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Shear behavior of sand-expanded polystyrene beads lightweight fills

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Abstract: Sand-expanded polystyrene (sand-EPS) beads lightweight fills are geomaterials formed by blending sands and EPS beads. Through direct shear and triaxial compression tests, effects of EPS ratios and stress status on materials' shear behavior were investigated. The shear behavior is marginally associated with the EPS ratios and normal/confining stresses. Hyperbolic curves were used to fit relationship between shear stress and shear displacement. Increases of EPS ratios and decreases of normal/confining stresses result in shear strength decreases. The shapes of Mohr-Coulomb's envelope include linear and piecewise linear types, which are basically determined by the EPS ratio. Such difference is thought related to the embedding or apparent cohesion effect under relatively high EPS ratio conditions. Shear strength parameters were presented to be used for further modeling and design purposes.

Key words: expanded polystyrene; lightweight fills; shear strength; mixing ratios; strength envelope; sands

1 Introduction

Over weak or sensitive areas where normal earthfill overburdens may cause excessive settlement (e.g. embankments rested on soft soils), or differential settlement (e.g. bridge abutment or embankment widening), or lateral displacement (e.g., retaining walls), or connection failures of flexible pipelines, a lightweight fill may be used as an alternative geomaterial by offsetting the normal weight of earthfills. This concept was verified through investigations on many geomaterials.

Deng et al.[1] proposed a lightweight geomaterial comprising sand and expanded polystyrene (EPS) beads, and addressed the general engineering properties of the materials. The shear behavior was yet performed. Liu et al.[2] formed a lightweight fill material by blending soil with polystyrene pre-puff (PSPP) beads and cement. Density of the lightweight fills could be effectively controlled via the inclusion of PSPP, whereas, cement inclusion became a barrier for economical saving. Tsuchida et al.[3] developed a lightweight fill based on dredged mud and EPS beads, which has limited applications. EPS block geofoam was applied to mitigate settlement of bridge approach embankments constructed over compressible soils[4-6], but not suitable for confined space and inaccessible locations. The soil-geofoam-structure interaction was numerical modeled[7].

Besides the lightweight geomaterials of EPS-based mixtures and EPS geofoams, tire-based lightweight fills have been growing in the lightweight geomaterial domain. Pierce and Blackwell[8] replaced sand with crumb rubber in flowable fill to produce a lightweight material. Pure fine and coarse grained tire-chips were mixed at ratios with a cohesive clayey soil[9]. Tanchaisawat et al.[10] investigated the behavior of lightweight geomaterials consisting of tire chip-sand mixture reinforced with geogrids for use as embankment construction on soft ground. The constitutive model of rubber tire-sand mixtures was proposed via triaxial compression tests[11]. Ghazavi[12] disclosed that the influencing parameters on shear strength characteristics of sand-rubber mixtures are normal stress, mixture unit weight, and rubber content. The lightweight geomaterials so formed have many attractive properties, perhaps the most useful being its low density and yet adequate strength, which are thought advantageous for earthfills rested on difficult underlying stratums or facilities. However, these investigations were limited to tire chips or shreds, yet to EPS-based mixtures.

For the sand-EPS bead lightweight geomaterial proposed by Deng et al.[1], the materials take advantages over other comparable geomaterials (e.g., EPS block geoforms and soil-EPS-cement lightweight fills). The advantages include irregular space filling, cement saving, fast placement and thermal isolation. As such, the materials are favorable to be used as lightweight fills over difficult areas as aforementioned.

As a granular material, the shear behavior of sand-EPS lightweight fills plays an important role in affecting its deformation and stability in practical works, and thus deserves a further investigation beyond its general engineering properties. For the two-phase (sand-EPS) solid geomaterial, its shear behavior is rather complicated than general geomaterials composed of pure soils. The behavior is essentially associated with mixing ratios and mechanical interaction of sands and beads. This research was performed as an initiative addressing the shear behavior of sand-EPS beads lightweight fills. An experimental program was conducted on the shear strengths, strength parameters and involved influencial factors. Technical data and analyses in this paper can be used to model materials' constitutive laws, and help their designs.

2 Laboratory procedures

Materials used in the tests included engineering standard sands and EPS beads. Specific gravity of sand was 2.62. Fig. 1 shows the sand gradation, which is identified as being well graded (C_u=6.5, C_c=0.7). EPS bead is a superlight polymer material, basically spherical. Such beads were made by pre-puffed polymer resins, at an enlargement ratio of 35-40. The particle size, bulk density and specific gravity of EPS beads were 2-3 mm, 0.015 g/cm^3 and 0.03, respectively. EPS beads were blended homogeneously with sands in accordance with the mass ratios (η) of beads to sands, i.e., η=0, 0.5%, 1.5% and 2.5%. The mixtures were compacted by controlling their relative density D_r being 0.5. Back pressure was used to saturate the mixtures. The physical properties of mixture specimens are presented in Table 1. Fast direct shear tests and consolidation-drained triaxial compression tests were conducted in accordance with state specifications presented in Standard for Soil Test Method (GB/T50123-1999).

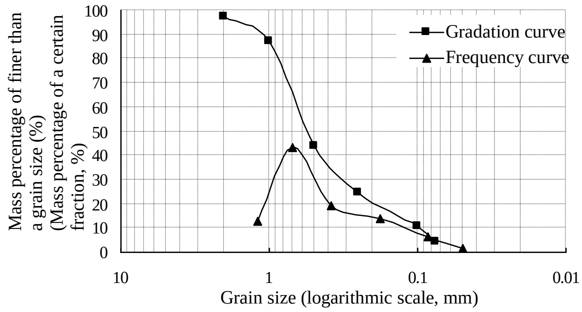

Fig. 1 Sand gradation curves

Table 1 Mixture proportions and densities

EPS ratio η /%	Relative density D_r	EPS mass m_{EPS} /g	Sand mass m_s /g	Water mass m_w /g	Density ρ g/cm^3
0	0.5	0.00	101.73	10.17	1.87
0.5	0.5	0.35	68.49	6.88	1.26
1.5	0.5	0.66	44.12	4.48	0.82
2.5	0.5	0.83	33.26	3.41	0.63

3 Results and discussion

3.1 Direct shear tests

3.1.1 Shear stress-displacement characteristics

Fig. 2 depicts the shear stress-displacement (τ - δ) curves of sand-EPS beads lightweight fills subjected to different normal stresses σ (i.e. 100, 200, 300 and 400 kPa). The observations were well simulated by hyperbolas. At a shear displacement, the shear stress increases with the increase of normal stress. It is interpreted that increase of normal stress results in compression of materials, as well as increase of relative density. Accordingly, the shear stress increases. With the increases of normal shear stresses and EPS ratios, the strain hardening level increases, and materials will be more plastic.

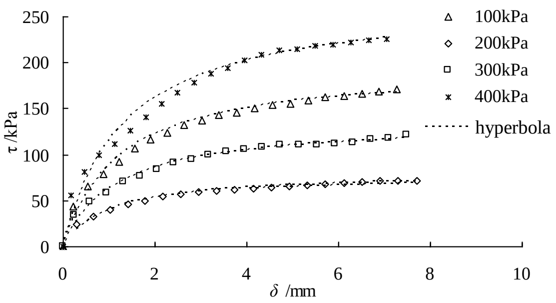

Fig. 2 Shear stress-displacement curves (η =1.5%)

Three parts are divided for a τ - δ curve, including initial part, yield part and failure part in sequences. In the initial part, the relationship between τ and δ is linear; the maximum elastic shear displacement increases with η and σ . Such increase eventually becomes unclear with the increase of η . In the yield part, when shear displacement exceeds the maximum elastic shear displacement, the curves become convex; the material was yielding, and plastic deformation was generated. The curvature of curves decreases with the increase of η and σ . In the failure part, both shear displacement and shear stress continue increasing slightly, and the increase of shear stress become clear with the increase of normal stresses. The τ - δ curves of sand-EPS mixtures are basically consistent with those of general soils.

Figs. 3 and 4 depict the τ - δ curves for soil-EPS beads lightweight fills of different EPS mixing ratios η . It is shown that shear stress increases with the decrease of EPS ratios. EPS beads are less rigid compared to sand grains, which might weaken the grain-to-grain interlocking and friction effect, and thus fade the strengths gains of mixtures. When σ is relatively low (σ =100 kPa in Fig. 3), the curves eventually end in the same level for materials of different η . When σ increases (σ =400 kPa in Fig. 4), the τ - δ curve for pure sand is isolated from the other curves. It is interpreted that, under low normal loads, shear resistance was low which were affordable by EPS beads; when the shear resistance increased along with the normal loads, EPS beads were not as rigid as sand grains to resist grain shears.

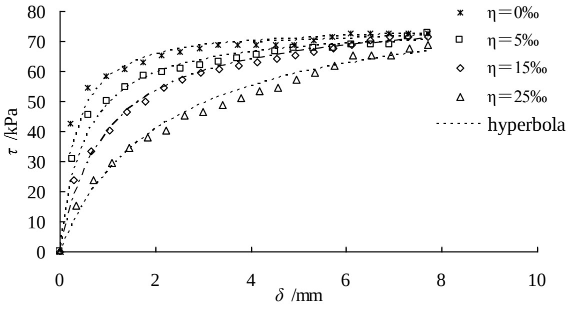

Fig. 3 Shear stress-displacement curves (σ_3 =100 kPa)

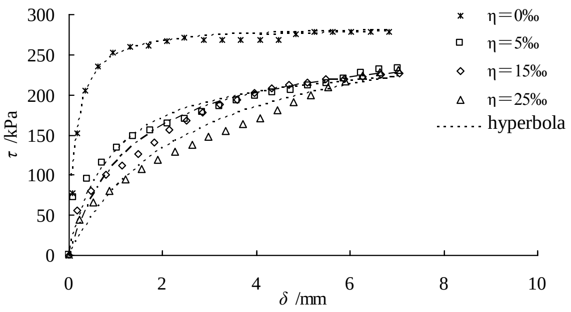

Fig. 4 Shear stress-displacement curves (σ_3 =400 kPa)

Fig. 5 presents the peak shear strength τ_f verse EPS ratio η . It is shown that τ_f decreases with the increase of η , as well as the decrease of normal stress σ . The shear strength variation associated with η is clearer under high normal stresses. It is also demonstrated that the relationship between τ_f and η is linear, as represented by Eq. 3. The fitting parameters a , b and R^2 are tabulated in Table 2.

$$\tau_f = a\eta + b \tag{3}$$

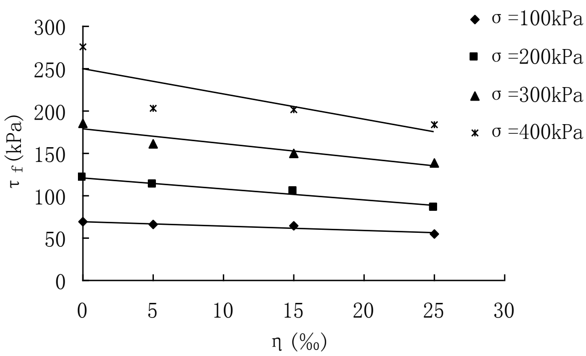

Fig. 5 Relationship between shear strength and EPS mixing ratio

Table 2 Parameters for fitting shear strength and mixing ratios

σ /kPa	a	b	R^2
100	-0.556	70.124	0.941
200	-1.308	120.890	0.970
300	-1.722	178.230	0.902
400	-2.930	249.280	0.640

When normal stresses are high (e.g., σ=300 and 400 kPa) and EPS ratios are small (η ≤0.5%), relationship between τ_f and η does not strictly follow a linear relationship compared to the other cases. It is interpreted that, under high σ and low η conditions, EPS beads were prone to be compressed into "plate". Sand particles and beads became actively rolling and/or sliding, according to the failure mechanism of sands[13-15]. While EPS ratios are relatively high (η ≥0.5%), EPS beads tend to stack together. Shear strength of the lightweight fills at the same EPS ratio increases with the increase of normal stresses. It is explained that the increase of normal stresses result in void reduction and density increase, which further renders the particle interlocking and shear strength increase.

3.1.2 Shear strength

Fig. 6 shows the Mohr-Column strength criteria lines obtained in direct shear tests. It is indicated that an apparent cohesion is present in sand-EPS bead mixtures, which is not expected in granular materials. The cohesion increases with the increase of EPS ratios. It is known that stiffness of sands is much higher than that of EPS beads. When compressed, sands would become embeded partially or fully into EPS beads, forming kind of interlocking or binding effect. As a result, apparent cohesion appears between grains, similar to that of clayey soils. With the increase of EPS ratios, such embedding prevails and apparent cohesion increases.

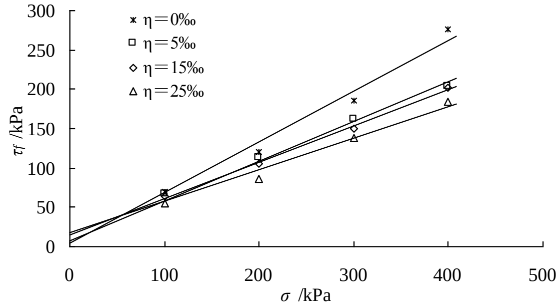

Fig. 6 Mohr-Column strength criteria lines in direct shear tests

It is also shown in Fig. 6 that the increase of EPS ratios slightly result in the decrease of internal friction angle φ, which is thought related to the special shear mechanism (shear contraction verse shear dilatancy) of granular materials. In general, internal friction angle φ of granular materials comprises three sub-angles [16-17], i.e., sliding sub-angle φ_μ, dilatancy sub-angle φ_d, and breakage and redistribution sub-angle φ_b. For sand-EPS beads mixtures, one more sub-angle should be included: EPS sub-angle φ_{EPS}, which is generated by the contraction and redistribution of EPS beads. With the increase of EPS ratios, φ_d decreases and φ_{EPS} increases (Fig. 6); the decreasing magnitude exceeds the increasing magnitude. By and large, internal friction angle φ decreases along with the increase of EPS ratios. The values of apparent cohesion c and internal friction angle φ are presented in Table 3.

Table 3 Shear strength parameters in direct shear tests

η /%	c /kPa	φ /°
0	5.0	32.6
0.5	8.0	26.7
1.5	15.5	24.7
2.5	18.0	21.8

3.2 Triaxial compression tests

3.2.1 Stress-strain characteristics

Figs 7-8 depict the deviatoric stress-axial strain-volumetric strain curves of sand-EPS beads lightweight fills. Under a confining pressure σ_3, the stresses decrease with the increase of EPS ratios. For pure sands (η=0), shear contraction was seen at first, then shortly and clearly transited into shear dilatancy. For the other EPS-based specimens, shear contraction was seen throughout.

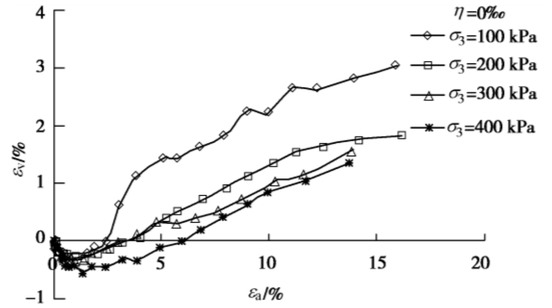

Fig. 7 Volumetric strain-axial strain curves of sand specimens

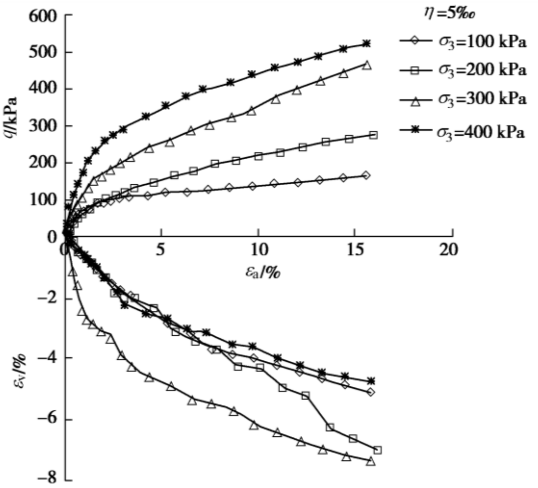

Fig. 8 Deviatoric stress-axial strain-volumetric strain curves of sand-EPS mixtures (η =0.5%)

It is also seen that strain-hardening levels increase with the confining pressure σ_3. It is interpreted that confining pressure enhances the densification of mixtures. Accordingly, the interlocking effect and shear resistance increase.

The volumetric strain ε_v does not vary consistently with that of general soils. Two distinctions were identified: shear contraction and inconsistency with confining pressures. For the former distinction, it is seen that EPS-based mixtures keep contracting in shearing processes. Unlike sands, EPS beads are compressible materials and the compression magnitude is not neglectable. As such, sand shear dilatancy, if took place, was fully offset by EPS contraction. As a result, the mixtures underwent shear contractions throughout.

The next distinction is about the association of shear contraction with confining pressures σ_3. It is seen in Fig. 8 that volumetric strain (contraction) increases in accordance with the sequence of σ_3: 400 kPa, 100 kPa, 200 kPa and 300 kPa. When σ_3 was relatively high (σ_3 =400 kPa), the mixtures (mainly EPS beads) were largely compressed and densified in consolidation process. Most volumetric contractions were fulfilled before shearing. Much less shear contraction was then seen. When σ_3 was relatively low (σ_3 =100 kPa), relative less compacted structure was rendered prior to shearing. The materials failed under low shear stress where relatively low strain was observed. For the other two moderate confining pressures (σ_3 =200 and 300 kPa), the magnitude of volumetric strain was dependent on multiple factors, including contraction levels before and during shearing, sand dilatancy and mixture shear resistance, which eventually leaded to relatively high volumetric strains.

3.2.2 Shear strength

Fig. 9 summarizes the shear strengths of sand-EPS beads mixtures. It is indicated that shear strength decreases with the increase of EPS ratio η, and with the decrease of confining pressure σ_3. Confining pressures help densify materials, which increase particle interlocking effect and shear strength. When η ranges from 0 to 0.5%, a clear decrease in shear strength is seen. It is interpreted that under low η conditions, EPS beads are surrounded by sands, which facilitates the sand sliding on the surface of beads. The sliding causes shear strength loss more than that occurred to pure sands. Such shear strength decrease is seen clearer under high confining pressures than under low ones.

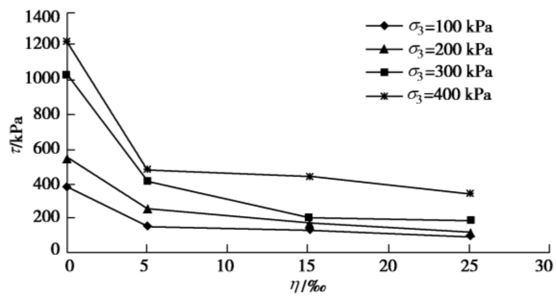

Fig. 9 Variation of shear strength with EPS ratios

Combine the shear strength variations in both direct and triaxial shear tests, it is inferred that EPS ratio has a marginal effect on the shear strength of sand-EPS beads lightweight fills.

Two types of Mohr-Coulomb envelopes

were identified, i.e., linear type and piecewise linear type. Envelopes of the former is a basically a line, applying to lightweight fills of low mixing ratios, i.e., $\eta \leq 0.5\%$ (Fig. 10). Envelopes of the latter are piecewise linear lines, applying to fills of relatively high mixing ratios, i.e., $\eta \geq 1.5\%$ (Fig. 11), where apparent over-consolidation characteristics appear. The apparent over-consolidation characteristics are thought relevant to the inclusion of EPS beads. As aforementioned, stiffness difference leads to the embedding of sands into EPS beads. This kind of grain interaction is far different from that between sand grains. Such interaction renders some binding effect between grains. The binding force could be strong, moderate and slight, depending upon the embedding magnitude, manners and angles. Nevertheless, such force tends to hold grains together, apparently making them a cohesive soil or dense cohesionless soil. As such, under confining pressures from 100 to 400 kPa, the lightweight fills behaved like over-consolidated clayey soils or dense sands.

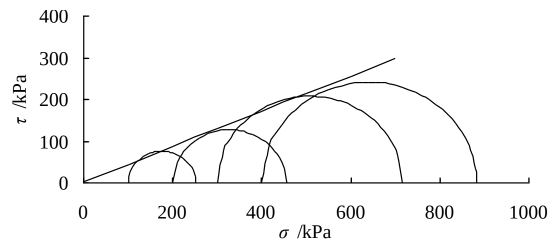

Fig. 10 Mohr-Coulomb envelope in triaxial compression tests (η =0.5%)

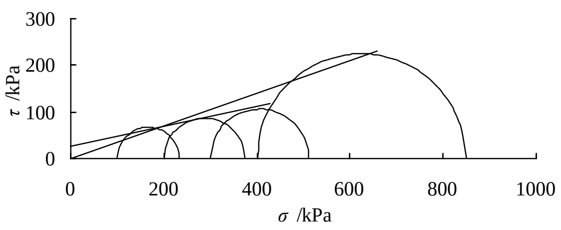

Fig. 11 Mohr- Coulomb envelope in triaxial compression tests (η =1.5%)

Table 4 summarizes the shear strength parameters c and φ of sand-EPS beads lightweight fills under consolidation-drained triaxial shear conditions. As envelops are piecewise linear lines under high η conditions (η =1.5% and 2.5%), two sets of parameters are presented, e.g., 1.5(A) and 1.5(B), representing two parts of envelops.

Table 4 Shear strength parameters in triaxial compression tests

η /%	φ /°	c /kPa
0	37.9	0.0
0.5	23.0	0.0
1.5(A)	12.8	22.4
1.5(B)	19.2	0.0
2.5(A)	11.0	17.5
2.5(B)	16.3	0.0

Note: 1.5(A) and 1.5(B) represent the two parts of Mohr-Coulomb envelopes (η =1.5%). So do 2.5(A) and 2.5(B).

4 Conclusions

1) EPS inclusion results in substantial decrease in densities of sand-EPS mixtures; however, weakens shear strength gains of mixtures. In particular, the decrease of shear strength is clear for low EPS mixtures subjected to high normal or confining stresses.

2) An apparent cohesion and over-consolidation characteristics present when the EPS ratio increases, which is relevant to the embedding of sands into beads.

3) EPS-based mixtures undergo contraction throughout shears, which is ascribed to the substantial contraction of EPS beads.

4) The critical ratio of EPS, which determines the shapes of Mohr-Coulomb's strength envelopes, is 0.5%. When EPS ratio ranges between 0 and 0.5%, the envelopes are linear; when EPS ratio ranges between 0.5% and 2.5%, the envelopes are piecewise linear.

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