

Weight-Credit Foundation Construction Using Artificial Fills

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A description of the origin and evolution of a major type of artificial fill, foam plastics, is given. Case histories of weight-credit applications for a variety of materials, including solid (precast) foam plastics, cast-in-place and poured plastics, Elastizell, Solite, and waste materials (wood chips and shredded rubber tires), are described. Abstract information about pertinent mechanical and chemical properties is given and evaluated. Aspects of permanence and durability, including problems and caveats, are reviewed. An approach called "hybrid design" is suggested. A case is made for greater use of artificial fills. The literature that will enable a comprehensive study of weight-credit design and construction, with particular emphasis on case histories, is cited.

In the history of construction, the lightest material that would suffice, whether a wood pile in a prehistoric bog or a titanium alloy for today's jets, was chosen.

Perhaps the first known public reference to a conscious choice of a lightweight fill to achieve a weight credit was made by Benjamin Hough in a lecture before the Geotechnical Group of the New York Metropolitan Section, ASCE (about 1960). If a lightweight cinder fill with acceptable strength and stability was used, a significant "credit" in the form of a correspondingly higher structural load (payload) could be obtained.

It has been common practice among geotechnical engineers to specify the use of clean, well-graded granular materials for fills to replace unsuitable surface soils of relatively shallow depth (for example, peats). The compacted fill would, of course, be of significantly higher unit weight than the peat it replaced—perhaps 2000 kg/m³ (125 pcf) for the compacted granular fill and 1600 kg/m³ (100 pcf) for the peat. This would diminish the payload (structure weight) that would be permissible. Nevertheless, the procedure is routinely followed, because the readily available suitable lightweight fill, such as the cinder material suggested by Hough, is expensive.

In about 1965, the use of solid foam plastic for the hulls of small recreation sailboats was introduced at the New York Coliseum Boat Show. One of the selling points was its light weight. Indeed, potential customers were invited to lift the hull with an index finger to illustrate effectively this advantage. This material had to be strong as well as light to withstand the pressure of the foot of an adult male. The idea to use the material as a fill evolved. After preliminary investigation, it became evident that the weight credit that could be achieved was dramatic, far surpassing any so far possible. Accordingly, patents were applied for and awarded in 1971 and 1973 (1,2).

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One of the materials covered by the patents is known by the more technically explicit term, "expanded polystyrene." It is typically produced as "boards" that are tied together to form "bundles," or "blocks," commonly called EPS blocks.

The first known use of EPS blocks in highway construction was as insulation for highway subgrades in cold regions to protect against frost heave. This method of construction was patented in 1966 by Leonards. Applications for purposes of weight credit were not a part of the Leonards patent. By 1967, pavements insulated with EPS had been installed in 11 states and 3 Canadian provinces (3).

WEIGHT-CREDIT CONSTRUCTION WITH FOAM PLASTIC

Foam Materials

The only foam plastic for which specific properties are known, and has been used in weight-credit construction, is a solid precast extruded polystyrene foam made by Dow Chemical. The broad potential for the general use of foam plastics is illustrated by the following: "[F]oams may be produced which have densities ranging from less than one pcf to about 70 pcf, with an almost limitless range of chemical and mechanical properties" (4).

It appears feasible that for very large jobs, or very special circumstances, the expense of producing a special formulation to suit the particular use could be justified. In addition, combinations of existing products could be used to effect a design. Just as in the design of a pavement cross section, better materials could be placed where the stresses are highest, and lesser materials could be used where the stresses are lower.

Pickford Bridge

In the early 1970s, a representative of Dow Chemical was granted permission by the author to pursue a construction project covered by patents (1,2). The EPS blocks would be used, on a job for the Michigan Highway Department, to replace a badly deteriorating abutment and approach fill for a bridge at Pickford, Michigan (5, p. 83). The existing abutment and approach fill had settled to the point at which action was necessary (A. Maki, engineer, Dow Chemical, personal communication). The fill was replaced by a conventional compacted soil. However, because of the existence of deep deposits of soft clay below the fill, the new fill started to settle rapidly, with obvious potential damage to the abutment and

bridge. To avoid complete failure, the approach fill was removed. The weight-credit construction that was then used is described by Coleman (6) but augmented here by commentary and results of follow-up inquiries.

Before the weight-credit construction began, the clay upon which the foam bundles were to be placed was reported to be extremely soft. The EPS bundles were placed by hand by two men in ½ day (A. Maki, personal communication).

The fill at the abutment was about 3m (10 ft) high. However, the thickness of plastic necessary to achieve the required weight credit was about 1.5m (5 ft), thus sensibly diminishing the amount and cost of the plastic fill. [The cost of the in-place foam at the Pickford Bridge was \$52/m³ (\$40/yd³), but subsequent costs fluctuated greatly because the plastic is an oil-based product.] The EPS bundles were covered with a polyethylene sheet to protect against oil or gasoline spills. Normal soil fill was placed to subgrade, serving to pin down the foam plastic to guard against floating during periods of high water table.

Because this project represents the earliest known use of large thicknesses of foam plastic for weight-credit construction, inquiries by the author about the performance record of the construction were recently made. The answer was that

on the basis of my periodic on-site visual inspections . . . the longitudinal section of the bridge has remained stable. On the return-wall section, where the potential for movement was deemed greatest, there has been "some movement" . . . but it has been "manageable." All things considered, the construction has been satisfactory over its approximately 20-year history. (P. O'Rourke, Engineer, Materials and Technology Section, Michigan Department of Transportation, 1992.)

EXPANDED POLYSTYRENE: SELECTED TECHNICAL DATA

The following table gives properties of Styrofoam HI-35, the EPS that was used at the Pickford Bridge:

	<i>Test Data</i>	<i>Test Method</i>
Compressive strength at 5% deflection	241 kPa (2.5 tsf)	ASTM D1621-59T
Water absorption	0.25% (by volume)	ASTM C272-53
Density	40 kg/m ³ (2.5 pcf)	

Permanence and Durability

Although no direct inspection (by coring or excavation) has been made at the Pickford Bridge, periodic visual on-site inspections have shown that the material remains stable.

Between 1962 and 1966, EPS blocks have been used in at least 39 installations as insulation for highway pavement systems. In most cases, the amount of plastic used has been about 25 to 75 mm (1 to 3 in.), typically placed directly on the subgrade. Samples of foam taken from various highways after several years of service show very little water absorption. Accelerated laboratory tests, such as freeze-thaw cycling and soak tests, have shown very little moisture absorption (7).

Deformations caused by trafficking were measured in two insulated sections and one noninsulated (control) section. Deformations were of the order of 0.5 mm (0.02 in.) in the

insulated sections and were well below those of the control section, reaching a maximum of about 0.8 mm (0.03 in.), during the spring thaw (7).

Problems and Caveats

Differential Icing

The purpose of the foam plastic on highway insulation installations is to minimize frost action in susceptible subgrade soils. However, there is danger of creating a much more serious, indeed dangerous, problem—differential icing. On days when the ambient temperature is at or slightly below freezing, an untreated section of the pavement receives heat from both the sun and the subgrade. Thus, if it rains, the water on the pavement will remain fluid. On an adjacent treated section, where the foam provides insulation from the heating effects of the subgrade, pavement water may freeze. This can be especially dangerous for a motorist driving fast on the untreated section who believes that the pavement is merely wet. Entering the iced section can be disastrous. In fact, in the early 1970s, a serious accident did occur and was judged to have been caused by the icing described. As a result, the manufacturer decided to stop using foam as an artificial fill. The company has done some studies of the icing problem and determined that icing would not be a problem in regions of less than 1000 degree-days. (Dow Chemical Co., early 1970s, personal communication) This is a partial explanation of why the techniques have not been used as extensively as they might have been, or as extensively as in Norway.

In most cases of weight-credit construction, however, the problem would not exist or would be manageable. At the Pickford Bridge, for example, the foam plastic is sufficiently buried not to create the problem of icing. In similar bridge approaches where the foam might be at shallower depths (for greater weight-credit), it would be advisable to install a hazard sign.

Ozone Depletion

Depletion of the ozone layer by the release of chlorofluorocarbons (CFCs) into the atmosphere is of major worldwide concern. Some scientists estimate that projected rates of depletion could cause major increases in skin cancers and eye cataracts and deplete humans' ability to fight infection. Crop damage and disruption of the ocean food chain could also result.

One of the sources of CFCs is reported to be "the propellants that are used in the production of foam plastics" (8). It is not known whether that includes the foams currently used for insulation of highways and weight-credit applications, but it is suspected to be the case. Recent United Nations talks have established a deadline for banning certain CFC-producing products by 1996 (9).

Flotation

Where soil overburden will not be sufficient to prevent flotation, provision would have to be incorporated in the design

to pin down the foam. Soil "pins" analogous to anchor bolts in tunnel construction might be used. Studies need to be done to determine design specifics and to assess the effects on the integrity of the foam fill.

Chemical Resistance

Exposure of the in-ground foam to gasolines should be prevented. It is well known that this causes very rapid deterioration of the foam.

Sunlight

Direct exposure of foam plastic to sunlight for extended periods should be avoided. The manufacturer of Styrofoam HI-35 reports, "discoloration and degradation of properties may occur at the surfaces exposed to direct sunlight. Covering the product with a white plastic sheet is recommended if it will be exposed for more than three days" (A. Maki, Dow Chemical Company, personal communication).

Other Case Histories

Monahan (10,11) describes a variety of applications, actual projects, (route construction, highways, pipelines), and hypothetical applications. Cast-in-place applications that deal mainly with confined spaces (such as behind retaining walls, trenches) and a suggested plastic-filled weight-credit pile are described. A grade-separation case study for an intersection in a major eastern city is included. (An embankment slope stability problem is described that suggests the combined use of reinforced earth principles with those of weight-credit.) A poured plastic, called Poleset, has been used for installing utility poles. The method is quicker and neater than standard earth backfills. Pulling tests are reported that claim the material is stronger than poles backfilled with compacted soils (12). Although not a weight-credit application, the material could be used effectively as such.

An extensive amount of work using EPS blocks has been done in Norway. It has been reported that almost 100 road projects have been successfully completed in Norway since 1972 (13,14). EPS backfill has been used behind seven newly constructed bridge and overpass abutments in soft foundation areas near Vancouver, Canada (15, p.25).

Other Foam Plastics

Many foam plastics from which the designer may choose are available. One manufacturer makes about 12 varieties of solid foam materials, each with different properties, but all extremely lightweight. For example, Styrofoam HI-300 has a density of 53 kg/m³ (3.3 pcf), compared with the Pickford foam density of 40 kg/m³ (2.5 pcf), yet its compressive strength is approximately 3½ times greater (16). Thus, much stronger, but undoubtedly more expensive, materials are available with very little sacrifice of weight credit.

Another EPS product, Styropor, is made by the BASF company. A slope stabilization application was completed in Colorado (17).

WEIGHT-CREDIT CONSTRUCTION WITH NONFOAM MATERIALS

Materials other than foam plastics have been developed in recent years for weight-credit applications.

Elastizell

Elastizell is a pumpable lightweight "concrete," produced on site by adding a liquid concentrate of hydrolized protein to a cement and water slurry. There are six classes, I through VI, with cast densities ranging from about 300 to 1300 kg/m³ (18 to 80 pcf). Corresponding compressive strengths range from about 280 to 4800 kPa (40 to 700 psi).

One of the larger jobs done with Elastizell (a proprietary product) was for a bridge abutment over weak soils on I-94 near Minneapolis, Minnesota. About 92 000 m³ was poured (42,000 yd³) (18). Typical designs using Elastizell incorporate more than one class, placing the stronger materials where performance requirements warrant.

An extension of this approach would be to use the much lighter foam plastics with the Elastizell where extremely weak soils require dramatic weight credit. Elastizell does not require compaction and, once set, does not apply lateral pressure to walls (18).

Solite

Depending on the locale of its manufacture, Solite, also a proprietary product, is produced from either shale, clay, or slate. It is expanded in a rotary kiln at high temperature to produce a lightweight, subangular granular material that is free-draining (19). The material is used either as a soil fill or as aggregate to produce lightweight concrete.

As a fill, it is normally compacted to densities less than 960 kg/m³ (60 pcf), yielding a material with an angle of internal friction of about 40 degrees. The material is chemically inert.

As a concrete, its unit weight is about 1900 kg/m³ (116 pcf), with a 28-day compressive strength of about 44 900 kPa (6,510 psi).

Hybrid Design

A combination of materials could be considered for overall weight-credit approaches. Because Solite may be used as a lightweight concrete in the main structural members of a bridge, it would be feasible to design an entire project using super-lightweight materials (foam plastics) and lightweight materials (for example, Elastizell) for all fills (fitting the material selections to the weight-credit needs) and to use lightweight concrete (Solite) for many of the structure components—a true hybrid design.

Waste Fills

Waste or recycled materials have been used successfully and often provide the secondary benefit of weight credit.

One such job, designed by a company in Minnesota, involved the use of geotextile, wood chips, and shredded rubber

tires as fill that crossed unstable peat soils. Geotextile was placed at the bottom of a 1.5-m (5-ft) excavation, and wood chips were placed to a height of 0.3 m (1 ft) above the water table, as required by the Minnesota Pollution Control Agency. Shredded tires were then placed to a height one m (3 ft) above the original road surface. The tire layer was covered with geotextile, and the fabric was then sewn together with the lower fabric to form an enclosing bag. The shredded tires weigh about one-sixth what conventional soil fill weighs.

Much more extensive descriptions of the use of waste fills are contained in a work by Monahan (11).

CONCLUSIONS

The use of artificial fills will become more widespread for a number of reasons. Clean soil fills of suitable gradation are becoming scarcer, especially in more congested areas. In the 1970s, it had often become necessary to search for enough fill for a job, often using three or more borrow areas to obtain the necessary quantity of suitable fill. This situation developed before environmental regulations became widespread. Engineers looking for suitable soil must now be concerned with both suitable texture and the very complicated problems of possible contamination.

Another factor that would favor the increased use of artificial fills is the reported market lag of recycled materials, including plastics, glass, paper, and aluminum (20).

There are many benefits to be gained by the increased use of artificial fills: the avoidance of environmental entanglements (paperwork and possible law suits), economic benefits associated with conservation and recycling, perhaps indirectly major savings in energy consumption, and, very important, weight credit.

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DISCUSSION

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I am actively involved in research dealing with the application of rigid plastic foams to a wide variety of geotechnical problems, including lightweight fills (weight-credit construction). Such materials are now recognized as geosynthetics under the newly created product category of geofoams. An inventory of geofoam materials and functions identified to date is found in a work by Horvath (1).

I would like to clarify or correct several items in the paper by Monahan on the basis of current information relative to geofoams.

1. *Expanded polystyrene* and the corresponding acronym *EPS* as used by the author are not consistent with current plastics-industry terminology throughout the world (the only known exception is Japan). There are two types of rigid polystyrene foams manufactured by different processes: molded bead and extrusion. Differentiation between these two polystyrene foams is not trivial. There are significant differences in cost, environmental effects related to manufacture, finished product size, and material properties. The term expanded polystyrene (EPS) is used only when referring to the molded-bead product. The extruded product is called extruded polystyrene (XPS). Consequently, readers of the paper should be aware that the author appears to mean XPS in most instances in which he uses EPS (Dow Chemical, referenced extensively in the paper, produces only XPS and not "true" EPS). To complicate matters, there are cases in which the author uses the acronym EPS correctly. These exceptions are toward the end of the paper where projects in Norway, Canada, and Colorado are noted. On these projects, the molded-bead product (EPS) is meant.

Other terminology issues are that the word Styrofoam is not a generic name for all plastic foams (as many believe) or even a generic name for XPS. It is the brand name of the particular XPS product manufactured by the Dow Chemical Company (there are at least three manufacturers in the United States besides Dow that produce XPS, each with its own product brand name). Also, Styropor is the BASF Corporation's brand name of the basic polystyrene beads (called expandable polystyrene) from which EPS is produced, not the finished EPS product. (BASF does not make the finished product.) The remainder of this discussion will use the correct terminology as defined.

2. EPS was invented more than 40 years ago and has been used in geotechnical applications for more than 30 years. Ini-

tial use was for thermal insulation below roads to prevent frost heave (XPS was used for this also, as noted by the author), followed by use as lightweight fill for a highway embankment in Norway in 1972. Thus there have been decades of experience in which the geotechnical marketplace has compared EPS with other plastic foams (primarily XPS). The overwhelming choice has been and still is EPS. The primary reason is cost. EPS is typically half, or less than, the cost per unit volume of XPS. In addition, EPS blocks are larger (in the United States, typically 610 mm thick versus 102 mm maximum for XPS); therefore, placement is faster because fewer pieces must be handled.

Another issue that is increasingly more important (it is already a significant concern in Europe) is that EPS is the only rigid plastic foam that does not use gases such as CFC or HCFC (which deplete the upper-atmosphere ozone layer) in its manufacture. Thus the statement by the author that "the only foam plastic for which specific properties are known, and which has been used in weight-credit construction, is a solid precast extruded polystyrene foam . . ." (i.e., XPS) is incorrect and, unfortunately, gives a very misleading impression as to past and current geofoam use. Examples and references of the extensive use of EPS for lightweight fill and other functions are found elsewhere (2,3). Material behavior of EPS for engineering analysis purposes is well defined in literature readily available from the EPS industry (4-9). A synthesis of basic EPS properties for geotechnical application has recently been prepared (10).

3. The statement that XPS can be produced with a density of 70 pcf does not seem plausible. Solid polystyrene has a specific gravity of approximately 1.1. Thus a solid block of polystyrene would have a density less than 70 pcf, making it physically impossible that a polystyrene-based foam with voids could be denser.

In summary, potential users of geofoams should be aware that EPS, not XPS, is the material of choice for lightweight fill, as well as other geotechnical applications in which a rigid plastic foam is being considered. This has been true for more than 20 years. In addition, technical data are available that allow EPS to be "engineered" probably better than any other plastic foam because of its extensive geotechnical use.

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AUTHOR'S CLOSURE

I thank the discussant for pointing out the important distinctions between expanded polystyrene (EPS) and extruded polystyrene (XPS). The standardization and codification of these terms and their acronyms appear to be a very recent development, as evidenced by the references cited by the discussant.

In my early writings and presentations, the broader terms "rigid foam plastics" and "cast-in-place" (or "poured") were used exclusively. Indeed, my patents (1,2) are couched in terms that include all forms of such foam plastics. Early writings by others used such terms as "polystyrene foam" or simply "plastic foam" (3,6). The first use of an acronym, as far as I am aware, was in September 1987 (14). I erroneously assumed that this was simply a shorthand notation to designate all solid foam plastics and thus assumed this usage for the first time for the preparation of my paper. The term XPS was seen for the first time in the discussion submitted in response to this paper.

The discussant points out that two important distinctions between EPS and XPS are cost and potential environmental hazard and says that Dow Chemical "produces only XPS" and that "EPS is the only rigid plastic foam that does not use gases such as CFC or HCFC in its manufacture." However, I spoke with the research director of Dow Chemical a few days before the presentation and was told that Dow's product has been made without the generation of such gases for some 2 years or so (Dow Chemical Company, personal communication). Because there appears to be a discrepancy between the discussant's statement and that made by the Dow research director, future users should be aware of the apparently conflicting claims.

Relative to other distinctions between EPS and XPS, potential users are advised to evaluate other aspects of physical, mechanical, and chemical properties (particularly water absorption and compressive strength), and of course relative cost, before making a design choice.

The discussant asserts that the "material behavior of EPS is readily available from the EPS industry" and cites five references of the BASF Corporation (4-9). However, I wrote to the BASF Corporation in 1989 but was not told of the availability of their technical literature. Other references cited by the discussant are either in press or of very recent vintage in journals not widely circulated, so there is some question about the discussant's assertion that the information is "readily available."

On a technical matter, the discussant states that it is "physically impossible" that a polystyrene-based foam could have a density as high as 70 pcf, inasmuch as the "solid polystyrene has a specific gravity of approximately 1.1." This matter is not pertinent to the principal focus of my paper, because no

one would consider plastics of such high density for weight-credit applications.

However, because the point was raised, a response is warranted. I do not agree. First, specific gravity is not an absolute quantity (such as e or π). The discussant implicitly acknowledges this by using the correct term: "approximately." Second, there is documentation that the experimental determination of specific gravity (and other properties) can vary surprisingly widely from laboratory to laboratory. Finally, the discussant assumes that the voids in a block of polystyrene are all air and thus "weightless." In my experience, the air-dried moisture content of even granular soils, which have mineralogy with the least affinity for water, assumes values of 3 or 4 percent in a temperate region. Because the plastics are presumably produced in "normal" ambient settings, it is reasonable to assume that moisture (and other impurities) will be trapped in the voids. A moisture content of less than 2 percent would yield a density of about 70 pcf, and this seems reasonable. Thus an upper limit of 70 pcf is not only possible, it is a virtual certainty. Moreover, the 70 pcf figure was a quotation from the *Modern Plastics Encyclopaedia* (4) and was probably based on these factors.

I would like to close with additional comments about the reticence of some to respond to inquiries. During the ap-

proximately 23 years since I first conceived of and patented the use of foam plastics for weight-credit foundation construction, there have been a number of incidents of unanswered inquiries.

I am at a loss to understand how the discussant, after reading my paper, prepared a discussion that contained the history of EPS usage as perhaps its principal focus and yet made no reference to the fact that I was issued a patent (1) on the method in the year before Flaate's first use. Indeed, the discussant even continues to imply that the weight-credit idea originated with the Norwegians, by saying, "Initial use was for thermal insulation . . . , followed by use as lightweight fill for a highway embankment in Norway in 1972." Not mentioned, of course, is the intervening issuance of the patent to me. Most curious.

I can think of a number of reasons for the lack of response over the years, some having to do with legal (patent) rights and some relating to personal and corporate ethics, but I recognize that this closure is not the forum in which to expound on these matters at any length. It is hoped that the publication of this paper, especially the discussion and closure, will result in better communication between members of the profession toward the betterment of the profession and the public we serve.