Comparison of Some Engineering Properties of Expanded Polystyrene with Those of Soils

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The engineering behavior of expanded polystyrene (EPS) was investigated for potential applications as an alternative geomaterial. Background on European experience with EPS in road construction over the past 20 years is provided. Tests were performed on EPS samples of two densities in constrained and unconfined deformation with loads applied in stress-controlled mode. Strength and deformation behavior and lateral stress coefficients for soils and EPS are compared. The results indicate that the engineering properties of EPS can be quantified in a manner similar to those of earth materials. For some applications that involve infrastructure rehabilitation and construction of transportation facilities, EPS offers unique advantages over soils. EPS needed for subsurface construction may contain recycled portions, and this would be an important environmental incentive for using EPS as a geomaterial.

Expanded polystyrene (EPS) is a synthetic material that is widely used to manufacture disposable utensils and for product packaging. Most applications of EPS involve a short service life and one-time use with virtually no recycling. EPS is not a readily biodegradable waste product. There appears to be a good deal of interest in reducing EPS solid waste.

EPS has peculiar characteristics that would be desirable for subsurface construction applications. It is very light compared with soil and concrete and has energy absorption and insulation properties. EPS has been used as superlightweight fill and for foundation insulation to reduce frost cover requirements. Reported applications of EPS in subsurface construction have mostly been related to roads. There have been some large and small unpublished applications in the United States. Norway has been the pioneer in EPS applications, and much of the experience to date has been guided more by rule of thumb and field observation.

Sorlie et al. (*1*) presented the Norwegian road construction experience with lightweight soil substitute materials. They suggest that EPS should have a compressive strength of 100 kPa at 5 percent deformation and an air resistance number of better than 70 to limit moisture pickup. Inflammability, dissolving by petroleum fluids, and increased icing potential at near-freezing temperatures are practical problems that require design consideration. A fire-resisting variety of EPS can be specified at an additional cost of 5 to 10 percent above standard quality (*2*). Potential damage of EPS by spilled fuel can be mitigated by providing a membrane cover in addition to and below concrete slabs that are normally placed on top of EPS fills for improved load distribution (*3*). Icing problems can be minimized by using a thicker pavement structure and by restricting moisture access (*1*).

A 4.5-m EPS fill is reported to have been used as lightweight fill on soft ground for a temporary overpass bridge in Norway (*4*). Creep deformations at stress levels of up to 60 percent of yield were negligible. Transient heavy wheel loads did not induce residual stresses.

Satisfactory performance of EPS as fill above rigid pipes to promote induced trench conditions has been reported (*5*). This application is of special interest because EPS replaces the more commonly used organic materials, which degrade in time. Furthermore, EPS for trench fill may consist entirely of sorted or recycled waste material.

Rygg and Sorlie (*3*) report on three applications in Norway that involved repair of a road across a bog, new road construction on a bog, and road embankment adjoining a bridge abutment, all using EPS. These case histories indicate successful use of EPS for road rehabilitation and construction over difficult foundation soils.

EPS fills that remain submerged for extended durations are found to retain about 4 percent water by volume in the first year and about 9 percent in 9 to 12 years (*6*). Even in cases of significant groundwater lowering, this level of moisture retention does not compromise the superlightweight advantages of EPS. However, adequate cover must be provided to prevent EPS breakout in times of submergence due to flooding or general rise in groundwater level.

Norwegian experiences with EPS road fills over the past 20 years indicate aging effects to be insignificant within the design life of transportation facilities. The performance of roads built on EPS fill is reported to have been satisfactory (*7*).

Future trends envisioned for EPS in transportation include high embankments with steep side slopes for concrete form work, floating bridges, and fill for buried structures (*8*). EPS has also been used for slope stabilization along troublesome transportation corridors in mountainous country. The option of using recycled EPS or EPS with recycled fraction in subsurface construction is a new concept that would be worth exploring. Familiarity with EPS behavior and comparison with geomaterials should help promote broader applications in transportation and other geotechnical construction.

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TEST MATERIALS

EPS

Production of EPS blocks begins from EPS pellets that contain a blowing agent. The specific gravity, G_s, of polystyrene in amorphous or crystalline form is about 1.1 (*9*). The pellets are first subjected to steam to form prepuffs. Initial pellet size and duration of steam exposure determine the prepuff and final block density. The prepuff to pellet volume ratio is in the range of 40 to 1. Approximately 10 percent of recycled EPS reclaimed from plant waste is shredded and mixed with the prepuffs. The shredded EPS and prepuffs are poured into a Teflon-lined molding box. Steam is injected through small perforations along the molding box inside boundaries to induce additional expansion and fusion of the prepuffs. EPS blocks of typically 1.25 × 0.6 × 4 m or 1.25 × 0.6 × 8 m are formed by this process. Commercially available densities range from 15 to 50 kg/m³, with 20 and 30 kg/m³ varieties being more common. Depending on quantity and location, the more common 20 and 30 kg/m³ densities may cost between \$25/m³ and \$50/m³, with the higher-density EPS costing more. Cylindrical EPS blocks 76 mm in diameter and 150 mm in height were provided for the investigation by Thermal Foams/ Syracuse, Inc.

Clay

A soft inorganic clay of medium plasticity was tested to compare with the EPS behavior. The clay is used for making pottery and has a water content of 30 percent and liquid and plastic limits of 41 and 24 percent, respectively. The specific gravity was determined to be 2.8 and the portion finer than 2μ amounted to 46 percent by weight. The dry density of the clay sample was about 1520 kg/m³.

Sand

Results of tests on silica sand are also compared with the behavior of EPS. The sand has a D_{50} of 0.55 mm and is uniform, having a uniformity coefficient, C_u, of 1.9. Quartz is the predominant mineral in silica sand, and individual grains are mostly subangular. The fines content of silica sand is less than 1 percent, and the specific gravity is 2.6. The dry density of the sand sample was about 1550 kg/m³.

EQUIPMENT

Constrained deformation tests were performed using a laterally instrumented oedometer 76 mm in diameter and 38 mm in height. Details of the oedometer are shown in Figure 1. Along the outside of a thin section near the midheight of the oedometer, strain gauges are mounted to sense lateral strain due to bending and hoop stresses. The instrumented ring adapts to a base fitted with a central porous stone and an outer O-ring seal. A retaining ring clamps the ring to the base to seal. Drainage connection is provided along the base block. A spacer with a top O-ring seal and narrow section along the thin section fits inside the oedometer. With the spacer block in place and restrained vertically, the instrumented ring can be pressurized. The response of the strain gauges was calibrated against precise changes in pressure set by a deadweight tester. The instrumented section provides a sensitivity of about 1 Mv/volt. The output is linear to lateral pressures in excess of 700 kPa.

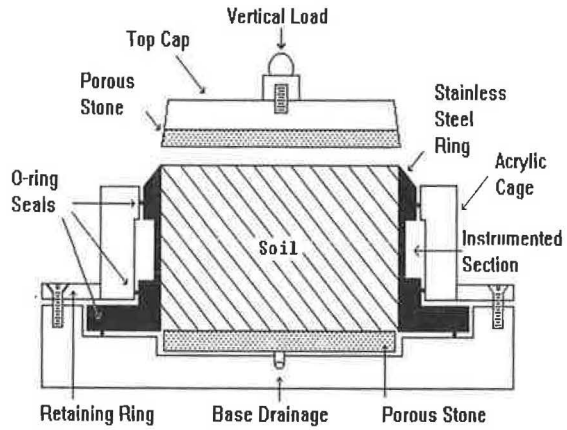

FIGURE 1 Oedometer with lateral pressure sensors.

PROCEDURE

EPS test samples 38 mm high and 76 mm in diameter were cut from EPS rods of the same diameter using a hot nichrome wire. An EPS rod was placed in a glass tube of a slightly larger diameter and having smooth cut perpendicular ends. With the block held in position and the glass end as guide, test samples were cut. The weight and dimensions of cut samples were recorded. Samples for confined tests were installed in the oedometer, and those for unconfined tests were placed directly in the loading frame. In both cases vertical loading was applied pneumatically in steps, and the applied load was sensed by a load cell positioned above the top cap. Vertical movement was monitored by a displacement transducer.

Confined compression tests were also performed on the clay and sand soils in the instrumented oedometer. The consolidation test on the clay soil was performed under constant rate of displacement. The clay soil was also tested in unconfined compression. Procedures followed for the latter tests were in accordance with ASTM standards.

RESULTS

Test results from one-dimensional compression of a low-density EPS (21.0 kg/m³) in Figure 2 show a behavior very similar to consolidation of clay soils. Segments of reloading, loading, and unloading are evident. A yield stress at an apparent maximum past pressure of about 80 kPa can be identified. Before yield, void ratio state changes are moderate as would be in an overconsolidated stress range. Postyield, void ratio states traverse in a path much similar to virgin compression, and associated deformations are relatively large. Unloading and reloading are associated with smaller rates of void ratio change.

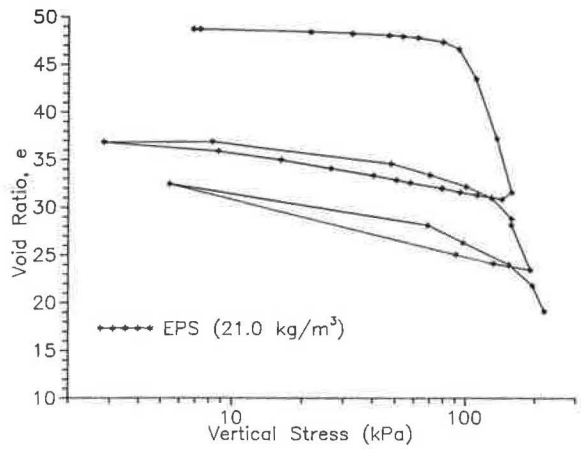

FIGURE 2 Characteristic behavior of EPS under one-dimensional deformation.

The state of maximum past pressure is recalled on reloading, and the material shows evidence of having a "memory."

One-dimensional compression test results for EPS samples of 21.0 and 30.4 kg/m³ are compared in Figure 3. The upper curve represents a portion of the results shown in Figure 2 for the lower-density EPS. The lower curve represents results for the higher-density EPS, and the yield stress is about 155 kPa. Neither sample had a prior history of loading. The observed differences in apparent maximum past pressures are due to different product initial densities. In the manufacture of EPS blocks, densities are controlled by duration of expansion time rather than applied pressure. Yet initial density effects are much like prestress effects in soils.

Constrained deformation test results for EPS are compared with those for silica sand and normally consolidated clay soil in the familiar semilog space [see Figure 4(a)]. Because the void ratio contrast between EPS and soils is very large, the comparison is based on strain rather than void ratio. The results indicate that EPS behavior compares favorably with the behavior of soils in the stress range before yield. For loading past yield, the EPS compression is much more severe even when compared with that of the clay.

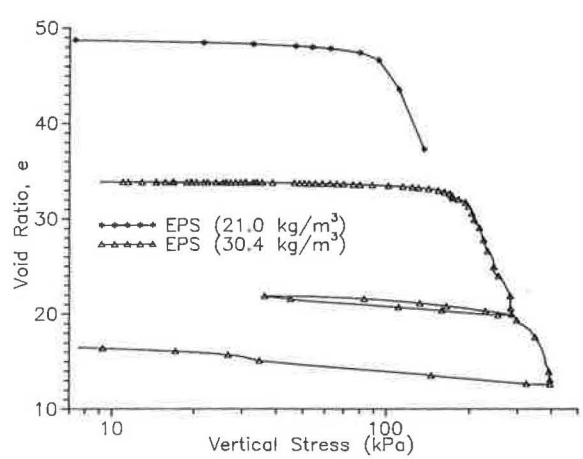

FIGURE 3 One-dimensional deformation behavior of EPS at two densities.

When the constrained deformation of EPS and the soils is compared in vertical stress and strain space [see Figure 4(b)], the soil response curves show a tendency to stiffen with strain. As expected, the sand develops much less strain and stiffens more rapidly than the clay. The EPS maintains a relatively constant modulus up to yielding near 155 kPa and almost 4 percent strain. Initial moduli for the sand, clay, and EPS are approximately 25,000 kPa, 3,000 kPa, and 4,000 kPa, respectively. Being on the higher side, the EPS modulus compares favorably with the clay. The postyield EPS response is characterized by a much lower modulus than the preyield. Even though confined, the EPS response curve simulates a behavior typical of unconfined compression.

A plot of restraining lateral stress against applied vertical stress to the soils and the EPS is shown in Figure 5. Lateral stresses are highest in the clay and are least in the EPS. K_o values for the clay, sand, and EPS are about 0.55, 0.43, and 0.15, respectively. In terms of customary approximations of K_o with reference to friction angle, the observed values for the soils are in a general range common for normally consolidated clay and loose sand, respectively. However, the EPS response up to yield approximates a low Poisson's ratio material and closer to very stiff to hard clay or very dense sand. With further loading beyond yield, lateral stresses in the EPS (and hence K_o states) decrease as would be the case for a

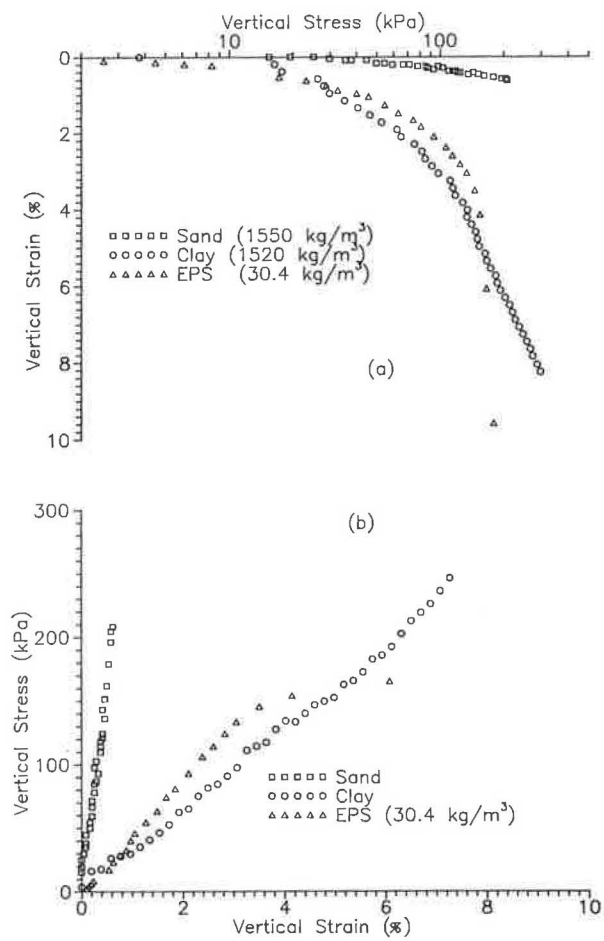

FIGURE 4 Comparison of one-dimensional deformation behavior of EPS with that of soils.

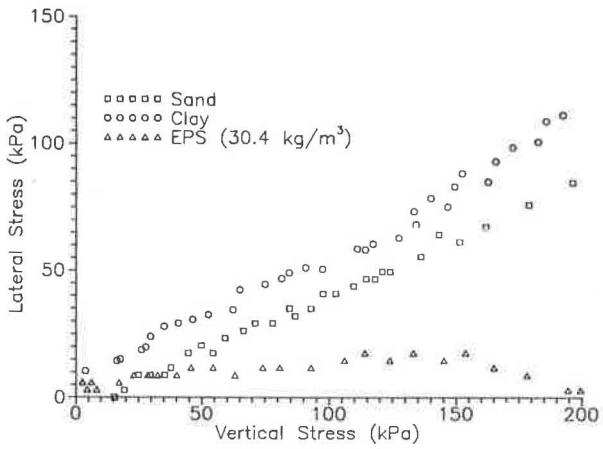

FIGURE 5 Induced lateral stresses under constrained deformation in EPS and soils.

material possessing a negative Poisson's ratio. This implies that lateral restraint is not essential to maintain features of constrained deformation in EPS and lends support to the observation that constrained and unconfined deformation responses of EPS are alike [see Figure 4(b)].

Test results of constrained deformation and unconfined compression of EPS (30.4 kg/m³) are compared in Figure 6(a) in natural vertical strain against applied vertical stress space. These results are also presented in the customary semilog space of void ratio and vertical stress in Figure 6(b). The yield state in unconfined compression corresponds closely to the apparent maximum past pressure in the constrained test. As implied by the earlier interpretation of a low Poisson's ratio for EPS, constrained modulus and Young's modulus are about the same. Loading, unloading, and reloading responses are also similar for constrained and unconstrained conditions. Virgin compression in constrained mode resembles postyield unconfined loading response. A preferred shear plane does not develop, and lateral spreading does not occur in response to unconfined loading.

The unconfined compression strength of EPS increases with density (Figure 7). Compared with the soft clay unconfined compression strength, the low-density (21.0 kg/m³) EPS is much stronger and would be equivalent to a firm clay. The unconfined compression strength of the denser EPS (30.4 kg/m³) is closer to that of stiff to hard clay. There is generally small additional increase in strength between 5 and 10 percent strain, but this may depend on strain rate and load duration. EPS compression strength is usually reported at 5 percent strain. In practice, applied loads must be distributed with a concrete pad or soil cover to prevent stress concentrations and punching failure to realize the indicated high strengths.

Figure 8(a) shows unconfined compression results in which EPS continues to support a stepwise increasing load past yield and at large strains. Postyield deformations are nonrecoverable and time dependent. Hysteresis loops are relatively small both at states below and past yield [Figure 6(a)]. Thus damping and energy absorption features of EPS are most favorable with virgin loading. As noted earlier, there was no evidence of a shear plane or lateral spreading at any stage of loading or deformation. The initial and final diameter of the sample was about the same even though very large vertical strains occurred.

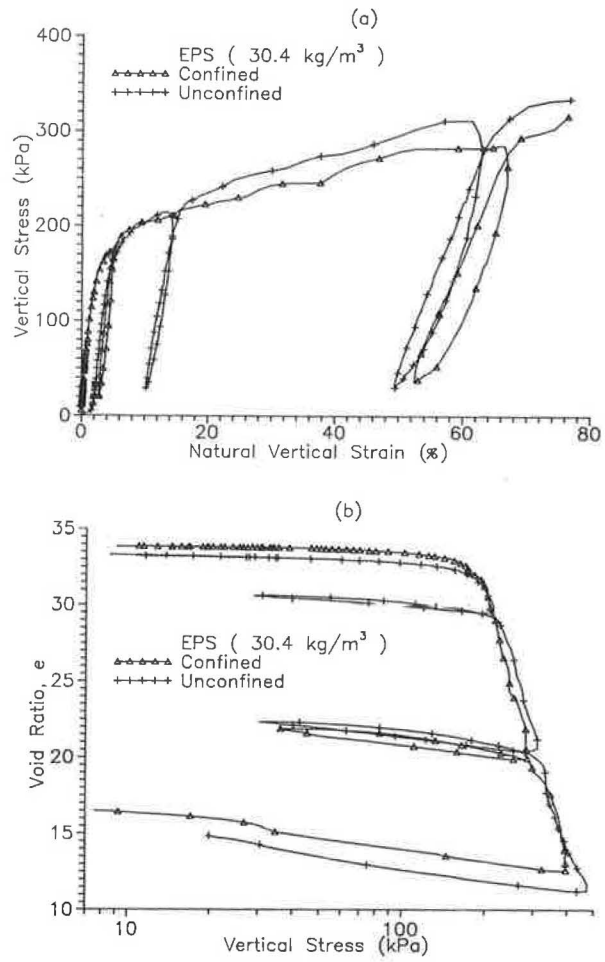

FIGURE 6 Comparison of EPS compression behavior under constrained and unconstrained lateral deformation.

Results in Figure 8(b) also show that EPS deformations have time dependence and that the degree of dependence is a function of stress level, stress history, and void ratio. These results are for unconfined compression, but the similarity of confined and unconfined compression behavior of EPS was shown in Figures 6(a) and 6(b). Each load increment was

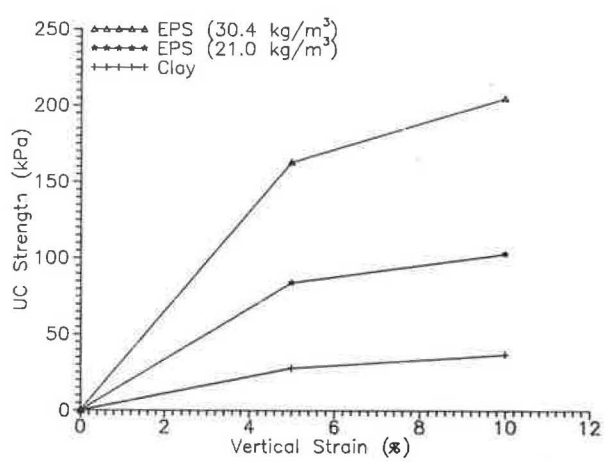

FIGURE 7 Comparison of unconfined compression strengths of EPS and clay.

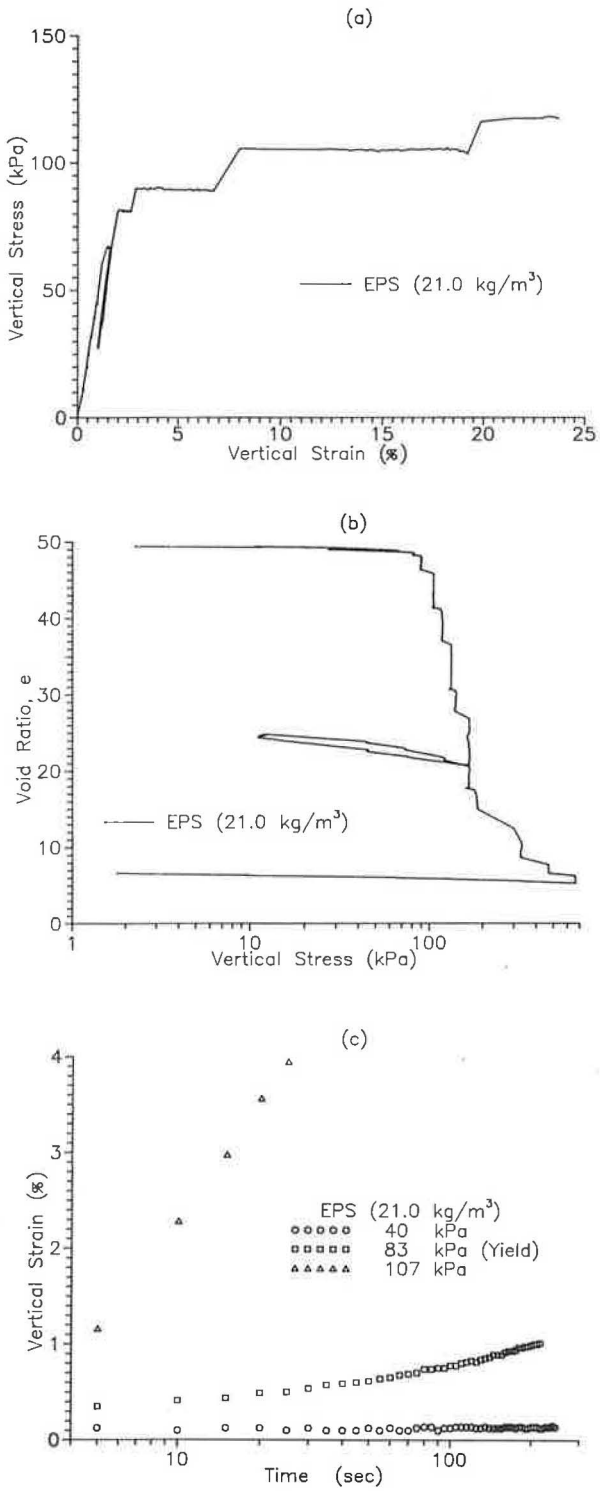

FIGURE 8 Time-dependent behavior of EPS.

sustained until time-dependent deformations subsided. States of stress near and postyield show evidence of time dependence in that deformations occur without change in stress state. Time-dependent deformations are small in the stress range below yield and along unloading and reloading segments when unloading is initiated before arresting time-dependent deformations; in subsequent loading, time-dependent deformations commence when the previous maximum stress level is reestablished. The magnitude of creep deformations diminish with decreasing void ratio states.

Isolated observations of time-dependent deformations at three selected stresses are presented in Figure 8(c) for EPS (21 kg/m³). The selected stresses are at about 50 percent of yield, yield at 83 kPa, and in postyield at 107 kPa. Elapsed times are referenced to load application. The curves resemble conventional primary and secondary creep stages for all three load steps. A tertiary type of creep stage may be inferred for the load steps corresponding to yield and postyield but not for the 50 percent of yield or lowest load stage. For the first load step, the resulting strain over the entire load duration is reasonably small. Essentially all of the deformation in this stage occurs in the first few seconds and during primary creep. Deformations in the secondary creep stage are relatively insignificant, and the stress level of 40 kPa is in the range of practical interest for geotechnical applications. A higher EPS density has been shown to result in a higher yield stress, and the corresponding stress threshold for time-dependent deformations should be higher.

Some of the observed engineering properties of EPS offer benefits superior to soils for certain subsurface applications. Fire hazard and chemical attack possibilities will require careful consideration and attention to storage arrangements and construction practice. Delivery of EPS to project sites and handling during construction will be easy. This should make EPS use more attractive in projects where site access is difficult. Environmental concerns and anticipated increased engineering activity in infrastructure rehabilitation and development over the coming years will offer challenges and opportunities to adapt new construction materials such as EPS. In a manner similar to geotextiles and geomembranes, geofoams (EPS for geotechnical applications) may be the next wave of cost-effective and environmentally compatible construction materials.

CONCLUSIONS

1. EPS is a superlightweight material with a wide range of possible applications in geotechnical and infrastructure engineering.
2. The stress-strain response and yield of EPS are well conditioned and bear close resemblance to some aspects of soil behavior.
3. Young's modulus and yield of EPS compare favorably with those of natural soils in the stress and strain range of practical interest for most geotechnical applications.
4. The yield stress for EPS is a function of initial density induced by the manufacturing process and can be specified.
5. EPS behaves as a low Poisson's ratio material and has similar confined and unconfined compression response.
6. During confined compression, induced lateral stresses are very low, and hence EPS has a low K_o property.
7. Time-dependent deformations of EPS assume significance at stress levels approaching yield and postyield but are reasonably small at working stress levels of about half of yield.
8. EPS for subsurface construction may be derived, in part, from recycling.
9. EPS has been used in Europe for geotechnical applications over the past 20 years, and the experience to date has been positive.

ACKNOWLEDGMENTS

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DISCUSSION

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I am actively involved in researching the application of rigid plastic foams to a wide variety of geotechnical problems. 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 summarized elsewhere (*1*). EPS has been and still is the most widely used geofoam (*2,3*). Among the reasons are its relative cost, environmental effects related to manufacture, finished product size, and material properties. A summary of basic EPS material properties of interest to geotechnical engineers is presented elsewhere (*4*).

In the light of this ongoing research, I would like to comment on or question several items in this paper:

1. The most significant comment is a general one concerning the soil samples used for comparison with EPS behavior. It is well established that the load-deformation behavior of soil is highly dependent on stress history, aging, relative density (for sand), and other factors in addition to particle size distribution. Information concerning specimen preparation and conditioning was lacking for the soils tested. Consequently, the conclusions drawn concerning whether EPS is behaviorally "better" or "worse" than soil are misleading. The conclusions of the paper in this regard are strictly applicable to two specific types of soil, each at a stress state that is undefined.

2. Whereas recycling is an admirable goal, the contribution of EPS to the domestic solid waste stream in the United States should be kept in perspective. Recently published work detailing the scientific exhumation and evaluation of actual landfills in the United States has demonstrated that all polystyrene products combined occupy less than 0.25 percent of landfill volumes. In comparison, paper occupies approximately 40 percent. Furthermore, the potential for using postconsumer recycled EPS for geofoam is complicated by the fact that in the United States, flame-retardant expandable polystyrene beads are used routinely to produce EPS for construction products such as geofoam (this is not true in some other countries, Norway being one example) but normal beads for other products. If flame-retardant EPS is commingled with normal EPS, the flame retardancy of the end product is compromised. Because the two types of EPS are visually indistinguishable, separation of the postconsumer recycled EPS is difficult unless special measures (e.g., coloring) were to be implemented industrywide during manufacture. As noted in the paper, recycling of in-plant scrap produced during manufacturing is already practiced by the EPS industry.

3. On the basis of recent (1992) correspondence with both the Norwegian Road Research Laboratory and the world's largest manufacturer of expandable polystyrene beads for EPS (BASF), the air-resistance test is no longer used for EPS geofoam quality control because it was found to provide inconsistent results.

4. Final, trimmed dimensions of EPS blocks in the United States are usually 610 by 1209 by 2438 mm (2 by 4 by 8 ft). Molding lengths are 4.9 m (16 ft) or 7.3 m (24 ft).

5. Current definitions of EPS compressive strength or yield strength are based on tests performed at a relatively rapid strain rate. Industry practice at present is to define EPS compressive strength as the stress at 10 percent strain, not 5 percent (*5*). The 5 percent strain criterion is used in Norway and perhaps elsewhere. However, it is correct that the difference in compressive stress between 5 percent strain and 10 percent strain in the typical short-term test is relatively small. This is because the elastic range ends and yielding begins for EPS at a compressive strain between 1 and 2 percent depending on product density. As will be discussed later, the compressive strength defined using such short-term tests does not provide insight into behavior under the more typical geotechnical loads of long duration.

6. Was the inside of the instrument oedometer lined with any low-friction material or substance? Axial strains of EPS specimens in excess of 50 percent were implied for some of the one-dimensional compression tests, and friction along the wall of the oedometer, which would reduce the actual axial compressive stress on the test specimen, is of concern.

7. It was stated that constant-rate-of-strain loading rather than the traditional incremental loading was used for the one-

dimensional compression tests on the clay specimen. What was the strain rate?

8. Incremental loading was used for both the one-dimensional and unconfined compression tests on EPS specimens. What was the duration of each load increment? As noted previously, estimation of yield stress for EPS is highly dependent on the load duration.

9. With reference to Figures 8(a) and 8(b), what were the durations of each load increment for which creep effects were observed? What criteria were used to select a time for which the strain rate appeared to be zero? EPS is a thermoplastic material, and time-dependent deformations will continue for some as-yet-unknown duration at all stress levels. The question becomes whether such time-dependent deformations are acceptable in a given application. Tests of EPS creep behavior in unconfined compression indicate that test durations of 10,000 hr or more are required to draw correct inferences as to whether tertiary creep effects will occur at a given stress level (*5*). By comparison, load durations of only about 0.1 hr are shown in Figure 8(c). Figure 9 shows the creep behavior for an EPS specimen with a density close to that used for the results shown in the authors' Figure 8(c). The "yield strength" of the specimen in Figure 9 in the standard short-term test (strain rate of 10 percent/min) was slightly greater than 100 kPa. For stresses greater than about 50 percent of yield, the long-term creep would likely be excessive for many engineering applications.

10. The qualitative similarity between EPS and soil with regard to the shape of the load-deformation curves is not a unique aspect of EPS. Rather, EPS and soil both exhibit rather classical material behavior. For example, as discussed elsewhere (*6*), annealed copper wire has behavior identical to that shown in Figure 2. The key difference is that for solids such as EPS and copper wire, yield stress is built in during manufacture, so soil mechanics concepts such as "maximum past stress" have no physical relevance. On the other hand, for a particulate material such as soil, yield stress is not unique to the particular soil but depends primarily on stress history and other factors such as aging.

In summary, I believe that the authors have provided some potentially useful information concerning the relative behavior of EPS in unconfined versus one-dimensional axial compression if additional information concerning the type and duration of test loading is given. On the other hand, the comparisons with soil behavior are misleading because of the lack of key soil mechanics information concerning stress history and so forth of the soil specimens. Conclusions as to the relative strength and stiffness of EPS and soil are probably

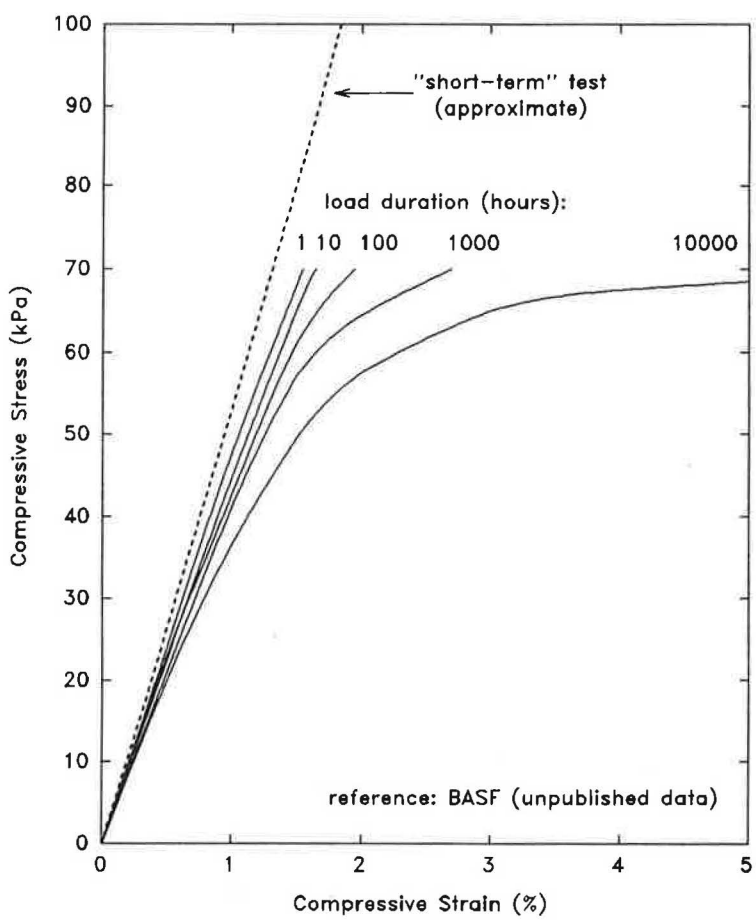

FIGURE 9 Creep behavior of 23.5-kg/m³ EPS in unconfined axial compression.

impossible to generalize because of the lack of unique behavior for a given type of soil.

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AUTHORS' CLOSURE

We thank the discussant for his interest in the paper and contribution to a discussion.

At this stage and in this context, the comparison of EPS behavior with that of soils is general. The two broad but important classes of soils compared, clay and sand, are meant to be referenced generically. The range in compared behavior for a clean medium quartz sand, loose or dense, and a soft normally consolidated inactive clay would not overlap under conceivable sets of practical circumstances at corresponding stress levels. Physical, chemical, age, and stress attributes have individual and collective influence on the response and performance of a given soil. Drainage conditions, stress path, and loading rate would also be important. In a strict sense, quantitative results for a soil apply to the soil in question and prevailing test conditions. That is why specific soils for specific applications are tested in practice, and this approach will no doubt continue, when justified, in important applications that involve EPS and soils. However, useful qualitative and, in some cases, practically adequate quantitative observations are often drawn for a class of soils from results on specific soils through use of index properties. This is, of course, common in geotechnical engineering practice and is the sense we attempted to convey in the comparison of EPS with a clay and sand soils.

The arguments made by the discusser against recycling EPS are unfortunate and represent a special interest position. At present, the support for and awareness of the need for and benefits of recycling nonbiodegradable wastes are broad and do not require our further justification. For many subsurface applications of EPS, flame retardancy would not be critical. Potential compromise in flame retardancy due to mixing when recycling, as argued by the discussant, should not be a reason for discouraging EPS recycling.

The reference to air-resistance number made in the paper is in the context of a literature survey of published and acknowledged information. The discussant's information is presented as undocumented personal communication with sources that are not well defined. Mention of a traceable source reference would have been more useful than the name and rather flattering size description of a very large multinational manufacturer.

The behavior of EPS shows time dependence in preyield, at yield, and in postyield. This is shown by our results as well as by the unpublished secondhand data furnished by the discussant. We have noted that creep effects beyond 50 percent of yield and in postyield may be potentially excessive for most geotechnical applications. The specification of yield for EPS will no doubt benefit from further refinements in experimental observations.

In testing soils, special techniques are used to mitigate the influence of undesirable conditions that violate test assumptions. Side friction reduction in one-dimensional deformation tests by lubrication with vacuum grease is a well-known procedure. A very important finding shown in the paper is the observation that lateral stresses are low before yield, compared with vertical stresses, and actually diminish in postyield. One-dimensional and unconfined compression behavior are shown to be similar, and lateral stresses at large strains and large vertical stresses become insignificant. The interface friction between EPS and a smooth metal surface is low in addition to lateral stresses being small and becoming negligible. In view of the foregoing, the discussant's expressed concern regarding adverse effects of side friction and suggested need for lubrication is, in our view, not rational.

The strain rate for the constant rate of strain loading test on the clay soil was 0.006 percent/min. Load steps were maintained for 5 and 2 min during incremental loading and unloading of EPS, respectively. Creep observations were made within the load increment time base. Longer tests and other areas of EPS behavior are the focus of present and future investigations.

Uniqueness of engineering behavior is relative and contextual. The density, correspondence between constrained and unconfined compressions, lateral stress coefficients that develop during confined compression, and other properties of EPS would be considered unique compared with soils. To forge a favorable connection between these unique and important features of EPS and soils, the senior author proposed to representatives of the Society of the Plastics Industry and others, at a workshop held at Syracuse University in 1991, that EPS be referred to as geofoam.

We were careful to describe the observed breaks in one-dimensional response of EPS as apparent maximum past pressure. Because of the demonstrated correspondence between confined and unconfined behavior of EPS, yield and apparent maximum past pressure would be synonymous since they apply to EPS only.

The discussant views built-in stress in manufactured solids, and here he lumps copper and EPS, as not being analogous to maximum past pressure in soils. His reflections on this point are interestingly referenced to a textbook on soil behavior and critical state soil mechanics. The irony in the discussant's argument is that the development of critical state soil mechanics appealed to experimental studies of Cam-clay, a manufactured clay with built-in stress history. Needless to say, the critical state soil model is alternatively known as the Cam-clay model.

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