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Mechanical properties of expanded polystyrene beads stabilized lightweight soil

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Abstract. To investigate the mechanical properties of Expanded Polystyrene (EPS) Beads Stabilized Lightweight Soil (EBSLS), Laboratory studies were conducted. Totally 20 sets of specimens according to the complete test design were prepared and tested with unconfined compressive test and consolidated drained triaxial test. Results showed that dry density of EBSLS (0.67-1.62 g/cm^3) decreases dramatically with the increase of EPS beads volumetric content, while increase slightly with the increase of cement content. Unconfined compressive strength (10-2580 kPa) increases dramatically in parabolic relationship with the increase of cement content, while decreases with the increase of EPS beads volumetric content in hyperbolic relationship. Cohesion (31.1-257.5 kPa) increases with the increase of cement content because it is mainly caused by the bonding function of hydration products of cement. The more EPS beads volumetric content is, the less dramatically the increase is, which is a result of the cohesion between hydration products of cement and EPS beads is less than that between hydration products of cement and sand particles. Friction angle (14.92-47.42°) decreases with the increase of EPS beads volumetric content, which is caused by the smoother surfaces of EPS beads than sand grains. The stress strain curves of EBSLS tend to be more softening with the increase of EPS beads content or the decrease of cement content. The shear contraction of EBSLS increases with the increase of c_e or the decrease of c_c. The results provided quantitative relationships between physico-mechanical properties of EBSLS and material proportion, and design process for engineering application of EBSLS.

Keywords: lightweight soil; density; strength; cohesion; friction angle; deformation behavior

1. Introduction

Mixing expanded polystyrene (EPS) beads with soil is one of the alternative lightweight soils, which is a kind of good embankment material to reduce earth pressure and to limit settlement of soft subgrade soil (Liu 2013, Kim *et al*. 2013), just as waste rubber (Moghaddas Tafreshi and Norouzi 2015, Terzi *et al*. 2015, Karabash and Cabalar 2015), In addition, it can be used in frost

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regions to control settlement with the advantage of outstanding thermal insulation (Wang *et al.* 2016), Kim *et al.* (2008) reported that inclusion of EPS beads made the lightweight soil much lighter than the ordinary soil, in the range of unit weight of 6 to 15 kN/m^3. The use of a lightweight fill can reduce the total weight of an embankment by 30 to 50%, which is beneficial for the control of settlement and avoid of possible bearing failure (Gu 2013, Miao *et al.* 2013), The advantages of using mixture of EPS and soil are" (1) density, strength and stiffness can be adjusted; (2) wasted packaging EPS can be recycled (Hema 2007); (3) local soil and recycled materials can be used, including sand (Deng and Xiao 2010), clay (Nicholas and Ronaldo 2013), drugged sediment (Park and Kim 2011) and fly ash (Padade and Mandal 2014), The strength and stiffness of a mixture of EPS and soil can be adjusted by changing the type and/or content of stabilizer.

When sand is used as material soil and cement is added, the lightweight soil is known as Sand-EPS beads Stabilized Lightweight Soil (EBSLS). In compaction process of EBSLS, moisture content and compaction energy have significant impacts on its mechanical properties (Zhu *et al.* 2009, Hou 2015). Results showed that moisture content in the compaction have limited impact on the dry unit weight of EBSLS. But the different moisture content in the mixture can cause one order of magnitude difference in the compressive strength of EBSLS. Optimum moisture content exists for the compressive strength in the EBSLS (Zhu *et al.* 2009), Li *et al.* (2006) found that dry density, unconfined compression strength and shear strength of EBSLS increase with more compaction energy.

EPS beads can be plastically compressed that is different from ordinary soils. The plastic compression of EPS beads is important for the increase of the density of EBSLS. Therefore, EBSLS should be compacted with low compaction capacity within more compaction times. Zhu *et al.* (2009) reported that the optimized compaction energy as 10.87 kJ/m^3 and compacted in 16 times per layer. The properties of EBSLS have been found that its density decreases with more EPS beads, its strength increases with the more binder content (Liu 2013, Kim *et al.* 2014). Most researches on EBSLS didn't conduct their study under optimal compaction conditions, e.g., the work by Miao *et al.* (2013).

The main objective of this study is to investigate the physico-mechanical properties of EBSLS, especially quantitative relationships with material proportion when it is constructed under the optimal compaction condition, including compaction energy and optimum moisture content. A series of unconfined compressive tests and consolidated drained triaxial tests were carried out on EBSLS that were prepared at different cement contents (20, 40, 60, 80, 100 kg/m^3) and various EPS beads volumetric contents (33%, 50%, 60%, and 67%). The tests results and corresponding mechanisms were discussed.

2. Materials and testing methods

2.1 Sands

Local clean sand was used as the main soil in the study. Its grain-size distribution curve is shown in Fig. 1. By relative density test, the minimum density was measured as $\rho_{\min}$ = 1.54 g/cm^3, and the maximum density as $\rho_{\max}$ = 1.79 g/cm^3. The maximum void ratio was calculated as $e_{\max}$ = 0.72, and the minimum void ratio as $e_{\min}$ = 0.48. Its specific gravity is 2.65. The average particle diameter of the sand (D_{50}) is 0.5 mm. The D_{10}, D_{30}, and D_{60} for the sand are 0.2 mm, 0.43 mm, and 0.6 mm, respectively. The coefficient of uniformity (C_u) is 3.0 and the coefficient of gradation (C_c) is 0.65. The soil is classified as poorly-graded sand according to the Unified Soil Classification

System (USCS).

2.2 EPS beads

The EPS beads are white, rounded particles with diameters of 1 mm to 3 mm, as shown in Fig. 2. Its specific gravity is 0.0618, and natural accumulated density is 0.0368 g/cm^3 with maximum void ratio of 0.68.

2.3 Binder

Portland cement was used as bonding material. The cement was used with water as a binder to bond the cohesionless sand and EPS beads together for property testing after curing. The properties of the cement were provided by manufactory as shown in Table 1.

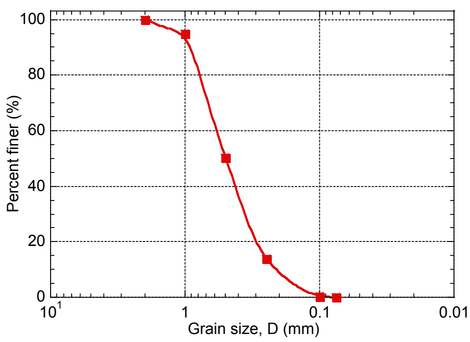


Fig. 1 Particle size distribution of sand

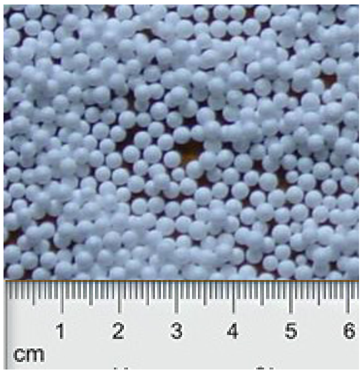


Fig. 2 Photo of EPS beads (grain size 1-3 mm)

Table 1 Properties of cement as binding agent (from manufacturer)

Property		unit	value
Density		g/cm^3	1.3
Specific density		g/cm^3	3.0
Fineness (residue on 0.08 mm sieve)		%	2.50
Normal consistency		%	25.2
Setting time	Initial setting	hour	2:35
	Final setting	hour	3:50
Strength of cement mortar (ISO)	3d fracture resistance	MPa	3.8
	28d fracture resistance	MPa	8.0
	3d compression strength	MPa	16.0
	28d compression strength	MPa	42.0
SO_3 content		%	2.17
MgO content		%	4.2
ignition loss		%	1.20

Table 2 Optimal compaction moisture content of the 25 matches (Calculated with Eq. (1) provided by Zhu *et al*. 2009)

Optimal compaction moisture content (%)					
	EPS beads volumetric content (%)				
Cement content (kg/m^3)	0	33	50	60	67
20	2.4	4.0	5.7	7.3	9.0
40	2.8	4.4	6.0	7.7	9.4
60	3.2	4.8	6.4	8.0	9.7
80	3.5	5.1	6.8	8.4	10.1
100	3.9	5.5	7.2	8.8	10.5

2.4 Specimens preparation

EBSLS mixtures were prepared at five cement contents as 20, 40, 60, 80, and 100 kg/m^3 and five EPS beads volumetric contents as 0%, 33%, 50%, 60%, and 67%, resulting in totally 25 different matches. The compacted moisture contents of all the EBSLSs were calculated by the optimal compaction moisture content equation provided by Zhu (Zhu *et al*. 2009), as shown in Eq. (1), and the values were listed in Table 2.

$$\omega_{wopt} = \frac{c_c}{G_s}\omega_c + \frac{G_e c_e}{(1-a_e)G_s}\omega_e + \omega_s \tag{1}$$

where:

ω_{opt} is optimal compaction moisture content of EBSLS;
c_c is cement content;
c_e is EPS beads volumetric contents;
ω_s is moisture for per m^3 sand, ω_s = 2.05 % for the material sand;
ω_e is moisture for per m^3 EPS beads, ω_e = 138.8% for the material EPS beads;
ω_c is moisture for per m^3 cement, ω_c = 49.5% for the material cement;
G_e is specific gravity of EPS beads, G_e = 0.0618 g/cm^3 for the material EPS beads;
G_s is specific gravity of sand, G_s = 2.65 g/cm^3 for the material sand.

After the samples were mixed thoroughly, the mixtures were put in spilt mold that was 3.91 cm in diameter and 8.0 cm in height, and then compacted for 16 times in three layers. The mini compaction hammer was 295.8 g in weight, and 12 cm in drop distance, as shown in Fig. 3. The compaction capacity was calculated as10.87 kJ/m^3 (Li 2008), After compaction, the molds with specimens were put in standard curing box with temperature 20°C and humidity of 100% for 24 hours. The specimens were taken out of molds, collected in plastic bags, and put in standard curing box for continuing 27 days. Triplicate specimens were prepared for the mechanical properties tests.

2.5 Physical properties tests

The diameter of each specimen was dimensioned for 4 times along the specimen length, every quarter. The height dimensioned similarly for 4 times, each position 90° away from the previous

(a) (b)

Fig. 3 (a) Compaction of EBSLS; with (b) mini compactor

angle. The average value of the dimensions was calculated as the diameter and height of the specimens, and then the volumes were calculated. The moisture masses, saturated masses and oven-dry masses were determined in sequence. Density, dry density, saturated density, moisture content and saturated moisture content were calculated. Three replicates were done and averaged for each match.

2.6 Mechanical properties tests

Unconfined compression tests were conducted under strain rate of 1.18 mm/min in accordance with ASTM D2166 after been saturated. Consolidated drained triaxial compression tests were conducted under 50, 100, 150, or 200 kPa cell pressure at a constant axial strain rate of 0.02% strain/min in accordance with ASTM D2850. The tests were halted after axial strain had reached 15% (Lambe and Whitman 1979).

3. Results and discussion

As a kind of lightweight soil, the most important engineering properties of EBSLS are density which affects the earth pressure, and shear strength which affects its stability. Moisture content, stress-strain relationship, failure strain and volumetric strain characteristics are also important. These properties are all influenced by material proportions, which include the EPS beads volumetric content and cement content. The engineering properties, as well as the effects of the influence factors are presented as follows.

3.1 Physical properties

Dry Density was thought to be the most important physical properties, which is analyzed and discussed specially. Fig. 4 shows the dry density of EBSLS as a function of cement content and EPS beads volumetric content. With cement content increased from 20 kg/m^3 to 100 kg/m^3, dry density of EBSLS slightly changed. This is due to the cement content was relatively small. The EBSLS with 100 kg of cement is estimated about 118 kg after hydration reaction, so the cement content only cause the dry density of EBSLS increasing in 0.118 g/cm^3. However, dry density of EBSLS decreases with more EPS beads volumetric content (Fig. 4(b)), This is due to the sand being replaced by EPS beads whose has an extremely low density. When EPS beads volumetric content is 0.4, the Dry density of EBSLS is around 1.0 g/m^3, which is in good condition for engineering practice.

Based on change of density of EBSLS relative to the density of sand, taking considering of the filling effect of cement and the replacement effect of EPS beads, the dry density can be calculated as Eq. (2)

$$\rho_\mathrm{d} = \rho_\mathrm{s} + k_\mathrm{c} c_\mathrm{c} - (\rho_\mathrm{s} - \rho_\mathrm{e}) c_\mathrm{e} \tag{2}$$

Where,

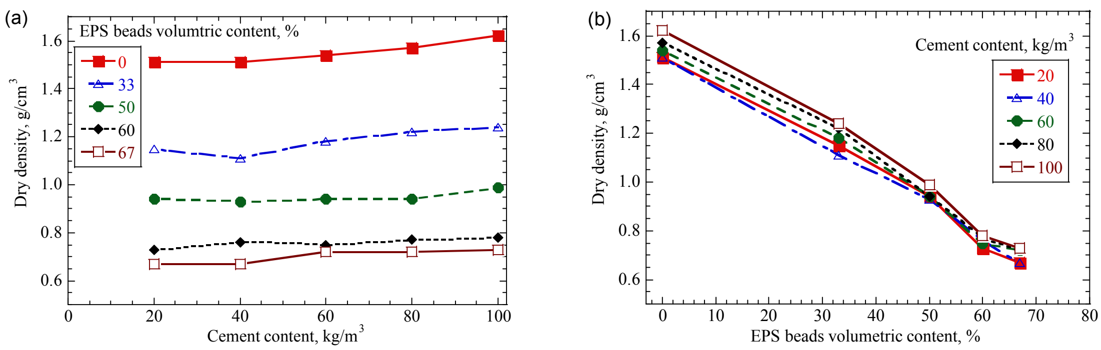
ρ_d is dry density of sand in EBSLS of a specific material proportion, g/cm^3.
ρ_s means dry density of sand in EBSLS, g/cm^3.
k_c is a ratio between the increase of dry density and the increase of cement content.
c_c is cement content, kg/m^3.
ρ_e is dry density of EPS beads in EBSLS, g/cm^3.
c_e is EPS beads volumetric content,%.

The parameters in Eq. (2) can be evaluated using the data presented in Table 1. Multivariate linear regression was done and the parameters in Eq. (2) were revealed, so Eq. (2) can be expressed as Eq. (3) for the materials used in this study.

$$\rho_\mathrm{d} = 1.5 + 0.002 c_\mathrm{c} - 1.45 c_\mathrm{e} \tag{3}$$

R^2 of the multivariate line regression is 0.962, so the form of the theoretical equation, Eq. (2), was verified. But, Eq. (3) was derived for the materials in this study. For different materials, the data should be changed.

The other fundamental physical properties of all the EBSLSs of the 25 matches are presented in



(a) (b)

Fig. 4 Dry density of EBSLS mixture as a function of (a) cement content; (b) EPS beads volumetric content

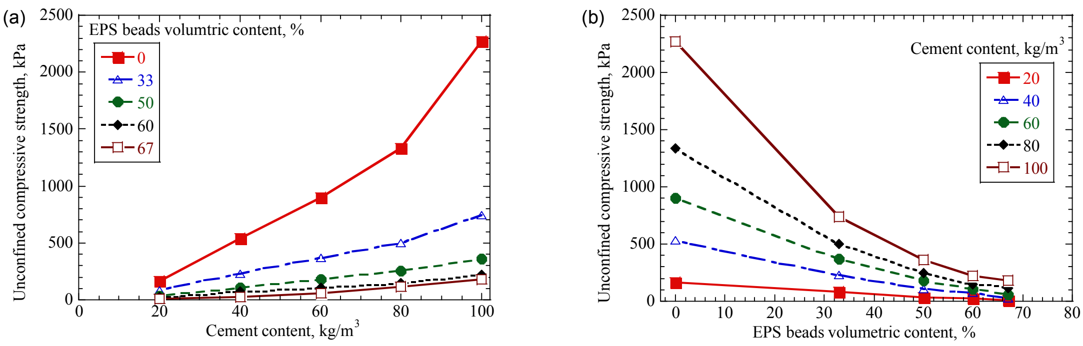
Table 3 Physical properties of EBSLS

EPS beads volumetric content	Cement content	Cement content	Density ρ	Moisture content w	Saturated density ρ_{sat}	Saturated moisture content w_{sat}
%	kg/m^3	% (weight)	g/cm^3	%	g/cm^3	%
0	20	3.25	1.59	5.62	1.95	22.63
0	40	6.50	1.61	6.77	1.91	21.03
0	60	9.75	1.66	7.61	1.96	21.10
0	80	13.00	1.69	8.17	1.84	15.02
0	100	16.25	1.72	6.13	1.91	15.12
33	20	3.25	1.24	7.59	1.47	21.50
33	40	6.50	1.20	7.42	1.35	17.55
33	60	9.75	1.26	6.60	1.42	16.57
33	80	13.00	1.31	7.32	1.45	15.86
33	100	16.25	1.33	7.54	1.44	13.87
50	20	3.25	1.00	6.17	1.17	19.88
50	40	6.50	1.02	9.36	1.14	18.62
50	60	9.75	1.02	8.13	1.13	16.61
50	80	13.00	1.04	10.41	1.16	19.09
50	100	16.25	1.08	9.50	1.20	17.61
60	20	3.25	0.85	15.72	0.94	22.47
60	40	6.50	0.86	13.41	0.97	21.17
60	60	9.75	0.84	11.14	0.96	21.20
60	80	13.00	0.87	12.31	0.99	21.87
60	100	16.25	0.92	17.38	1.00	22.01
67	20	3.25	0.72	6.24	0.79	14.21
67	40	6.50	0.75	8.39	0.81	13.67
67	60	9.75	0.80	10.34	0.83	13.54
67	80	13.00	0.80	10.52	0.82	12.24
67	100	16.25	0.82	11.81	0.87	15.90

Table 3. The density and saturated density decrease with the increase of EPS beads volumetric content, while change a little with cement content. As a whole, Moisture content and its sensitivity increase with the increase of EPS beads volumetric content, which is due to the reduction of mass of solid particles. Which should be noted is that moisture content of EBSLS is different from compaction moisture content because of the hydraulic of cement and moisture movement in curing oven. Saturated moisture content is between 13% and 23% without any distinct regularity to material proportions.

3.2 Unconfined compressive strength

Fig. 5 shows the unconfined compressive strength of EBSLS as a function of cement content



(a) (b)

Fig. 5 Unconfined compressive strength of EBSLS mixture as a function of (a) cement content; (b) EPS beads volumetric content

and EPS beads volumetric content. When the cement content increased from 20 kg/m^3 to 100 kg/m^3, unconfined compressive strength of EBSLS increased dramatically in parabolic relationship. This is due to the bonding function of hydration products of cement. Unconfined compressive strength decreased with EPS beads volumetric content in hyperbolic relationship. It is caused by the lower cohesion between EPS beads and cement hydration products and the lower strength of EPS beads comparing to sand particles.

Based on the relationships between unconfined compressive strength and material proportions, which are parabolic relationship to cement content and hyperbolic relationship to EPS beads volumetric content, Multivariate nonlinear regression analysis was done and Eq. (4) was given.

$$q_u = \frac{k_1 c_c^2 + k_2 c_c}{k_3 + c_e} \quad (4)$$

Where, q_u is unconfined compressive strength of EBSLS of a specific material proportion, kPa.
k_1, k_2 and k_3 are coefficients to be determined.
c_c is cement content, kg/m^3, no unit when the equation calculated.
c_e is the EPS beads volumetric content, %, no unit when the equation calculated.

The coefficients, k_1, k_2 and k_3, were obtained by the multivariate nonlinear regression analysis, as shown in Eq. (5), R^2 in the multivariate nonlinear regression analysis is equal to 0.972, which represented that Eq. (4) was suitable for the prediction of unconfined compressive strength of EBSLS using its material proportion. Based on the research by Kim (Kim *et al*. 2014), the relationship between the compressive and tensile strengths was a straight line, with means that the tensile strengths show the same changing law as unconfined compressive strength.

$$q_u = \frac{1.9 c_c^2 + 57.6 c_c}{11.4 + c_e} \quad (5)$$

3.3 Stress-strain relationship

The stress-strain curves of EBSLS vary with matches and cell pressures. Fig. 6 shows the stress-strain curves of 4 typical matches, which are minimum EPS beads volumetric content

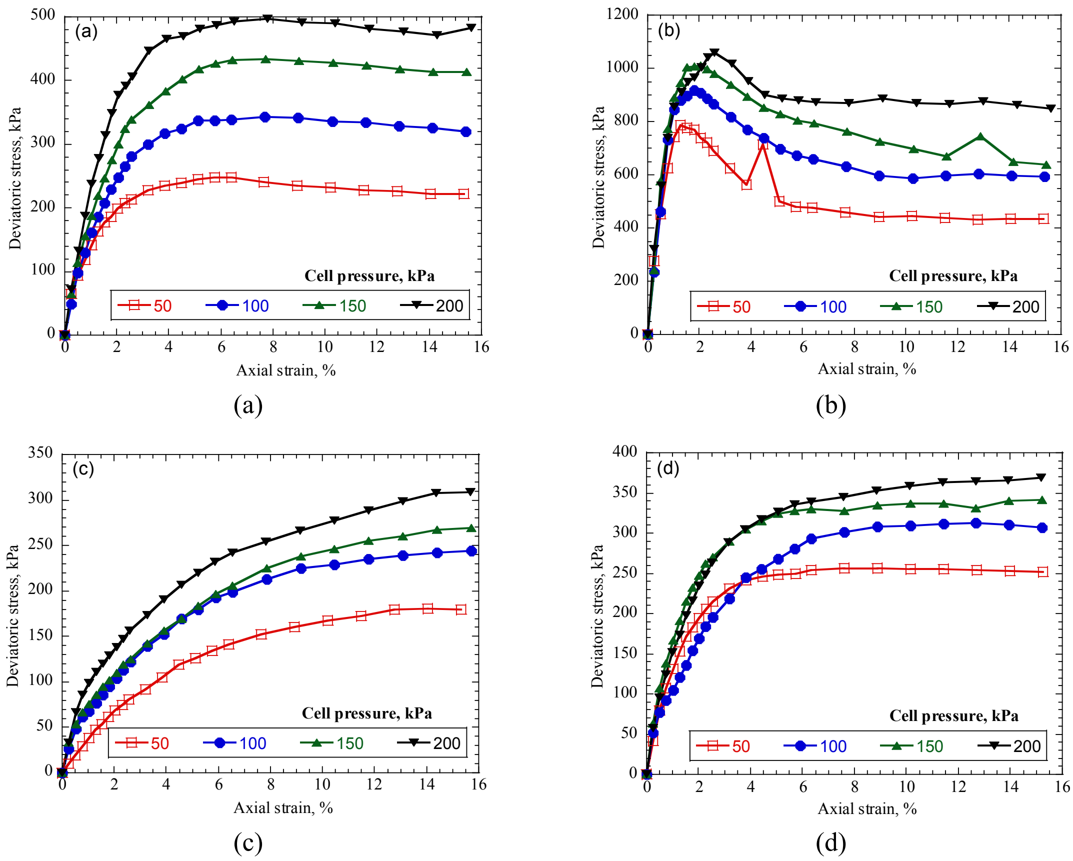


Fig. 6 Stress–strain curves of EBSLS mixture as a function of cement content (c_c) and EPS beads volumetric content (c_e): (a) c_c = 20 kg/m^3 and c$_e$ = 33%;, (b) c_c = 100 kg/m^3 and c_e = 33%; (c) c_c = 20 kg/m^3 and c_e = 67%; and (d) c_c = 100 kg/m^3 and c_e = 67%

couple with minimum cement content, minimum EPS beads volumetric content couple with maximum cement content, maximum EPS beads volumetric content couple with minimum cement content and maximum EPS beads volumetric content couple with maximum cement content. Results show both strain hardening and strain softening occur on EBSLS. The stress strain curves of EBSLS tend to be more softening with the increase of c_e or the decrease of c_c. The law is applicable for all 25 material proportions tested, except for the 4 typical ones showed here. When c_c = 100 kg/m^3 and c_e = 33%,with the highest cement content and lowest EPS beads content of all the 25 matches, the strength of EBSLS is the highest, and the specimens are friable. Thus, jumping in Fig. 6(b) is probable caused by the resistance and fracture of caked mass near the shear zone.

3.4 Shear strength, cohesion and friction angle

From consolidated drained triaxial compressive tests, effective stress (total stress) shear strengths at the four cell pressures of 50, 100, 150, 200 kPa were obtained. Fig. 7 shows an example of Mohr circles of the specimens at different cell pressure, indicating the failure criterion line is a good straight line under consolidated drained conditions. In Ji's (2005) research on shear strength of EBSLS under consolidated undrained conditions, the failure criterion line can be combined of two oblique straight lines when structural yield stress of the soil was in the scope of highest cell pressure and lowest cell pressure. In these tests, not any crack was found as consolidated, so it was seen as the highest cell pressure (200 kPa) is less than the structural yield stresses of the EBSLS. In the research under unconsolidated undrained conditions, the failure criterion lines were combined of a horizontal line and anoblique line (Miao *et al*. 2013). There is no horizontal failure criterion line existed in these results, so the sets of Mohr circles should be looked upon as ordinary consolidated soils. The comparison shows the effect of triaxial shear conditions on the failure criterion line of EBSLS.

Cohesion and friction angles of EBSLS were calculated using classical Mohr-Coulomb failure criterion. Fig. 8 shows the variation of cohesion of EBSLS with cement content and EPS beads volumetric content. For all the five EPS beads volumetric contents, cohesions increase with the cement content, with the minimum value of 42 kPa and the maximum value of 260 kPa. Compared to the cohesion of 10 kPa for EPS beads sand mixture without cement (Zhu *et al*. 2009), it indicates that cohesion is mainly caused by the bonding function of hydration products of cement.

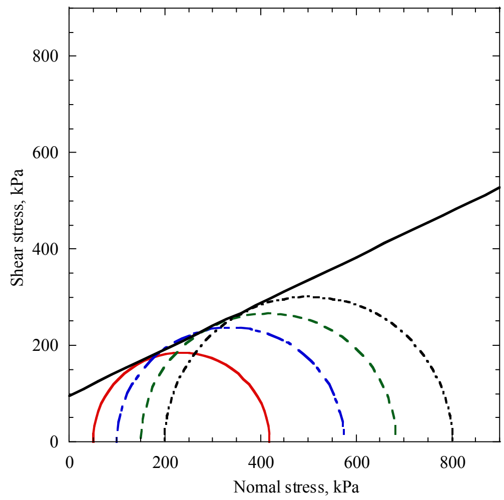


Fig. 7 Example of Mohr's circle and coulomb envelop of EBSLS mixture as a function of moisture content at the cement content of 60 kg/m^3, and EPS beads volumetric content of 50%

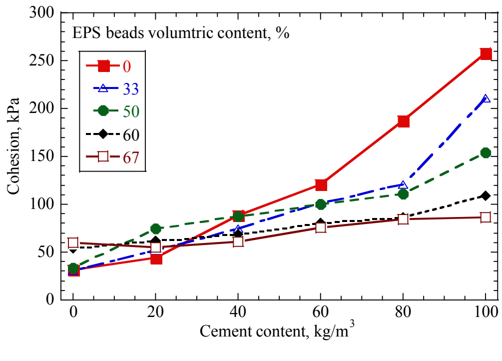
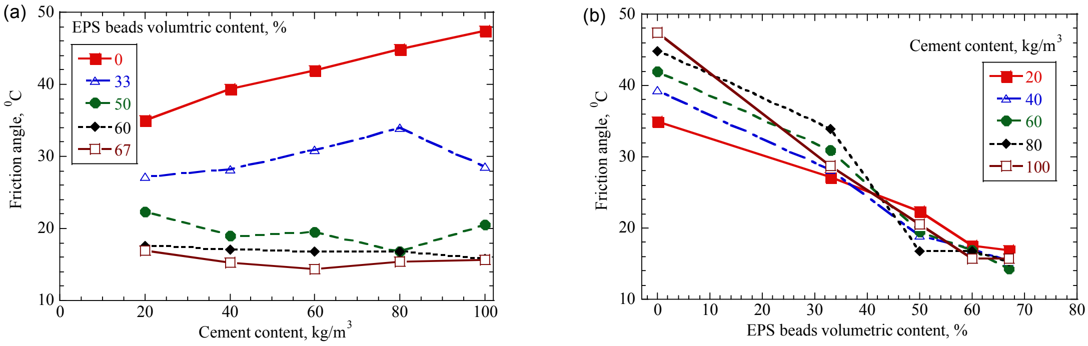


Fig. 8 Cohesion of EBSLS mixture as a function of cement content



(a) (b)

Fig. 9 Friction angle of EBSLS mixture as a function of: (a) cement content; (b) EPS beads volumetric content

Cohesions reduce with the increases of EPS beads content. More increasing of cohesion for the specimens with less EPS beads volumetric content. When cement content is 100 kg/m^3, the cohesion reduced from 260 kPa to 80 kPa as EPS beads volumetric content increased from 33% to 67%. There are two possible reasons for the reduction of cohesion with the increase of EPS beads when cement content is high: (1) The surfaces of EPS beads are smoother than that of sand particles, so the cohesion between hydration products of cement and EPS beads is less than that between hydration products of cement and sand particles; (2) EPS beads are weaker than sand grains. Therefore, more EPS beads content can reduce the overall shear resistance of the EBSLS and that would lead to the reduction of the EBSLS cohesion. When cement content is low, as 20 kg/m^3, changes little with the increase of EPS beads volumetric content, whose reason is unclear.

Fig. 9 shows the variation of friction angle of EBSLS with cement content and EPS beads volumetric content. Fig. 8(a) shows that friction angle increase with the increase of cement content when EPS beads volumetric content is less than 50%, while decrease slightly with the increase of cement content when EPS beads volumetric content is more than 50%. Fig. 8 shows that friction angle decreases with the increase of EPS beads volumetric content, which is because EPS beads are smoother and weaker than sand grains, whose mechanisms are similar to the reduction of cohesion with the increase of EPS beads volumetric content.

3.5 Volumetric strain characteristics

The Volumetric Strain curves of EBSLS vary with matches and cell pressures. Fig. 10 shows that of the 4 typical match the same with stress-strain relationship. There are two typical volumetric changing characteristics, which are shear dilating and shear contracting. The higher the EPS beads content is, the lower the cement content is, and the higher the cell pressure is, the more contracting the volumetric change is. On the contrary, the volumetric change tends to be dilating. These laws are applicable for all 25 material proportions tested, except for the 4 typical ones showed here.

3.6 Discussions on material proportions description

In the history of EBSLS which is no more than 35 years, there are several descriptions for matches. In all of the descriptions, material soil is considered to be datum, and other materials are

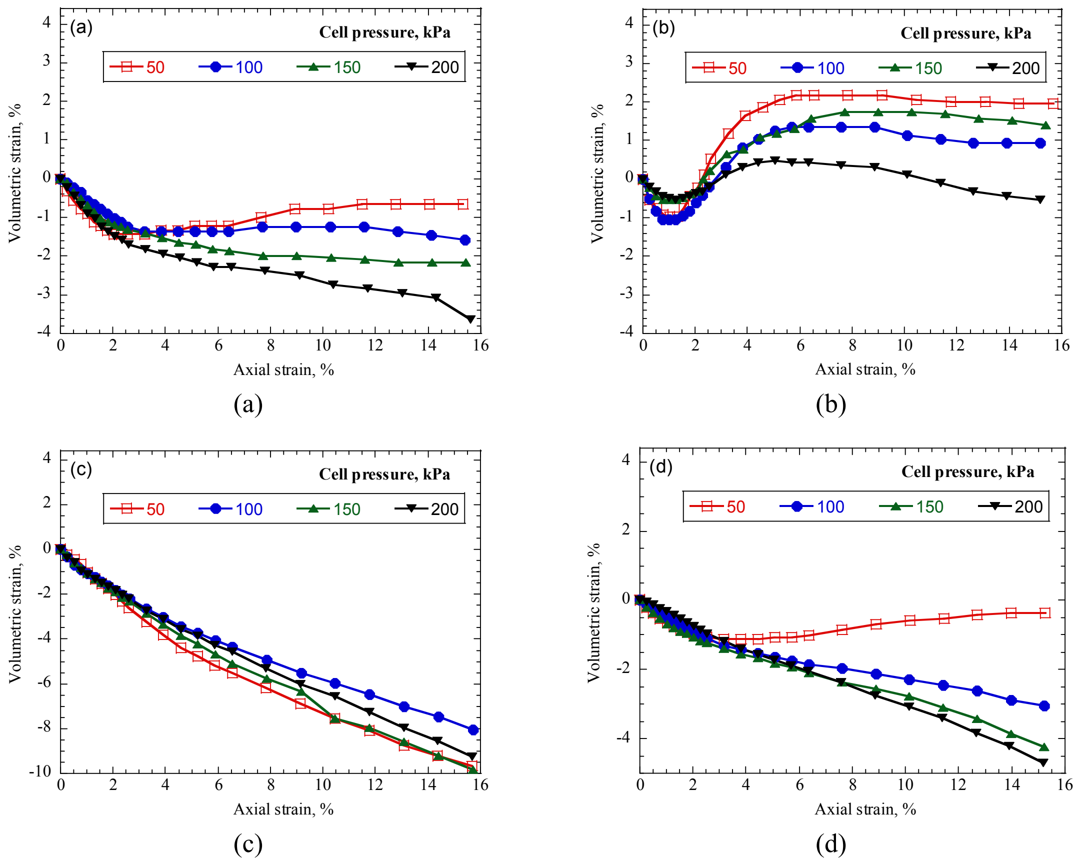


Fig. 10 Volumetric strain curves of EBSLS mixture as a function of cement content (c_c) and EPS beads volumetric content (c_e): (a) c_c = 20 kg/m^3 and c_e = 33%; (b) c_c = 100 kg/m^3 and c_e = 33%; (c) c_c = 20 kg/m^3 and c_e = 67%; and (d) c_c = 100 kg/m^3 and c_e = 67%

described based on the amount of material soil. As for the measurement of material soil, there are two ways, mass (Miao *et al*. 2013) and volume (Li 2008, Gu 2013), Due to volume is more conveniently to be measured in site than mass, volume is recommended. As for bonding materials content, mass is used as index in all descriptions because it is packed by mass and also can be balanced conveniently. There are two way to describe bonding material content, one is mass content in material soil with unit of % (Miao *et al*. 2013), the other is mass content in unit volume of material soil with the unit of kg/m^3 (Li 2008), Based on the recommendation on material soil description, mass content in unit volume is suggested. In terms of lightweight substitution content, the volume of substitution in unit volume of material soil or in unit volume of EBSLS is always used as description (Li *et al*. 2008, Zhu *et al*. 2009, Gu 2013) based on which one is more convenient.

In terms of moisture content, it should be pointed out that the moisture content when compacted is different from the moisture content in EBSLS because of the water transformation in hydration reactions of bonding material. To describe the compacted moisture content, two ways are used, one is water content in material soil (Ji 2005, Li 2008, Gu 2013), and the other is water-binder ratio (He 2007). Moisture content in material soil is suggested when soil is more than binder, while water-binder ratio is suggested when binder is more than soil.

Thus, in this work, cement content is the mass of cement in unit volume of soil, with the symbol c_c (abbreviation for Cement Content and the common unit kg/m^3. EPS beads volumetric content is its volume on the sum of the original volume of soil and EPS beads respectively, with the symbol c_e (abbreviation for EPS beads volumetric Content) and the unit %. Compacted moisture content is mass content of water on dry mother sand, with the symbol ω_c (abbreviation for construction moisture content) and the unit %.

3.7 Discussions on test condition of unconfined compressive strength (UCS)

UCS tests on EBSLS are usually conducted directly after curing (Liu 2013). In fact, moisture content impacts the adsorption capacity of cement hydraulic products a lot, which affect the strength of EBSLS. Triaxial tests and direct shear tests provide suitable results as they are conducted under saturated status, while unconined compressive test may provide undesirability results when conducted directly after curing.

Contrast tests were conducted and the influence of moisture content on UCS of EBSLS is shown in Fig. 11. Moisture content of the samples was adjusted by six ways, which are: (1) originally cured; (2) saturated; (3) seeped freely for 10 minutes after saturated; (4) dried indoor for 1 day; (5) dried indoor for 7 day; (6) Oven dried, respectively. The result shows that the maximum UCS can be twice of the minimum UCS under different test conditions. EBSLS get the highest strength when natural withered, while get the lowest strength when saturated. For consistency with triaxial test results, and the safety of engineering applications under water table, unconfined compressive test are recommended to be conducted after being saturated.

3.8 Discussions on the design of EBSLS based on the relationships between shear strength and lightweightness

The relationships between shear strength and dry density are shown in Fig. 12. Based on Fig. 12(a), it is clear that the unconfined compressive strength decreases with the decrease of dry density for any cement content. In other words, there is a trade-off between high strength and good lightweightness due to inclusions of EPS beads. Based on Fig. 12(b), it is clear that the unconfined compressive strength increases dramatically with the increase of cement content. This gives a

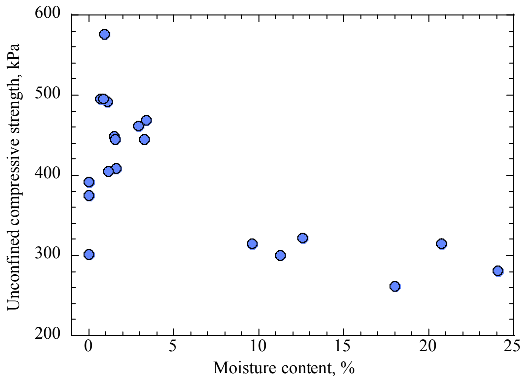
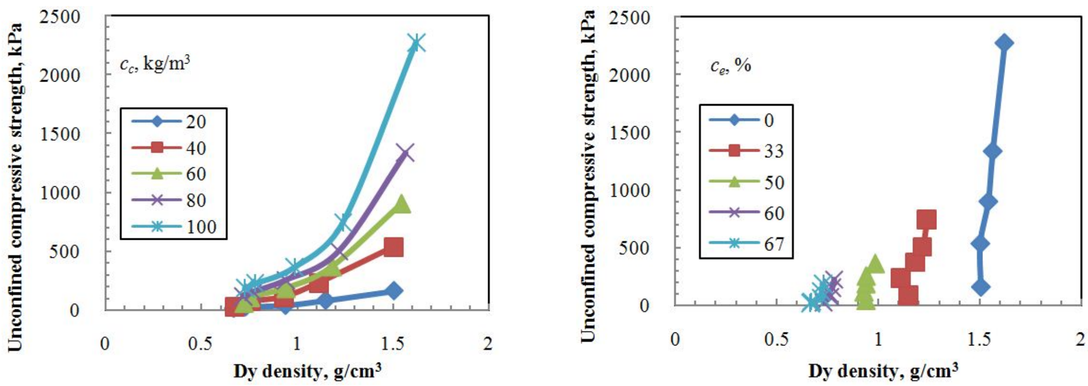


Fig. 11 Unconfined compressive strength of EBSLS mixture as a function of moisture content at the cement content of 100 kg/m^3, and EPS beads volumetric content of 50%



(a) Cement content is sedentary (b) EPS beads volumetric content is sedentary

Fig. 12 Relationships between shear strength and dry density

solution, which is adding more cement, to solve the trade-off between high strength and good lightweightness.

Thus, in practical design of EBSLS, EPS beads content should be determined firstly by reading from by Fig. 4(b), or by calculating with Eq. (2) assuming cement content is equal to zero. And then cement content can be determined by necessary calculating with Eq. (4), or specially Eq. (5) for the materials in this study. At last, redo the two steps to get results which are more accurate.

4. Conclusions

For EBSLS compacted under optimized compaction work and moisture content, the following conclusions can be summarized.

(1) Cured density and saturated density decrease with the increase of EPS beads volumetric content, while change a little with cement content. Dry density decreases dramatically with the increase of EPS beads volumetric content, while increase slightly with the increase of cement content, both of which are in linear relationship.

(2) EBSLS get the lowest strength when saturated. For consistency with triaxial test results, and the safety of engineering under water table, unconfined compressive test are recommended to be conducted after being saturated.

(3) Unconfined compressive strength increases dramatically in parabolic relationship while decreases with the increase of EPS beads volumetric content in hyperbolic relationship.

(4) Cohesion increases with the increase of cement content because it is mainly caused by the bonding function of hydration products of cement. The more EPS beads volumetric content is, the less dramatically the increase is, which is a result of the cohesion between hydration products of cement and EPS beads is less than that between hydration products of cement and sand particles caused by The smoother surfaces of EPS beads than sand particles.

(5) Friction angle increases with the increase of cement content when EPS beads volumetric content is less than 50%, while decreases slightly with the increase of cement content when EPS beads volumetric content is more than 50%. Friction angle decreases with the

increase of EPS beads volumetric content, which is caused by the smoother surfaces of EPS beads than sand grains.

(6) The stress strain curves of EBSLS tend to be more softening with the increase of c_e or the decrease of c_c.

(7) The shear contraction of EBSLS increases with the increase of c_e or the decrease of c_c.

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