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Evaluation of Deformation and Settlement Properties of Cement-Stabilized Silt Mixed with EPS Beads of Various Sizes

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Abstract: The expansion of China's highways and railways, as well as the growing demand for them, has focused attention on the impact of traffic loads on foundation settling, uneven deformation, and ground cracking. These effects have garnered considerable research attention, with particular emphasis placed on integrating innovative materials into the soil matrix. This investigation involved loading experiments utilizing a combination of lightweight soil, expanded polystyrene (EPS), and cement. Consolidation tests assessed the extent of deformation and settlement, incorporating varying proportions of EPS and cement. The test results show that when subjected to confined conditions, the stress–strain relationship curve assumes a hyperbolic shape closely linked to the e-p curve. This shape effectively captures the unique structural characteristics exhibited by lightweight soils. As the size of the EPS particles and the applied stress increase, a corresponding rise in the strain of the specimens is observed. Simultaneously, as the strain magnitude increases, the elastic modulus experiences a decline. Additionally, it is noted that this trend further increases as the doping of the cement with EPS particles increases. When the EPS volume ratio and cement mix ratio remain constant across different specimens, there is a decrease in structural strength as the size of the EPS increases. In lightweight soil, settlement can occur rapidly, with approximately 95% of total consolidation deformation happening within a few minutes, which suggests that the settlement is instantaneous and primarily consolidation settlement. The structural strength of lightweight soil shows a negative correlation with the size of EPS, implying that larger EPS size may lead to a reduction in strength. Therefore, it is recommended to consistently use EPS beads with a diameter of 3–4 mm during construction.

Keywords: lightweight soil; settlement; deformation; consolidation test; stress–strain

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1. Introduction

Lightweight soil is a novel geotechnical material developed to address specific challenges in geotechnical engineering. This field is an interdisciplinary domain encompassing material environmental engineering, material science, and geotechnical engineering. Geofoam is a type of lightweight material that can be categorized into various materials based on their properties, such as polystyrene (PS), phenol-formaldehyde (PF), polyethylene (PE), epoxy resin (EP), and polyvinyl chloride (PVC), among others. However, expanded polystyrene (EPS) is the most frequently used material due to its affordability and ease of construction. When the volume ratio of lightweight material remains constant, increasing the size of EPS beads does not significantly impact the mechanical properties of the soil mixture. Thus, creating large-scale, lightweight soil using ultra-light materials is feasible. This approach effectively reduces project costs and holds significant engineering value.

Infrastructures, including highways, railways, roads, bridges, tunnels, trains, and city subways, have encountered various issues, like soft ground settlement, bridgehead bumping on motorways, slope collapse, and unstable retaining walls [1,2]. The weight of backfilling is a critical consideration. Lightweight materials are commonly used in infrastructure upgrades to minimize their weight, such as EPS beads [3,4], EPS geofoam [5], foam glass aggregate [6,7], lightweight cemented clay [1,8], and EPS beads mixed with lightweight soil [9–11]. Lightweight soil (LWS) is a geotechnical material that offers numerous benefits, including lightness [12], density [9], and fluidity [13]. This material has found extensive use in various engineering applications, such as slope fill [2,14], backfill of pipelines [15–18], and highway broadening [19]. Marfu'ah et al. [20] developed new lightweight materials by replacing soft soil with EPS, achieving lightness and enhanced strength properties through the addition of EPS particle samples, thereby offering practical advantages for engineering applications.

In civil engineering projects involving the use of expanded polystyrene (EPS), it is crucial to pay special attention to the potential deviations that can be caused by significant deformations. One example of this is when EPS is employed in trench construction, where the main focus shifts towards enhancing structural stability during seismic events [21]. Saeedi Azizkandi et al. [22] investigated the use of vertical and inclined walls as a strategy to reduce the impact of reverse faulting on shallow foundations by conducting both centrifuge tests and numerical simulations. The results showed that implementing this suggested method can effectively reduce the risk of damage to surface and embedded foundations located at different positions relative to reverse faults, even when considering different dip angles. Zhuang and Zhao. Ref. [23] studied the impact of the EPS particle admixture and particle size on the unconfined compressive strength (UCS) of lightweight soil, which was discovered to be quite evident. It was observed that a higher amount of EPS or a larger particle size decreased the soil's UCS. Hou et al. [24,25] examined the dynamic shear modulus, dynamic elastic modulus, and damping ratio characteristics of EPS-modified lightweight soil. Yang et al. [26] focused their study on lightweight soil's static earth pressure behavior when combined with EPS particles behind retaining walls. The studies above consistently revealed that lightweight soils have favorable engineering properties when modified with EPS. Qiu et al. [27] proved that filling EPS silt light soil between the bridge backfill and ordinary soil is a feasible to deal with uneven settlement. Applying engineered backfill in run-on slabs at bridges presents a distinct scenario in addressing vehicular collisions. As the research on the compression modulus of the underlying soil layer beneath the lightweight soil progresses, scholars are increasingly focusing on the structure and utilization of lightweight silt soil. Ali et al. [28] studied the unconfined strength, shear strength, and stiffness of lightweight fill and examined the incorporation of cement into the soil. The presence of EPS particles in the lightweight blend decreased its compression strength. This is likely because the larger EPS beads replace the hydrate in the mixture. As the percentage of light particles increases, the composition of the material becomes porous, leading to a decrease in strength. Interestingly, reducing the cement percentage minimizes the compressive strength of lightweight soil when different EPS contents are used. Yuan et al. [29] conducted a study to examine the variables that impact the efficiency of a new technique for waterproofing tunnels in order to make athem more impermeable. The results of the tests demonstrated a clear connection between the difference in displacement and the number of times the materials were subjected to fatigue loading, which directly affects the amount of seepage. Yuan et al. [30] demonstrated that examining the sustainability of recycled residual soil reinforced with SH polymer, which involves evaluating its properties, physicochemical mechanisms, and possible uses, is an essential task. The importance of kaolinite in the reinforcement system is emphasized by the results of the characterization. Furthermore, the interaction between kaolinite and glass fiber, which is characterized by friction, enables the tensile strength of the glass fiber to be effectively expressed.

Gao et al. [31] employed an axial-torsional test to examine the dynamic properties of EPS light soil while subjecting it to the complex stress path created by a fictitious traffic load. The mixture and initial stress conditions determine the normal dynamic nonlinearity of the EPS lightweight soil. The damping mechanism of the EPS light soil largely depends on the porous contact between the EPS beads and the cement soil. The unconfined compressive strength of lightweight soil increases linearly with cement content, with EPS particle content having the most significant impact on solid development. Cement will only harden if the combination ratio exceeds the minimum cement content. The unconfined compressive strength of lightweight soil reduces linearly with the volume ratio of EPS particles, with cement concentration having the most significant impact. When the volume ratio of EPS particles exceeds the limit of the most critical risk, the mixed soil loses all marginal soil that may be utilized in engineering structures [32]. Regular triaxial and bending element tests may be used to examine the influence of EPS bead content on minor and major stresses and the deformation and damping factor of sand and EPS bead mixes. Despite the absence of cement-based components, it has been discovered that the dynamic shear/normal deformation factor of EPS bead and sand mixes is lowered and attenuated with each application of EPS beads and the ratio improves the results [33]. Jing et al. [34] investigated the effects of traffic loads on lightweight soil by conducting a triaxial shear test. Various cement mix ratios, confinement pressure, and soil conditions were studied for their influence on the axial cumulative strain, the elasticity of the impact, and the damping ratio. Dynamic quality must be considered when discussing the use of transportation infrastructure and the response to earthquakes. LSES visco-elastic-plastic behavior is linked with the appearance of permanent plastic stress and periodic axial strain over 1.0%. When the strain is cured, the LSES backbone curve is nonlinear [35].

The primary objective of this study was to investigate the deformation and settlement behavior of silt soil when mixed with cement and EPS beads. The focus is on understanding how adding cement and EPS beads influences lightweight soil's deformation and settlement characteristics. The aim was to evaluate the potential of using this composite as a stabilizing material in various construction projects. This research builds upon previous studies that explored the impact of cement and EPS beads on soil behavior. By examining different proportions of cement and EPS beads in silt soil mixtures, the study aimed to identify the optimal combination that minimizes deformation and settlement.

2. One-Dimensional Consolidation Test of Lightweight Soil

The unique composition of lightweight soil is attributed to including a curing agent and EPS beads with low density. One crucial factor involves decreasing the total weight of the heterogeneous soil, which is accomplished by employing lightweight materials that possess consistent physical and chemical attributes, assuring the stability of all pores. Concurrently, a firm structure is formed by the chemical and physical interactions between the curing agent and the soil. The cementation action of node development encases the stable pores. The abovementioned exchange impacts the stability of the soil structure and the void ratio of the lightweight elements, thereby affecting the overall performance of the combined soil. Based on these concepts, forthcoming advancements should prioritize the creation of materials that possess both low weight and high strength.

Compression deformation in the ground, especially under heavy loads, primarily manifests as foundation settlement. Elastic theory is used to analyze settlement, and consolidation tests are commonly used to study the deformation properties of soil materials. This testing approach was the primary research method, known for its remarkable simplicity. A thorough analysis of lightweight soil deformation was conducted using the one-dimensional consolidation theory.

The influence of EPS size is particularly evident in its impact on strength, highlighting the importance of EPS solely is not regarding as a pore-foaming agent. EPS is not just a void space; it possesses inherent strength. This is supported by tests conducted on waste EPS blocks with beads measuring 2–3 mm in diameter and with a block density of 0.015 g/cm^3. The obtained results show that the UCS of the material is 55 kPa. The shear strength parameters were also determined by a triaxial test as $\varphi = 13.09°$, $c = 4.17$ kPa. This finding challenges the assumption that EPS would have no structural integrity [36,37].

Compressing specimens presents difficulties in determining the void ratio of lightweight soil due to the progressive reduction in EPS and the resulting rise in the pure particle density of EPS. The challenge arises from the need for more feasibility in quantifying the absolute particle density of EPS under various loads. The one-dimensional consolidation hypothesis was first developed by Terzaghi in 1925, assuming that water and soil are incompressible, based on this idea the decrease in pore volume during the consolidation process of saturated soil is seen equal to the excluded water. While water is commonly considered to be incompressible, it can experience compression when subjected to high-pressure conditions and is added to lightweight soil to minimize weight and increase the void ratio. Thus, compromising EPS structure to increase soil density and strength is invalid. Therefore, porosity calculations should assume EPS has a specific gravity of 1. Lightweight soil becomes less homogeneous as EPS diameter grows, yet it can still be considered homogeneous in practical projects. Lightweight soil is non-saturated due to the interconnecting opening pores and closed cells in EPS and cement hydrolysis's robust closure action. When stress exceeds structural strength, the soil structure collapses, destroying EPS cavities and deviating from the original design. When stress is below structural soil strength, the stabilized soil structure bears the most stress, minimizing compression. Water and air are ejected simultaneously. First, complete saturation of lightweight soil is unlikely, and second, quantifying extruded air is difficult, especially when researching water–air interaction under load with standard equipment. Lightweight soil is saturated when stress is below structural strength.

3. Materials and Methods

3.1. Silt Soil

The soil sample utilized in this experiment consisted of dredged silt obtained from the tourism area of the Yellow River in Zhengzhou, located in the Yellow River Basin. This particular soil type is classified as marine sedimentary silt. Figure 1 displays the particle distribution curve of silt soil. Table 1 presents an overview of silt soil's fundamental physical characteristics, including moisture content, unit weight, liquid limit, plastic limit, plasticity index, specific gravity, volumetric weight, liquidity index, and void ratio. The silt is classified as a high-liquid-limit silt.

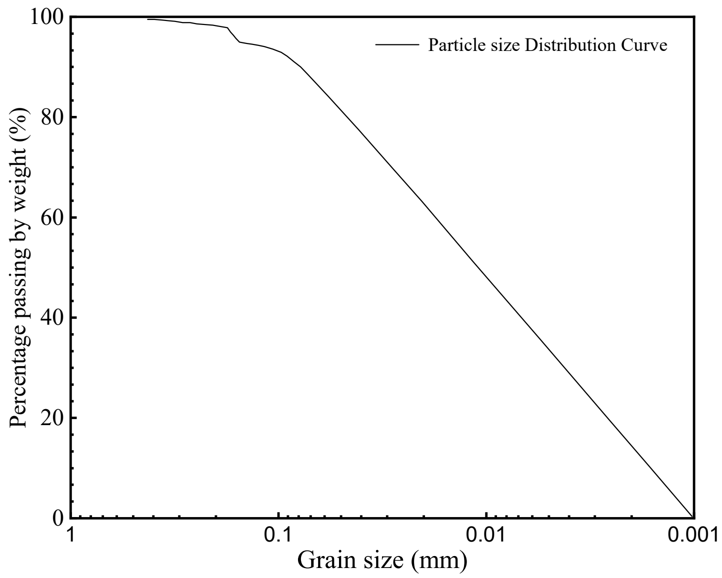

Figure 1. Particle size distribution curve.

Table 1. The basic physical characteristics of the silt used in the test.

Properties	Values
Water contents ω %	99.5
Specific Gravity G_s	2.72
Density g/cm^3	1.49

Table 1. *Cont.*

Properties	Values
Plastic limit %	30.32
Liquid limit %	52.63
Plasticity index %	22.31
Volumetric weight kN/m^3	14.90
Liquidity index %	3.10
Void ratio (e)	1.95

3.2. Cement

The cement used in this test was Yuhua brand ordinary Portland cement produced by Xinxiang Pingyuan Tongli Cement Co., Ltd., Xinxiang, China. The strength grade is 32.5, and the implemented standard is GB175-2007 "General Portland Cement" [38].

3.3. Expanded Polystyrene (EPS) Beads

EPS particles were selected as the lightweight filling material in the sample. The EPS beads employed in the test were purchased from Zhengzhou Qikang Group Co., Ltd., Zhengzhou, China, and spherical particles with diameters of 3–5 mm were selected, as shown in Figure 2. The particle densities are presented in Table 2.

(**a**) (**b**) (**c**)

Figure 2. EPS bead sizes: (**a**) d = 3 mm; (**b**) d = 4 mm; (**c**) d = 5 mm.

Table 2. Basic physical parameters of EPS.

Shape	EPS Bead Size (mm)	Densities (g/cm^3)	Bulk Densities (g/cm^3)
Spherical	3	0.0587	0.0364
	4	0.0331	0.0157
	5	0.0254	0.0125

3.4. Mix Ratio and Experimental Work

In this experiment, silt was employed as the base material. Before commencing the test, the silt underwent a curing process involving drying it for 24 h at a temperature of 105 °C in an oven. The test apparatus and equipment should be assembled and arranged following the test plan. Before commencing the test, it is essential to conduct thorough checks and tests to verify the proper functioning of the apparatus and equipment. The production and preservation of the lightweight silt soil samples are achieved in strict adherence to the prescribed sample preparation technique. The subsequent paragraphs describe the sequential procedures involved in sample preparation and maintenance. The detailed preparation process is shown in Figure 3.

Firstly, dry silt was blended with cement following the prescribed mix ratio. The mixture was stirred with a spatula for 5 min for a consistent dry cement–soil powder. After that, water was introduced to the dry cement–soil powder and the resulting slurry was mixed for 5 min until it reached a uniform state. In the next step, EPS beads were added to the cement soil slurry, and the entire mixture was stirred for 10 min, creating lightweight soil.

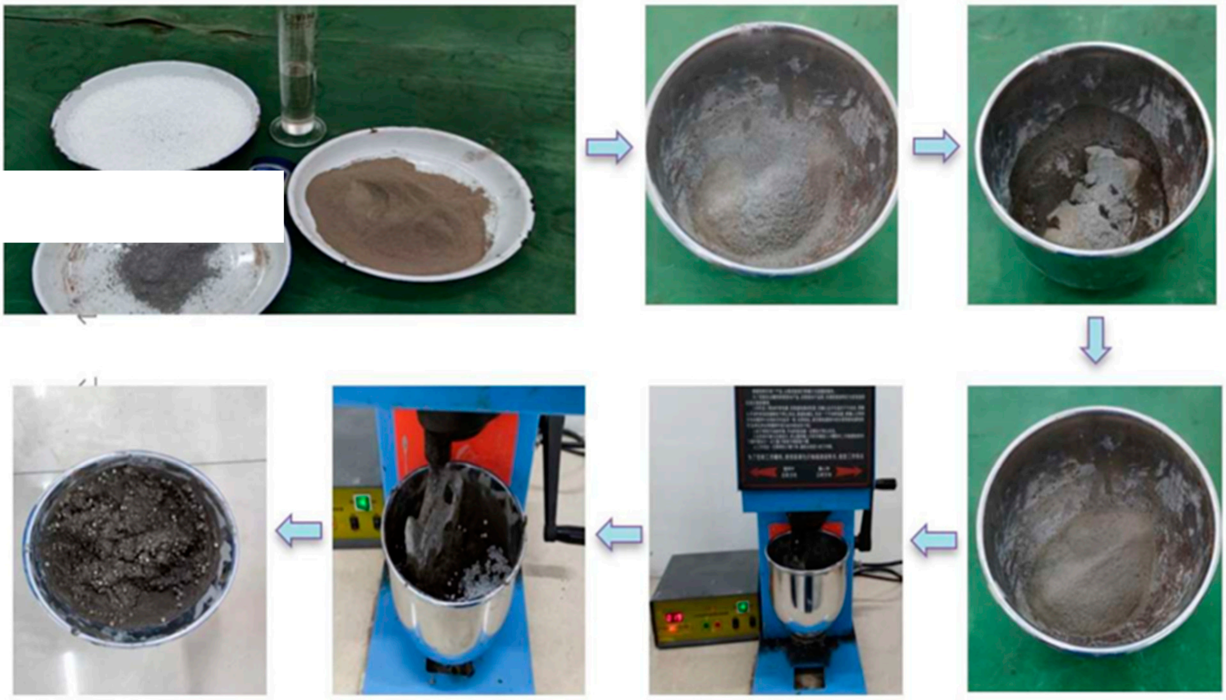

Figure 3. Preparation of samples with different mix ratios.

Following the principle of mass control, various specimens were placed into the mold with a uniform application of Vaseline on the inner surface. The sample within the mold underwent compaction through repeated strikes with a rubber hammer. Subsequently, the mold was removed, and the sample was transferred to a cutting ring with an even coating of Vaseline on its inner surface. Both surfaces of the sample were leveled until they achieved a flat state. The specimen with cutting rings underwent standard curing conditions (temperature: (20 ± 2) °C; humidity: >95%) for 24 h. After this curing period, the cutting rings were removed, and the samples were returned to the standard curing apparatus for 28 days. After being removed from the curing apparatus, the specimens were subjected to a 2 h air exhaustion process in a sealed container and then immersed in water for 24 h. The saturated samples were then tested in consolidometers. The loading sequence comprised 100 kPa, 200 kPa, 400 kPa, 800 kPa, 1000 kPa, and 1200 kPa. Deformation measurements were recorded at 24 h intervals for each load in 13 days, following the standard protocol. The consolidation test machine is shown in Figure 4.

Two different cement mix ratios (10% and 20%) were used to investigate the impact of EPS diameter on the deformation properties of lightweight soil. The EPS volume ratios, calculated by dividing the EPS volume by the total volume of the mixed soil, were consistently around 40%. Table 3 displays the test scheme, consisting of two specimens for each mix ratio.

Table 3. Mix ratio protocol.

Specimen	Cement Mix Ratio (%)	EPS Mix Ratio (%)	EPS Volume Ratio (%)	Water Content (%)	Curing Time (t/d)
Lightweight soil	10	1.0 (3 mm)	40	50	28
	10	0.75 (4 mm)	40	50	28
	10	0.50 (5 mm)	40	50	28

Table 3. *Cont.*

Specimen	Cement Mix Ratio (%)	EPS Mix Ratio (%)	EPS Volume Ratio (%)	Water Content (%)	Curing Time (t/d)
Lightweight soil	20	1.0 (3 mm)	40	50	28
	20	0.75 (4 mm)	40	50	28
	20	0.50 (5 mm)	40	50	28
Silt soil	-	-	-	50	-

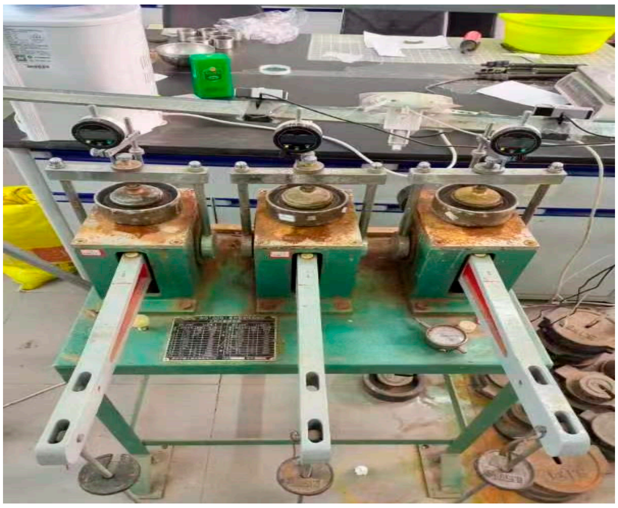

Figure 4. Consolidation test machine.

4. Results and Discussions

For research in soil mechanics, the theory and calculation of soil consolidation settlement deformation have always held a pivotal position, mainly including consolidation deformation over time, stress–strain, void ratio and stress, and analysis of post-construction consolidation settlement and other related aspects.

The foregoing shows that lightweight silt soil is a typical structural soil mass with complex composition, physical and mechanical properties, and a microstructure scale. It also possesses advantages such as lightness, high strength, easy construction, good self-supporting ability, and significant porosity. In the practical application process of engineering, lightweight silt soil is mainly used for the treatment of soft soil foundations and the filling of road embankments, typically bearing external loads such as traffic. Its deformation law often presents nonlinear characteristics. In summary, for ordinary soil, in Terzaghi's one-dimensional consolidation theory, the measured displacement is equal to the vertical compression of the soil. However, the consolidation deformation of lightweight silt soil in a saturated state is somewhat consistent with Terzaghi's one-dimensional consolidation theory. As its deformation is composed of EPS particles and pore compression deformation, the measured displacement is not equal to the total volume deformation of the sample, and the volume deformation of EPS particles inside the sample should also be added. Therefore, based on some conditional assumptions of Terzaghi's one-dimensional consolidation theory, this study establishes an EPS silt lightweight soil consolidation theoretical model and derives the relevant mathematical model and consolidation equation of its consolidation deformation theory, as shown in Figure 5.

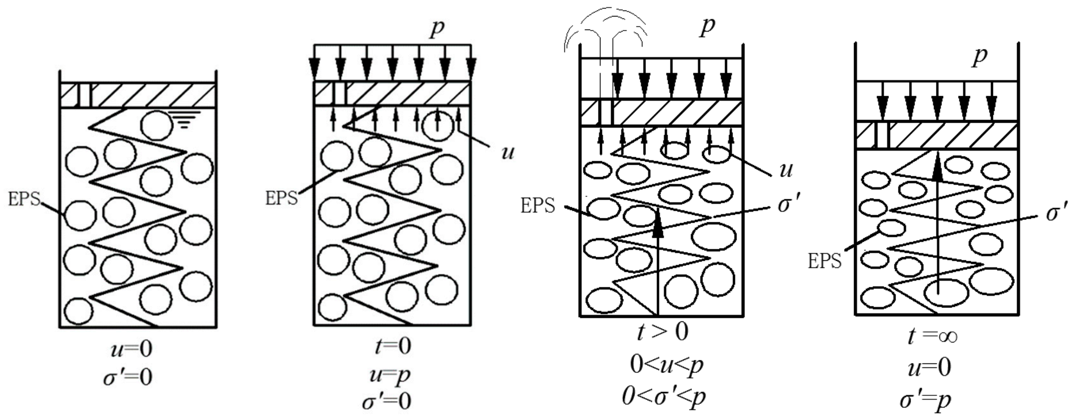

Figure 5. Spring-piston model of light soil consolidation settlement deformation.

In the above figure, p = stress, u = pore pressure, and σ′ = effective stress.

4.1. Consolidation Equation of Silt Lightweight Soil

Traditional indoor consolidation tests can only measure the pore portion, while measuring the deformation of EPS particles is difficult. It is determined that the EPS particles are in an impermeable medium phase, and the compression of pore water is relatively small. The consolidation state of the soil has a significant impact on the calculation of its settlement. The consolidation equation of silt lightweight soil must fully comply with Terzaghi's one-dimensional consolidation theory. Based on the physical model of silt lightweight soil mentioned above and some basic assumptions proposed by Terzaghi, a consolidated soil unit at a certain depth in the consolidated soil part of the sample was selected, as shown in Figure 6.

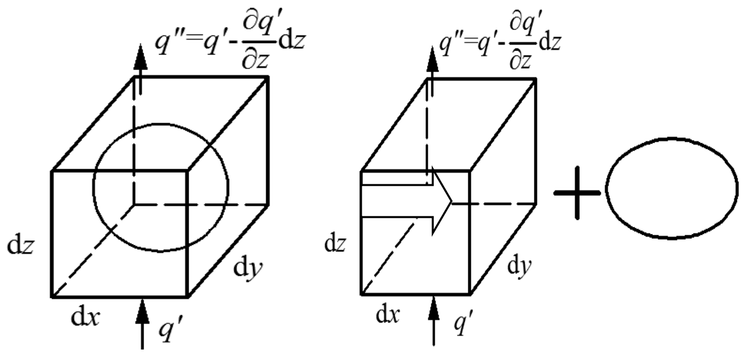

Figure 6. Consolidation of the unit body. Where q' is the flow of water entering the element at the bottom and q'' is the flow of water exiting the element at the top.

4.2. Terzaghi's One-Dimensional Consolidation Theory

In Terzaghi's one-dimensional consolidation theory, the assumption is relatively simple. It assumes the external load form is an instantaneous dead load applied simultaneously. Some soil parameters that undergo consolidation deformation in the foundation are treated as constants. Therefore, the differential equation of Terzaghi's one-dimensional consolidation equation is expressed as

$$C_V \cdot \frac{\partial^2 \mu}{\partial z^2} = \frac{\partial \mu}{\partial t} \tag{1}$$

In the above Equation (1) the term Cv is the coefficient of consolidation and μ is the pore pressure

$$C_V = \frac{k(1+e_0)}{\alpha \gamma_w} = \frac{k}{m_V \cdot \gamma_W}$$

where k is the coefficient of permeability, γw is the unit weight of water, a is the coefficient of compressibility, and m_v is the volume compressibility.

4.3. Consolidation Equation of Silt Lightweight Soil

According to Terzaghi's one-dimensional consolidation theory, it becomes evident that in the consolidation process of typical conventional soil, the displacement of the unit body over time equals the volume compression experienced by the unit body during that timeframe. However, in the case of lightweight silt soil comprised of composition materials, the volume compression of the unit body within a given period is not equal to the displacement of the unit body during that time. Instead, it is equivalent to the combined quantities of the measured displacement and the deformation of the EPS particle.

It is known that the compression of the silt lightweight soil unit is "dV" in time "dt," and the expression is

$$dV = \frac{\partial}{\partial t}\left(\frac{e}{1+e_0}\right)dzdxdydt \tag{2}$$

In the above formula,

e—void ratio of consolidated soil at any time.

e_0—the initial void ratio of the consolidated soil.

It is known that its displacement within time dt is "dQ", and its expression is

$$dQ = \frac{\partial v}{\partial z}dzdxdydt \tag{3}$$

In the above formula,

v—seepage velocity of water in silt lightweight soil (m/s).

The samples were exposed to different curing conditions with varying cement and EPS bead contents. Specimens containing 10% cement and 0.50% EPS beads were exposed to air for 2 h and then saturated for 24 h. However, the samples showed significant shrinkage deformation within the 5 mm diameter of EPS beads. This resulted in a substantial separation interface between the EPS and the stabilizing soil. Removal of the cutting ring completely collapsed the soil structure, preventing the successful completion of the test.

In contrast, in the specimens containing 10% cement and 0.75% EPS beads, the EPS beads had the least shrinkage deformation, with a diameter of 4 mm. However, there was no damage to the overall soil structure. As a result, additional samples were generated. For further testing, three specimens with different cement and EPS content ratios were prepared (cement 10% and 20%; EPS 1%, 0.75%, and 0.50%). After the specimens were cured for 28 days, they were directly immersed in water until saturated, without air evacuation beforehand. Subsequent steps followed the established protocols. The detailed mix ratio protocol is outlined in Table 3.

4.4. Impact of EPS Sizes on the Confined Stress–Strain Relation Curve

Figure 7 shows the stress–strain curves for samples with different sizes of EPS particles, when the EPS particle size is 3 mm, 4 mm, and 5 mm, respectively. Under a consistent additive content, the data reveal a rightward shift in the stress–strain curves. This shows that samples with an EPS size of 3–5 mm exhibit strength and ductility.

The confined stress–strain relation curves for the silt align with those of traditionally remolded silt. The compression modulus experiences an increase with growing stress, indicating a consistent compaction process for the silt. As stress rises, the rate of compression modulus increase in lightweight soil first ascends gradually, then reduces, resulting in the characteristic hyperbolic shape of the compression curves. The point of inflection of the compression modulus indicates the soil's strength, particularly the compression yield stress. When the cement dosage and EPS volume ratio remain constant among different specimens, it is seen that the structural strength decreases as the size of the EPS increases.

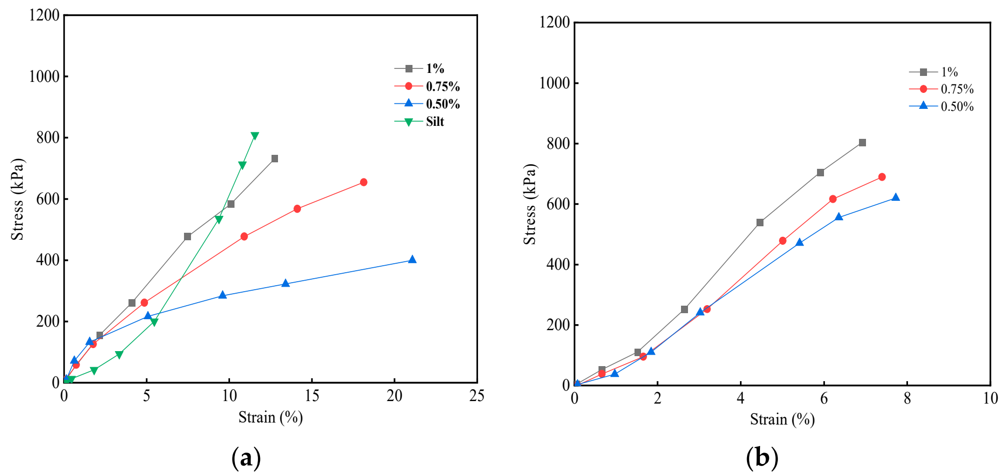

Figure 7. Relationship between stress and strain with (**a**) 10% cement content and (**b**) 20% cement content.

In addition, soil mixed with a higher amount of cement demonstrates increased structural strength compared to soil mixed with a lower amount of cement. Figure 7a shows a gradual increase in the structural strength of the silt. When the stress on the lightweight soil surpasses its structural strength, the structure undergoes a gradual deterioration and eventual collapse. This shows that the compression modulus of the silt exceeds that of the lightweight soil.

4.5. Impact of EPS Size on the Relationship between Stress Curves and the Void Ratio

The e-p curve in Figure 8 provides insight into the compression coefficient, indicating the void ratio reduction when subjected to stress. This relationship between void ratio and stress is depicted graphically by the e-p curve. In the context of the structure of lightweight soil, the hyperbolic-shaped e-p curve and e-lgp curve can be seen in Figures 8 and 9.

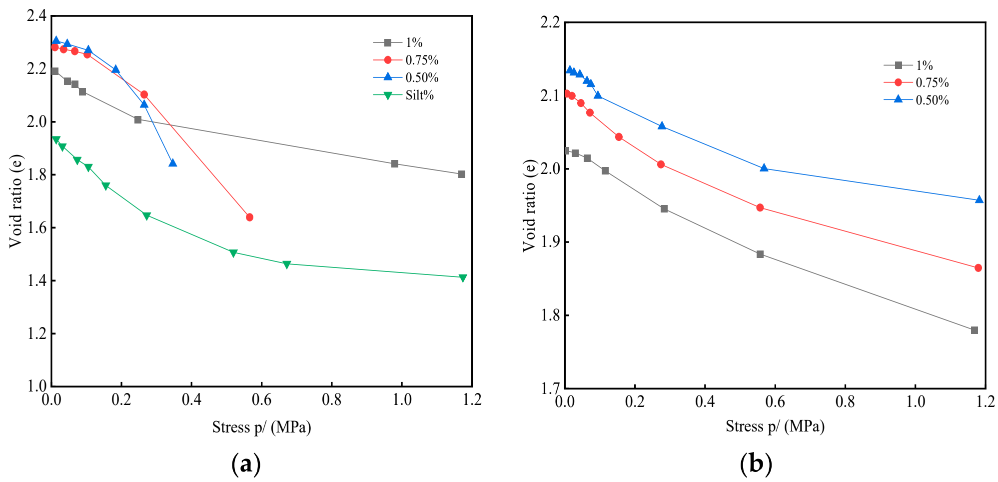

Figure 8. Stress–void ratio curves with (**a**) 10% cement content and (**b**) 20% cement content.

The relationship between the e-p curve and the confined stress–strain relationship curve is mutually reflective. However, it is essential to note that the e-p curve of lightweight soil differs from that observed in silt. The distinction emphasizes lightweight soil's unique characteristics and behavior compared to traditional silt composition. Notably, the void ratio of silt and lightweight soil displays structural strength. Compression yield stress curves for lightweight soil with varied mix ratios are depicted in Figure 10. Using 3 mm EPS lightweight soil with a cement content of 10% as a reference, the decreases in structural strength for 4 mm and 5 mm EPS lightweight soil are 520.91 kPa and 450.86 kPa, respectively

Similarly, employing 3 mm EPS lightweight soil with a cement content of 20% as a baseline, the corresponding reductions in structural strength for 4 mm and 5 mm EPS lightweight soils are 650.17 kPa and 580.94 kPa, respectively, as shown in Figure 9. It was evident that the compression yield stress decreases as EPS size increases, provided that the EPS volume ratio and cement dosage remain the same throughout the varied specimens. In addition, increasing the amount of cement used helps to increase the soil's strength.

Acknowledging that the void ratio undergoes a consistent decrease when exposed to stress levels below the compression yield stress is imperative. However, when the stress goes beyond the compression yield stress, the soil structure begins to collapse, leading to a quick reduction in the void ratio. This happens when the stress is greater than the compression yield stress.

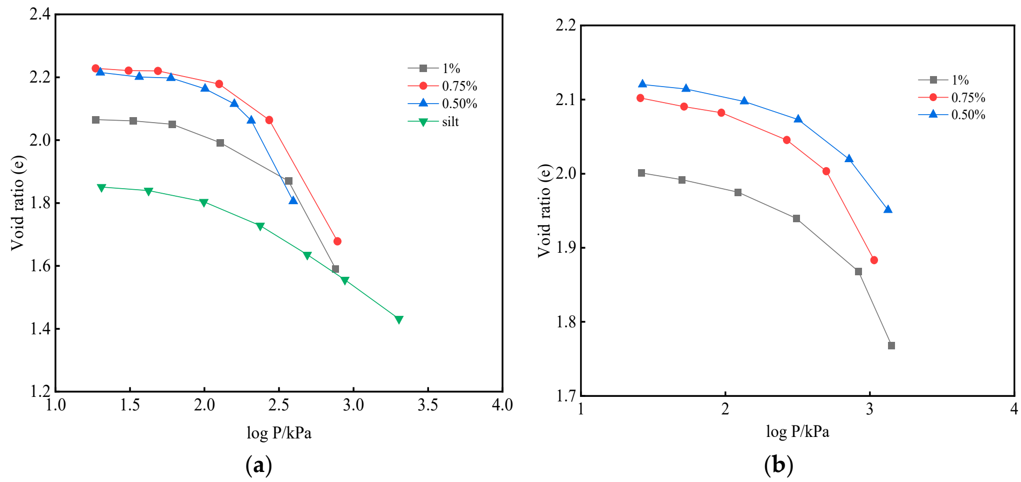

Figure 9. Stress–void ratio curves (logP-e curves) with (**a**) 10% cement content and (**b**) 20% cement content.

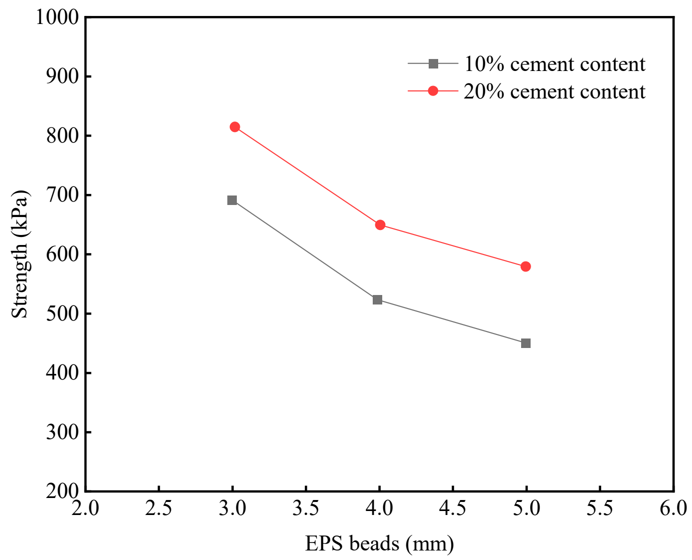

Figure 10. Curve illustrating the relationship between EPS size and strength.

4.6. Impact of the Size of EPS on Settlement Deformation

The settlement–time curves shown in Figure 11 illustrate the variances that can occur among specimens with different mix ratios. The settlement deformation (S) is observed to follow an incremental trend with time (t), ultimately arriving at a stable value. This is true for both silt and lightweight soil. When the stress applied to lightweight soil is below its compression yield stress, the consolidation deformation of lightweight soil is comparatively smaller than that of silt when subjected to an equivalent load. This is the case when the compression yield stress exceeds the stress.

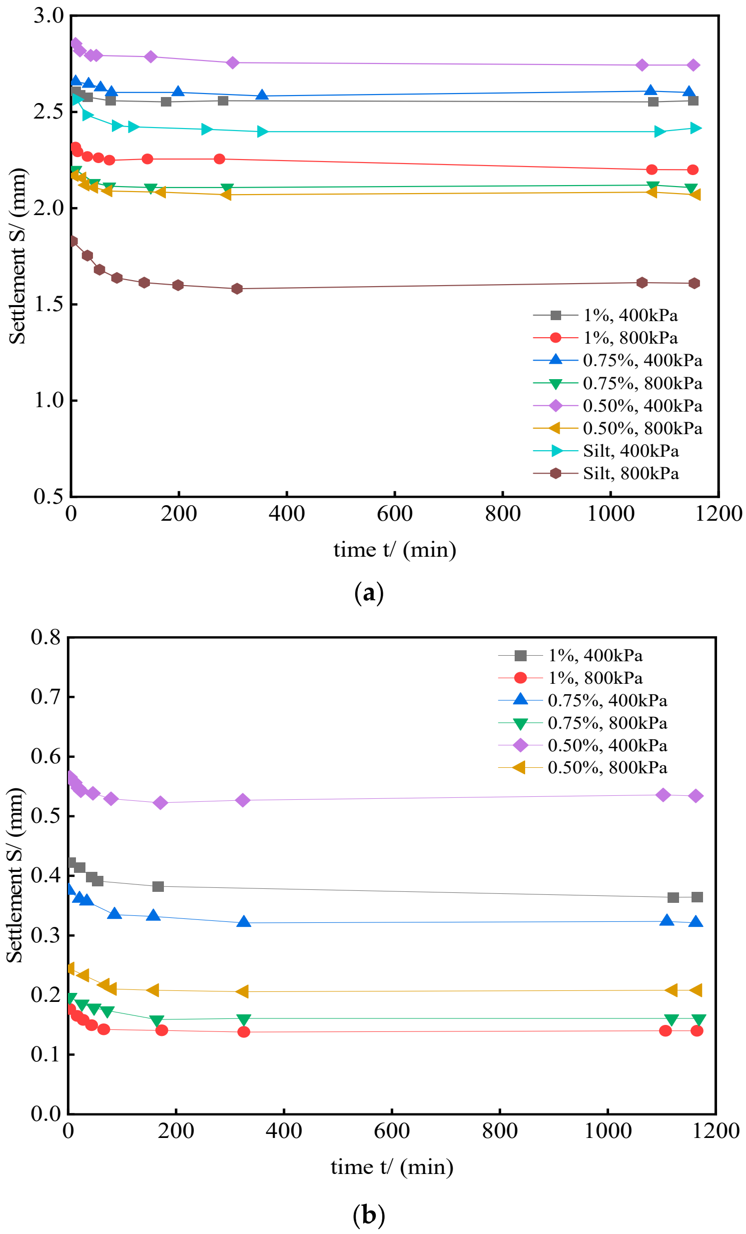

Figure 11. Settlement–time curves: (**a**) 10%; (**b**) 20%.

Nevertheless, once the structural strength of the structure has been compromised, the settlement of the lightweight soil occurs very quickly. In contrast to silt, lightweight soil experiences settlement deformation over a much shorter period, while silt undergoes a much longer process. When the EPS volume ratio, cement dose, and load remain the same, the settlement does not demonstrate a clear sequential pattern in correlation with the increase in EPS diameter.

An analysis of the S–t experimental curves suggests that a significant portion of settlement in lightweight soil, ranging from 80% to 95%, occurs within the first few minutes of loading. On average, approximately 95% of the settlement is completed quickly. In contrast, silt can achieve 90% of its settlement within 6 h.

The S–t curves of the lightweight soil do not show a secondary consolidation section. This scientific observation indicates that the settling of lightweight soil can be categorized as both instantaneous and primary consolidation settlement.

Notably, when the framework of the soil is disrupted, lightweight soil, which is classified as structural soil, exhibits rapid settlement deformation. The EPS undergoes a significant amount of compression, which results in a quick settlement. In contrast, the drainage–consolidation–compression process was significantly more drawn out because silt had a lower initial void ratio.

The deformation of lightweight soil typically lasts around 5 min before it is finished. In cases where stresses are below the yield stress, the fine soil structure depends on the volume effect of EPS, rather than the size effect, to determine the extent of deformation in the soil. In contrast, when the soil structure deteriorates, the EPS particles reach their maximum strength, and the size effect of the EPS becomes apparent.

When the stress levels are below the compression yield stress, it is clear that the size of the EPS does not have a visible impact on the material's stiffness. However, deformation becomes more pronounced once the stress exceeds the yield stress. This study optimized the material composition and assessed various approaches to achieve this objective. The strength of lightweight soil may decrease proportionally with an increase in its diameter.

5. Conclusions

(1) Lightweight soil's stress–strain relationship curve differs significantly from that of conventionally remolded silt. These curves have a hyperbolic shape, which shows that lightweight soil possesses characteristics of structural soil. Only minor deformations occur when the stress applied to a soil structure remains below its structural strength. However, once the stress exceeds the structural strength, the soil structure undergoes rapid destruction and collapse. Strong correlations between the e-p and curves depicting a confined stress–strain relationship can be observed.

(2) Lightweight soil's structural strength decreases with increased EPS size. However, elevated cement dosage can improve the stiffness of lightweight soil. In the context of structural strength, the soil structure bears the primary role in supporting loads. Conversely, the material is mainly shaped by the EPS volume effect rather than primarily determined by the EPS size effect.

(3) The structural strength experiences a decline as the size of EPS increases; nevertheless, the rate of reduction in structural strength is comparatively lower. When the size of EPS exceeds 4 mm, achieving homogeneity in the specimens becomes challenging. When mixed with soil, the EPS rises to the surface, creating distinct separation lines between the EPS and plastic cement paste inside the mixture. It is recommended to utilize EPS beads with a diameter ranging from 3 to 4 mm for practical projects. Furthermore, the optimization of material prescription is possible.

(4) The settlement of silt can be categorized into instantaneous, primary, and secondary consolidation settlement, which correspond to the consolidation attributes exhibited by the silt. On the other hand, settlement in lightweight soil is divided into two types, namely instantaneous and primary consolidation settlement. Approximately 95% of settlement in lightweight soil takes place within a few minutes, while silt achieves nearly 90% of its settlement within 6 h. When the stress applied to the soil is below its structural integrity, the soil structure remains intact, and any deformation is primarily influenced by the volume influence of EPS rather than its size. However, when the strength of EPS particles reaches its limit, the size effect of EPS becomes apparent.

(5) In a one-dimensional consolidation test, the compression modulus plays a crucial role in settlement calculations. Specifically, it is determined as the slope obtained from any two points on the curve depicting the relationship between confined stress and strain. The structural integrity of EPS particles may be compromised under excessive stress. It should be noted that the size of EPS does not affect the compression modulus when

the cement dosage and EPS volume ratio remain constant. However, an increase in the cement mix ratio results in a significant improvement in material stiffness.

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