form construction activities, confirm that the use of Geofoam blocks in civil engineering projects may provide satisfactory solutions. Whether Geofoam blocks are to be considered favourable on a certain project, will depend on many factors like local technical conditions, economy and construction time allowed. With the number of new countries adopting the method and with the increasing number of projects being completed, it will not come as a surprise if such use of Geofoam blocks will escalate further. New application forms may also well be introduced increasing the use even further.

So stick to the motto:

Be bright,
think light and
do it right.

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