Research Article

Effect of Expanded Polystyrene Particle Size on Engineering Properties of Clayey Soil

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The particle size of expanded polystyrene (EPS) has an effect on engineering properties of EPS-clay blends. However, the effect of differences between EPS particle size groups subdivided within 1–3 mm on engineering properties is usually ignored. In this study, different particle sizes of EPS pellets have been considered to separately investigate the effect on the optimum water content (OWC), maximum dry density (MDD), unconfined compressive strength (UCS), ductility, coefficient of permeability, and compression index of EPS-clay blends. Results show that the MDD, ductility, hydraulic conductivity, and compression index of EPS-clay blends do not increase with the increase in the EPS particle size in the range of 0.3–3 mm, while the OWC and UCS do not decrease. For a given EPS content, among samples with the EPS particle size of 0.3–1 mm, 1-2 mm, and 2-3 mm, the MDD and UCS of EPS-clay blends with 1-2 mm in EPS particle size are the largest, while the OWC, ductility, coefficient of permeability, and compression index are the smallest. Microstructure analyses reveal that, for samples with the EPS particle size of 1-2 mm, the pore volume is lower and the microstructure is denser, which are the main reasons why the EPS particle size can influence engineering properties of EPS-clay blends.

1. Introduction

Due to the excessive weight of the filling soil or the insufficient bearing capacity of the foundation, the uneven settlement of the soft foundation and the instability of the retaining wall are prone to occur in the engineering construction [1–3]. Conventional treatment methods include soil replacement cushion, drainage consolidation, grouting solidification, reinforcement methods, and so on [4]. These methods can improve properties and features of the foundation [5–7]. Applying the light-weight soil as the filling soil is a new method, which can decrease the stress level in the soft foundation by reducing the weight of the filling soil [8–10].

The light-weight soil which is made with renewable resources, such as the plastic foam, not only reduces the weight of filling soil but also solves the pollution of plastic waste [11].

Expanded polystyrene (EPS) is a kind of plastic foam and has many properties, such as light weight, pressure resistance, durability, and thermal insulation, which can be used to produce light-weight soil and widely applied in the engineering construction [12–14]. As early as 1970s, European countries such as Norway and Holland began to use the molded EPS to make light-weight embankments [15, 16]. In the 1980s, EPS mixed with other cementing materials was added into the soil to make the stabilized light soil in Japan and other countries [17–19]. Until the beginning of the

twenty-first century, the production technology of the light-weight soil was introduced into China and has been gained a lot of research studies on the light-weight soil made of EPS [20, 21].

Among research studies on the light-weight soil with EPS, the effect of the EPS particle size on engineering properties of soils (e.g., water permeability, unconfined compressive strength (UCS), and compression characteristics) cannot be ignored [22]. Yamada et al. [23] showed that the water permeability of samples increased with the increase in the EPS particle size when the EPS diameter was in the range of 1–5 mm. Subsequently, the fact that the UCS of spherical EPS particles with 1–3 mm was larger than that of broken and flaky EPS particles was reported [8]. In order to reduce the project cost, the influence of EPS beads with the particle size larger than 3 mm on the shear strength of the light-weight soil was studied [12]. Then, the influence of compaction test types on compaction characteristics of the light-weight soil with 3–5 mm in EPS particle size was investigated [24]. It can be found that current research studies mainly focus on the use of the group 1–3 mm and the group larger than 3 mm in EPS particle size [21, 25]. However, these studies ignore the effect of differences between EPS particle size groups subdivided within 1–3 mm, which are widely used in civil engineering projects, on engineering properties of EPS-clay blends [21, 25].

This study aims to investigate the effect of samples subdivided within 0.3–3 mm in EPS particle size on physical and mechanical properties of EPS-clay blends. First, a series of geotechnical tests including proctor compaction, unconfined compression, water permeability, and one-dimensional compression tests were carried out, respectively. Then, the microstructure was identified to reveal the mechanism of the EPS particle size on engineering properties of EPS-clay blends using a scanning electron microscope (SEM) test. It is expected to provide the fundamental data for related design and construction of civil engineering projects.

2. Materials and Methods

2.1. Test Materials. The clayey soil used in this investigation was from a construction site in Zhejiang, China. Table 1 shows physical and mechanical properties of this clayey soil. According to the Unified Soil Classification System (ASTM D2487-11), the clayey soil was classified as low plasticity clay (CL).

EPS used in this experimental programme was obtained commercially from a Guangzhou-based architecture company. Based on results of the previous study [8], EPS pellets were selected and sieved to ensure that the size of the EPS was in 0.3–1 mm, 1-2 mm, and 2-3 mm, respectively. Figure 1 shows photos of EPS with three different particle sizes. It can be seen that the particle size difference of 1-2 mm and 2-3 mm was larger than that of 0.3–1 mm and 1-2 mm.

2.2. Sample Preparation. Lower EPS contents, 1% and 2%, have been chosen to prevent segregation of EPS particles within the sample matrix. EPS content by weight of the dry sample was used for all samples to deduce comparative data for assessing effects of the EPS particle size. In order to minimize the influence of hydration products on test results, cement and lime were not added [26]. According to the particle size of EPS, samples were divided into three groups, namely, group 0.3–1 mm, group 1-2 mm, and group 2-3 mm. Unblended soil was taken as a control group. First, the optimum water content (OWC) and maximum dry density (MDD) of each group were determined by the proctor compaction test conforming to ASTM 2000, D698a. Next, EPS-clay blends were prepared in a large tray by constantly spraying water at amounts calculated for OWC through a spray bottle and mixing with the help of spatula till a homogeneous appearance was attained. The prepared EPS-clay blends were then wrapped with thick plastic sheets and placed for 24 hours to make the water disperse evenly in blends.

2.3. Test Plans. EPS-clay blends were compacted into standard cylindrical steel molds to produce samples with the size of 39 mm in diameter and 80 mm in height for the unconfined compressive test. According to the compactness standard of urban road soil subgrade, the compactness of samples was designed to be 95%. The strain controlled test was the type that was carried out with the sample sets and the apparatus applied strain at the rate of 1.6 mm/min. For the water permeability test, samples with the size of 61.8 mm in diameter and 40 mm in height were prepared for the variable head permeameter method. For the compression test, the size of samples was 61.8 mm in diameter and 20 mm in height. Based on requirements of geostatic stress and additional stress, the loading stress of 50 kPa, 100 kPa, 200 kPa, 400 kPa, and 800 kPa was applied step by step. When the deformation rate was less than 0.005 mm/h, the next stage loading stress was applied. For the SEM test, the lyophilized sample cut into cubes with $10 \, mm \times 10 \, mm \times 10 \, mm$ was coated with a gold layer to induce conductivity. SEM analysis of these samples was conducted using a scanning electron microscope. In this experiment, average value of 2 repeated tests was selected for calculation.

3. Results and Discussion

3.1. Compaction Characteristics. Figure 2 shows proctor compaction curves for the soil blended with varying sizes of EPS. With the increase in water content, the dry density of EPS-clay blends with different EPS particle sizes increases first and then decreases. There is a peak on the proctor compaction curve, which is similar to a parabola. This indicates that the OWC and MDD of EPS-clay blends with different EPS particle sizes can be obtained by the compaction test. For a given EPS content, the proctor compaction curve of the group 1-2 mm lays above that of the group 0.3–1 mm and 2-3 mm. This means that the dry density of the group 1-2 mm is larger than that of other groups at the same compaction work and water content. Compared with the EPS particle size of 0.3–1 mm and

TABLE 1: Physical and mechanical parameters of materials.

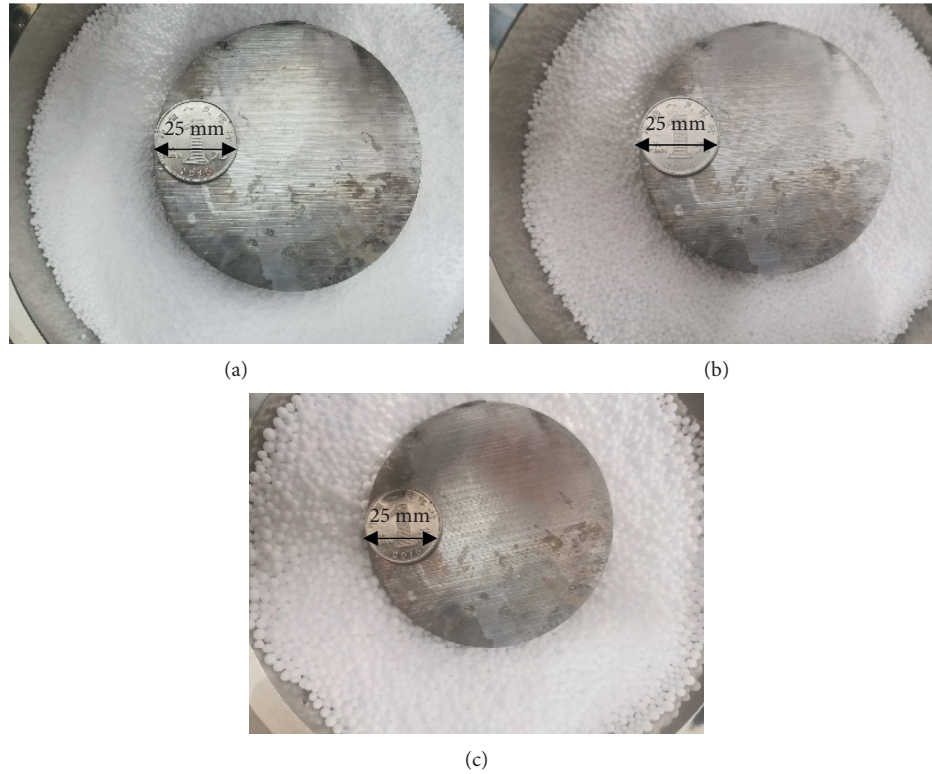| Materials	Liquid limit (%)	Plastic limit (%)	Plasticity index	Density (g/cm^3)	Water content (%)	UCS (kPa)
Clayey soil	39.15	21.75	17.4	1.82	34.95	143.31
EPS	—	—	—	0.02–0.04	—	30–200

(a)

(b)

(c)

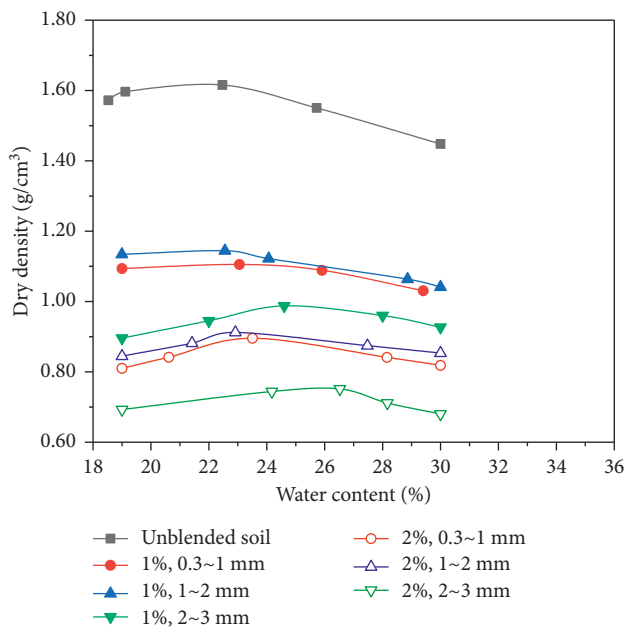FIGURE 1: EPS with particle size of (a) 0.3–1 mm, (b) 1-2 mm, and (c) 2-3 mm.

FIGURE 2: Proctor compaction curves of EPS-clay blends with different EPS particle sizes.

12 mm, 2-3 mm in EPS particle size is the largest and the adhesion between EPS particles and soil particles is poorer. Accordingly, with the same compaction work of hammer as that of other groups, the increasing of volume compression, plastic deformation, and density is small for the group 2-3 mm. On the other hand, when the water content is same, the group 2-3 mm is more difficult to be cemented due to the largest particle size and specific surface area, resulting in the smallest dry density. Compared with the EPS particle size of 1-2 mm and 2-3 mm, 0.3–1 mm in EPS particle size is the smallest, which is easy to be a strong adhesion between EPS particles and soil particles. This behavior dissipates part of the compaction energy, making EPS-clay blends difficult to be compacted when the compaction work is same. Moreover, at the same water content, a layer of water film forms more easily on the surface of EPS particles with 0.3–1 mm in EPS particle size, promoting the dissipation of compaction energy.

The OWC and MDD of soil are two important parameters to reflect its compaction characteristics [24]. Through the calculation of the dry density of soil after compaction, the effect of different particle sizes of the EPS on the compaction characteristics of EPS-clay blends is explored. Figure 3(a) shows the comparison of the OWC of
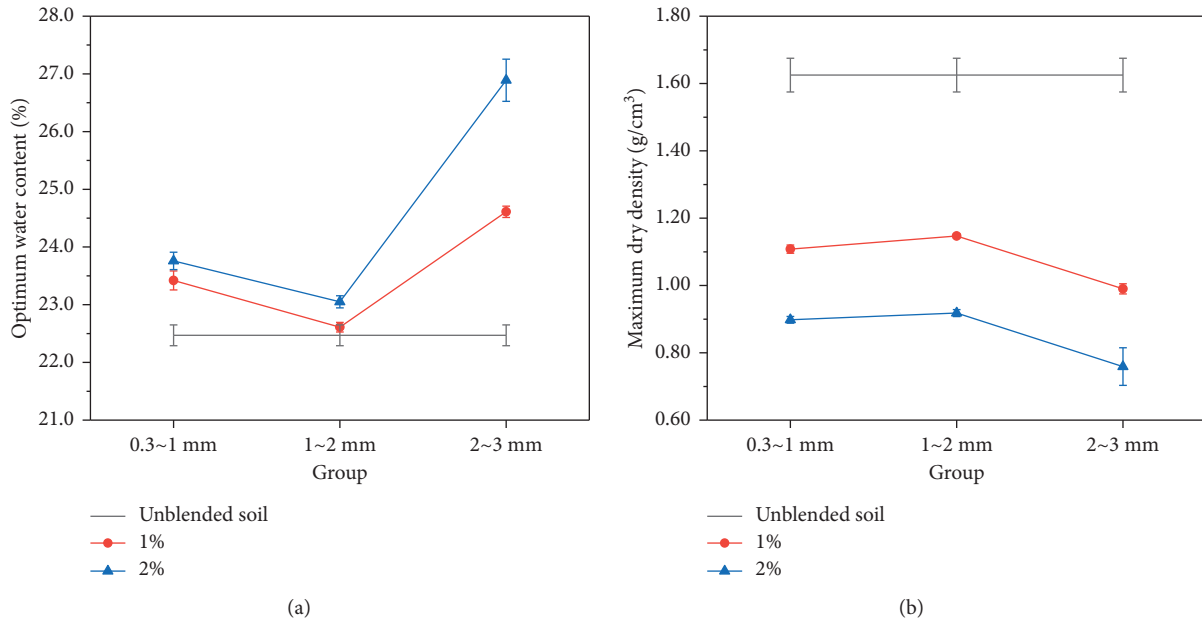
FIGURE 3: Comparison of (a) optimal water content and (b) maximum dry density of EPS-clay blends with different EPS particle sizes.

EPS-clay blends with different EPS particle sizes. For a given EPS content, the OWC of the group 1-2 mm is smaller than that of the group 0.3–1 mm and 2-3 mm. For example, the OWC of group 0.3–1 mm, 1-2 mm, and 2-3 mm is 23.42%, 22.61%, and 24.61%, respectively, at the EPS content of 1%. It can be seen that the OWC of EPS-clay blends does not increase with the increase in the EPS particle size. For the group 0.3–1 mm, a large number of small particles cause many pores between EPS particles, leading to much water being required to cohere with EPS and clay particles. For the group 2-3 mm, the EPS particle size is larger compared with the EPS size of 0.3–1 mm and 1-2 mm, resulting in a larger specific surface area and size of pores between particles due to the hydrophobicity of EPS [24]. Hence, EPS beads with 2-3 mm in particle size need much water to bond with clayey soil, which leads to a large OWC for the group 2-3 mm. Figure 3(b) shows the comparison of the MDD of EPS-clay blends with different EPS particle sizes. Similarly, the MDD of EPS-clay blends does not decrease with the increase in EPS particle size, e.g., the MDD of the group 1-2 mm is 1.147 g/cm^3, which is larger than that of the group 0.3–1 mm and 2-3 mm. For the group 0.3–1 mm, the particle size is close to that of clay particles, which is easy to cohere with soil particles to form an elastic body. As a result, it is more difficult to be compressed under the same compaction work as that of other groups. In addition, the small pore size of group 0.3–1 mm is easier to be filled with free water and form pore water pressure. This behavior results in the dissipation of energy of compaction work, leading to samples more difficult to be compacted. For the group 2-3 mm, the large particle size results in a great rebound effect of compaction work due to the elasticity of EPS, causing it more difficult to be compacted. Furthermore, the increase in the dry density of EPS-clay blends in the compaction process is not only due

to the decrease in the number and size of pores between particles but also due to the plastic deformation of EPS beads. Accordingly, it is difficult to increase the dry density by increasing the compaction work once reaching the deformation limit of EPS beads.

3.2. Strength Properties. Figure 4 shows the stress-strain curve for samples with different EPS particle sizes. For a given additive content, when EPS particle size is 1-2 mm, 0.3–1 mm, and 2-3 mm, respectively, the data indicate that stress-strain curves shift downwards and towards right. This means that samples with the EPS size of 1-2 mm present higher strength and lower ductility than those of the group 0.3–1 mm and 2-3 mm. Compared with that of other groups, under the same compactness, the density of the group 1-2 mm is the highest due to its largest MDD. The particles of the sample closely contact and occlude, which increases the shear strength of the sample. On the other hand, small pores between particles of the group 1-2 mm lead to the movement of particles more difficult. Once the shear stress reaches the shear strength of the sample, the sample of group 1-2 mm is easy to be destroyed in a very short time due to the energy more difficult to dissipate, which is the reason for decreasing the ductility of the sample. In addition, the strength decreases and the ductility increases with the increase in the EPS content. This behavior results from an increase in OWC and a decrease in MDD with the increase in the EPS content [27, 28]. Furthermore, as EPS, a material with lower strength and higher ductility, replaces the clayey soil in blends, the strength of EPS-clay blends decreases and the ductility increases. The failure of EPS beads to bond with soil particles is another reason for the decrease in the strength of EPS-clay blends. In order to explore the strength properties
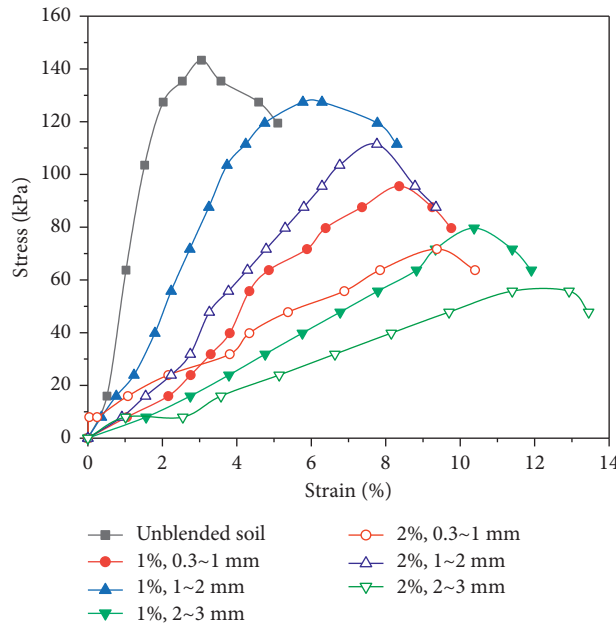
FIGURE 4: Stress-strain curves of EPS-clay blends with different EPS particle sizes.
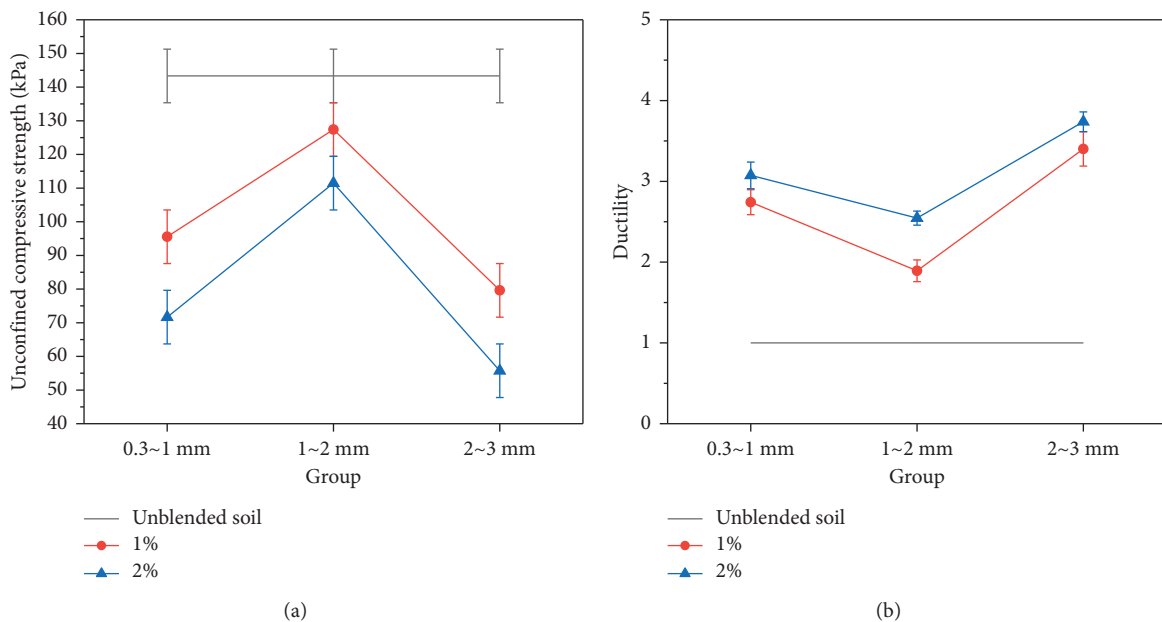

(a)

(b)

FIGURE 5: Comparison of (a) unconfined compressive strength and (b) ductility of EPS-clay blends with different EPS particle sizes.

quantitatively, the UCS and ductility are extracted for further comparative analysis.

Figure 5(a) shows the comparison of the UCS with different EPS particle sizes. For a given additive content, the UCS for the group 1-2 mm is higher than that for other groups. It can be seen that the UCS of EPS-clay blends does not decrease with the increase in the EPS particle size. For example, when the EPS content is 1%, the UCS of samples for the group 0.3–1 mm, 1-2 mm, and 2-3 mm is 95.5 kPa, 127.4 kPa, and 87.6 kPa, respectively. This can be attributed

to the highest MDD of the group 1-2 mm under the same additive content. As a result, a denser microstructure of samples with the EPS particle size of 1-2 mm is expected compared with that of other groups, leading to a higher strength. Furthermore, the difference of UCS between the group 0.3–1 mm and 1-2 mm is smaller than that between the group 1-2 mm and 2-3 mm. This indicates that the difference of soil structure of the group 0.3–1 mm and 1-2 mm is small because of approximately equal particle size. For the group 2-3 mm, the EPS particle size is much larger

than that of soil particles, which makes soil particles cannot be closely bonded with EPS particles. Moreover, the largest specific surface area and the smooth surface of EPS with 2-3 mm in particle size weaken the occlusal effect between soil particles, resulting in the smallest strength among all groups. Figure 5(b) shows the comparison of the ductility with different EPS particle sizes. Similarly, the ductility of EPS-clay blends does not increase with the EPS particle size increasing. Compared with the group 0.3–1 mm and 2-3 mm, the ductility of the sample with 1-2 mm in EPS particle size is the lowest, e.g., the ductility of samples is 2.91, 2.23, and 3.57, respectively, for the group 0.3–1 mm, 1-2 mm, and 2-3 mm with additive content of 1%. For samples of the group 0.3–1 mm, the size of pores is small but the number of pores is much. For samples of the group 2-3 mm, not only the size of pores is large but also the number of pores is much. When the shear stress is applied, pores between particles can help particles to adjust their position to dissipate energy, which increases the ductility of samples with 0.3–1 mm or 2-3 mm in EPS particle size. By contrary, the size of pores of the group 1-2 mm is small and the number of pores is little, which makes the sample bear great stress but prone to the brittle failure.

3.3. Hydraulic Characteristics.

As already mentioned, the hydraulic conductivity of EPS-clay blends is determined at the respective OWC and MDD of blends. Figure 6 shows the comparison of hydraulic conductivity with different EPS particle sizes. For a given additive content, the hydraulic conductivity of EPS-clay blends with 1-2 mm is lower than that of EPS-clay blends with 0.3–1 mm and 2-3 mm, i.e., the hydraulic conductivity of EPS-clay blends does not increase with the increase in the EPS particle size in the range of 0.3–3 mm. For example, for the additive content of 1%, the hydraulic conductivity of EPS-clay blends is 60.9×10^{-6} cm/s, 9.0×10^{-6} cm/s, and 710.6×10^{-6} cm/s, respectively, for the group 0.3–1 mm, 1-2 mm, and 2-3 mm. Since the MDD of the group 1-2 mm is the largest among all groups, the void ratio or void space of compacted blends is the smallest. Small and few pores result in the lowest hydraulic coefficient of the group 1-2 mm. Furthermore, the adsorbed water between particles of the group 1-2 mm provides larger viscous resistance due to the large density of the sample, which hinders the passage of free water. Hence, the hydraulic conductivity decreases for the group 1-2 mm. Compared with that of samples with 1-2 mm in EPS particle size, the larger hydraulic conductivity of the group 0.3–1 mm and 2-3 mm results from more pores between particles. In addition, the largest difference of hydraulic conductivity between the group 1-2 mm and 2-3 mm is attributed to the largest difference of MDD and OWC between them. The hydraulic conductivity of the group 2-3 mm is the highest at the same content of EPS due to the large number and size of pores in samples as well as large smooth surface of EPS beads.

3.4. Compression Characteristics.

Figure 7 shows compression curves of EPS-clay blends with different EPS particle sizes. When the loading stress is less than the yield stress, the
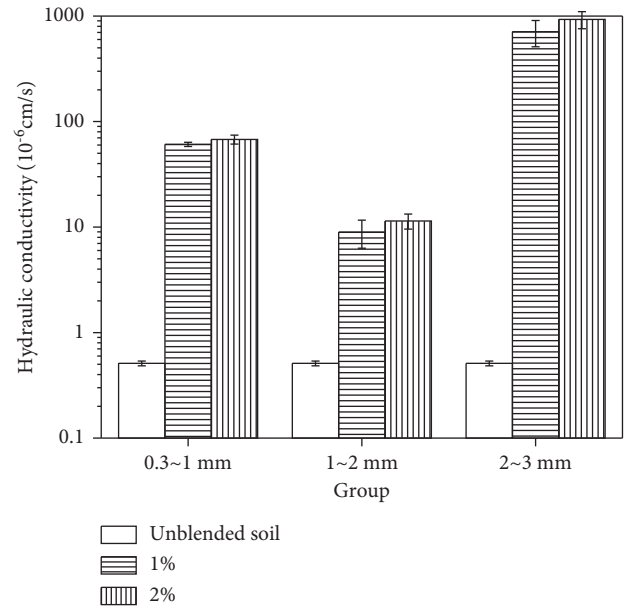

FIGURE 6: Comparison of hydraulic conductivity with different EPS particle sizes.
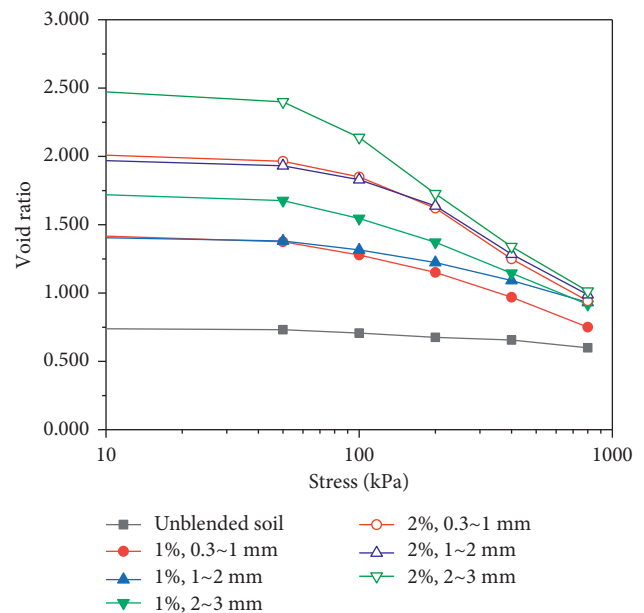

FIGURE 7: Compression curves of EPS-clay blends with different EPS particle sizes.

curve of samples with 1-2 mm in EPS particle size lays below the curve of the group 0.3–1 mm and 2-3 mm for a given additive content. This means that the initial void ratio of the group 1-2 mm is less than that of the group 0.3–1 mm and 2-3 mm. Under the same compactness, the dry density of the group 1-2 mm is the largest due to the highest MDD, which results in the largest initial porosity of the sample. Further, the difference of the initial void ratio between the group 1-2 mm and 2-3 mm is large because of the large difference of the MDD. When the loading stress is greater than the yield stress, the slope of the compression curve of the group 1-2 mm is
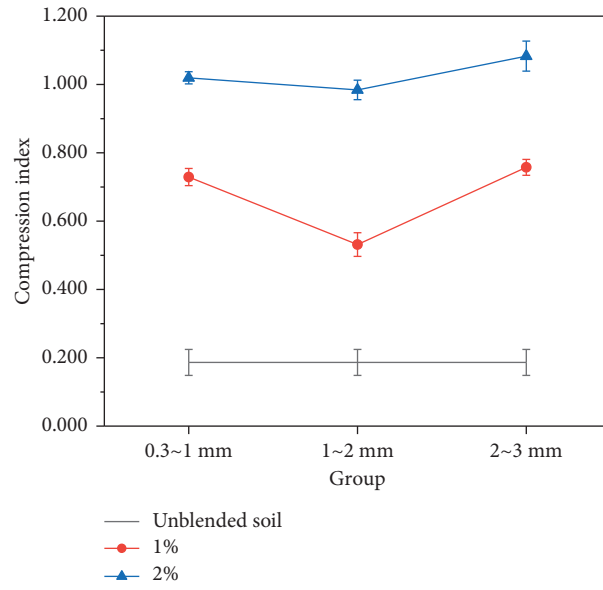
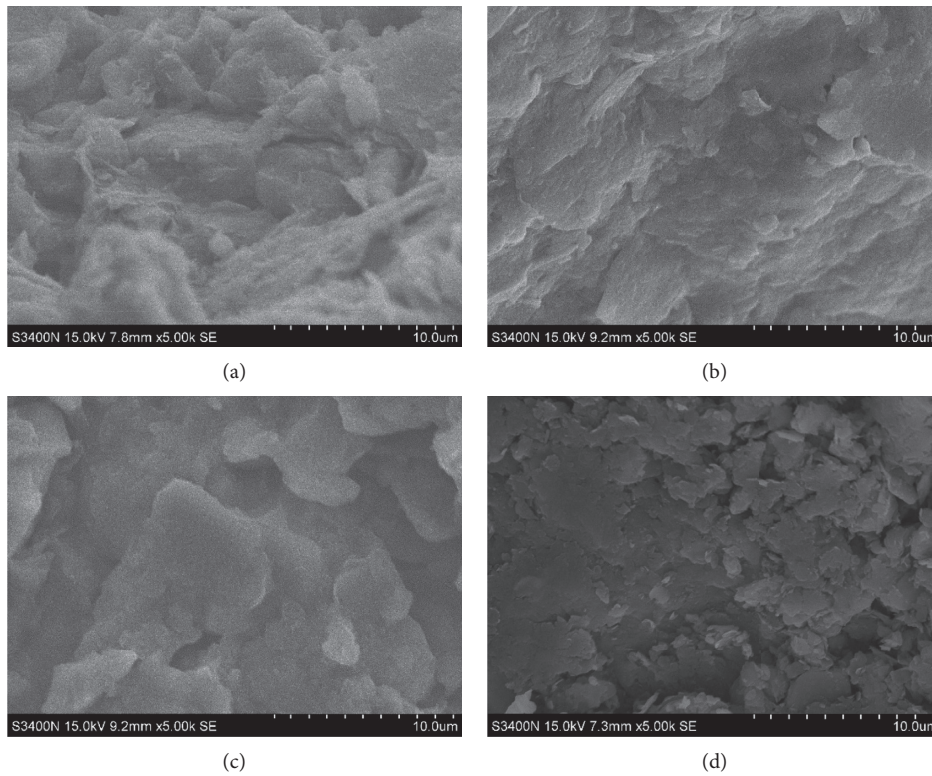Figure 8: Comparison of the compression index of EPS-clay blends with different EPS particle sizes.

(a)

(b)

(c)

(d)

Figure 9: Continued.

(e)   (f)
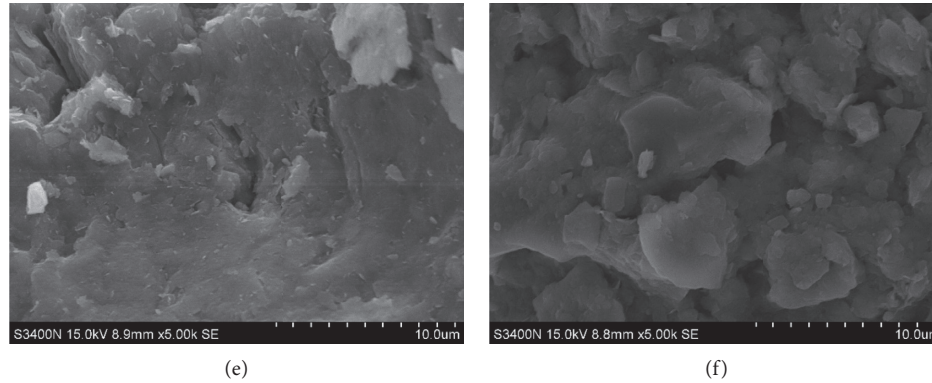
Figure 9: Comparison of SEM images of EPS-clay with different EPS particle sizes: (a) 1%, 0.3–1 mm; (b) 1%, 1-2 mm; (c) 1%, 2-3 mm: (d) 2%, 0.3–1 mm; (e) 2%, 1-2 mm; (f) 2%, 2-3 mm.

smaller than that of the group 0.3–1 mm and 2-3 mm, which is also attributed to the higher MDD of the group 1-2 mm. Due to the larger number and size of pores of the group 2-3 mm, the deformation of the sample is larger under each loading stress, resulting in a larger slope of the compression curve.

Figure 8 shows the comparison of the compression index with different EPS particle sizes. It can be seen that the compression index of samples does not increase with the increase in the EPS particle size. For a given additive content, the compression index of the group 1-2 mm is the smallest and that of the group 2-3 mm is the largest among all groups. The largest MDD and smallest OWC of the group 1-2 mm result in the smallest compressibility of samples compared with that of other groups. In other words, the sample is difficult to be compressed due to the small number and size of pores at the same loading stress. On the other hand, as a compressible material, the plastic deformation of EPS particles increases with the increase in the loading stress. For the group 2-3 mm, the largest compression deformation of EPS-clay blends is also attributed to the largest amount of the compression deformation of EPS beads with a large particle size. Hence, the compressibility of EPS-clay blends with 2-3 mm EPS particles increases. Moreover, with the increase in the EPS content, the compressibility of samples increases, which implies that the EPS can sustain a higher void ratio.

3.5. Microstructure Analysis. Figure 9 shows the comparison of SEM images of EPS-clay blends with different EPS particle sizes. It can be found that the main particle of soil samples is coarse silt with the particle size of $10–75\,\mu$m [29]. In addition, the EPS particle size influences the pore volume, leading to the loose state of the microstructure. When the EPS content is same, the pore size increases with the increase in the EPS particle size. For example, when the content of EPS is 1%, the pore size of the group 0.3–1 mm, 1-2 mm, and 2-3 mm is approximately $5–22\,\mu$m, $8–25\,\mu$m, and $15–36\,\mu$m, respectively. Compared with engineering properties of the group 2-3 mm, the lower OWC, ductility, permeability coefficient, and compression index as well as the higher MDD and UCS of the group 0.3–1 mm and 1-2 mm are

attributed to the lower pore volume and the denser microstructure. For the group 2-3 mm, the pore volume is the largest because the particle size of the EPS is the largest in all groups. Soil particles cannot contact closely, which makes the microstructure of the sample loose. The number of pores for the group 0.3–1 mm is more than that for the group 1-2 mm, resulting in a higher OWC, ductility, permeability coefficient, and compression index as well as a lower MDD and UCS. In other words, for the group 1-2 mm, soil particles are connected with each other, which leads to the microstructure of the sample in a more dense state. With the increase in the EPS content, the microstructure becomes loose and the pore volume increases.

4. Conclusion

With a view of comparing effects of various sizes of the EPS particle on engineering properties of clays, the OWC, MDD, coefficient of permeability, UCS, ductility, and compression index were determined at varying EPS particle sizes of EPS-clay blends. The study thus adds new aspects to what has been done so far in this research area and helps draw quite interesting and original conclusions. The following conclusions can be drawn from the experimental study:

(a) With the EPS particle size increasing, the OWC of EPS-clay blends does not increase and the MDD does not decrease. Among the group 0.3–1 mm, 1-2 mm, and 2-3 mm, the OWC of the group 1-2 mm is the smallest and the MDD is the largest. For the group 2-3 mm, the large specific surface area and pores between particles result in more water being needed to cohere with EPS and clay particles from a broken state to a complete state. Moreover, the rebound effect of the compaction work is great because of the large particle size for the group 2-3 mm. For the group 0.3–1 mm, the more number of pores between particles and the closest size of EPS particles to that of clay particles make EPS beads easily cohere with clay particles to form an elastic body.

(b) Engineering properties, including the ductility, hydraulic conductivity, and compression index of EPS-

clay blends, do not increase while the UCS does not decrease with the increase in the EPS particle size in the range of 0.3–3 mm. For a given additive content, the UCS of EPS-clay blends with 1-2 mm EPS is higher than that of other groups, while the ductility, hydraulic conductivity, and compression index are lower. This can be attributed to the highest MDD and the smallest OWC of the group 1-2 mm under the same additive content.

(c) SEM images reveal that, compared with that for the group 0.3–1 mm and 2-3 mm, the lower pore volume and the denser microstructure for the group 1-2 mm make samples able to bear more stress and larger deformation but more prone to a brittle failure.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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