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Effects of EPS Beads on the Unconfined Compressive Strength and Stiffness of Bentonite Soil-Cement Mixture

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Abstract. Expanded Polystyrene Beads (EPS Beads) have characteristics that are lightweight and low density. However, EPS is waste that does not pollute the soil, Therefore, EPS can be used as an alternative to reduce landfill area by improving soil quality. The study investigated the influence of different sizes of EPS beads on the mechanical properties of a bentonite soil-cement mixture using the unconfined compression test, with curing times ranging from 7 to 28 days. The results indicate that adding EPS beads to the soil-EPS beads-cement mixture improved its ductility and allowed it to withstand larger stresses at lower strain levels, less than 1%. Furthermore, the unconfined compressive strength of the mixture of bentonite, EPS, and cement increased with increasing curing time and decreased with increasing EPS beads size. Regardless of EPS bead size, incorporating EPS beads into the soil-cement mixture increased the stiffness of the samples compared to samples without EPS beads.

Keywords: Soil Improvement; Bentonite; EPS; Soil Strength; Soil Stiffness

INTRODUCTION

Expanded Polystyrene (EPS) is a thermoplastic material derived from petroleum and consists of only 2 compounds, carbon, and hydrogen. EPS seeds consist of 98% air and 2% raw material (by mass) [7]. This cellular polymer material is commonly used as a packaging medium for consumer appliances and electronic equipment due to its lightweight material and a very low density (0.10-0.20 kN/m^3).

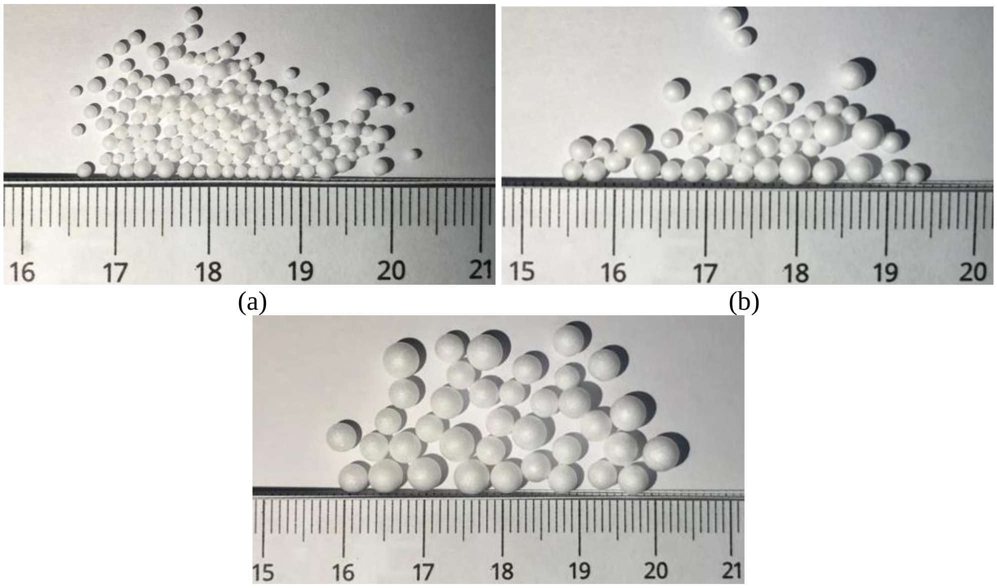
EPS is a type of waste that does not pollute the soil, but has hundreds of years to decompose, thereby reducing the area of Final Disposal Sites [6]. Although thermal and compression methods can be used for recycling. , some products are unsuitable for recycling due to the possibility of contamination during processing and transportation as well as their limited use. Therefore, innovative applications for the mass utilization of EPS waste are necessary [5]. One of such applications is to use EPS for soil improvement by mixing it with expansive soil at optimum moisture content, utilizing clay that cannot be used as construction materials. The granular form of EPS waste encourages recycling and significantly reduces the amount of EPS waste products that end up in landfill [1].

Soil improvement is a common practice in geotechnical engineering aimed at improving the physical and mechanical properties of the soil. Additives such as Portland cement can be used to improve soil properties chemically. This method is commonly used to reduce the swelling characteristic of expansive clay soils. Expansive clay is composed of minerals that exhibit swelling and shrinking as the moisture content changes [2]. Bentonite, which results from the transformation process of volcanic ash, is a fine expansive clay with a high water absorption capacity compared to other clay soils, Thus, it tends to change in volume, expand, soften, shrink, and develop dry cracks as the moisture content changes [1].

Based on the issues mentioned above, this study aims to investigate the impact of incorporating EPS beads on the mechanical properties of a bentonite soil-cement mixture using a series of unconfined compression tests. The study involved varying the size of the EPS beads and the curing time of the mixture. This paper presents the research methodology, including the experimental plan and materials used. Finally, the experimental results are presented and discussed in detail.

TABLE 1. Bentonite chemical compounds based on the XRF test

Chemical Compound	**Compound Name**	**Mass Percentage (%)**	**Chemical Compound**	**Compound Name**	**Mass Percentage (%)**	**Chemical Compound**	**Compound Name**	**Mass Percentage (%)**
SiO_2	Silicon dioxide	52.5	SO_3	Sulfur trioxide	0.667	ZrO_2	Zirconium dioxide	0.0458
Al_2O_3	Aluminum oxide	28.3	MgO	Magnesium oxide	0.623	MnO	Manganese (II) oxide	0.0251
Fe_2O_3	Iron (III) oxide	14.8	CaO	Calcium oxide	0.390	SrO	Strontium oxide	0.0149
TiO_2	Titanium dioxide	1.38	K_2O	Potassium oxide	0.319	As_2O_3	Arsenic trioxide	0.0148
Cl	Chloride	0.743	P_2O_5	Phosphorus pentoxide	0.0904	ZnO	Zinc oxide	0.0111



(a) (b)

(c)

FIGURE 1. (a) Small EPS, (b) Medium EPS, and (c) Large EPS

METHODOLOGY

The experimental study started with the preparation of the three primary substances: bentonite clay powder, expanded polystyrene beads (EPS beads), and ordinary Portland cement (OPC). Specific gravity and fall cone tests were then carried out to determine the specific gravity (G_s) and Atterberg's limits such as the plastic limit (PL) and liquid limit (LL) of the bentonite soil. The fall cone test was conducted in accordance with BS 1377-2:1990 to estimate the LL value [4], while Feng's method was used to determine the PL value [8]. The tests result showed that the G_s, PL, and LL values were 2.59, 46, and 105, respectively. According to Cassagrande's plasticity chart in [3], the bentonite sample was classified as CH or clay with high plasticity. The high LL (i.e., LL > 90) value also indicated that the soil sample had an extra high-swelling degree according to Dakshanamurthy & Raman's degree swelling classification [9]. Furthermore, an X-Ray fluorescence (XRF) test was also performed to identify the mineral composition of the bentonite clay powder, and the results are shown in Table 1. According to the XRF test, the mineral compositions of the bentonite clay powder primarily consisted of Silicon dioxide (SiO_2), Aluminum oxide (Al_2O_3), and Iron (III) oxide with a mass percentage of 52.5%, 28.3%, and 14.8%, respectively. In addition, the calcium mineral (Ca) was detected instead of sodium mineral (Na) in the bentonite soil sample. Therefore, it could be indicated that the bentonite used in this study could be classified as Ca-Bentonite. It is important to note that the XRF test could not fully confirm that the powder used in this study was a bentonite clay powder. Further tests such as the X-Ray diffraction (XRD) test were still required to confirm the identity of the clay. However, the powder was still considered clay due to the dominance of silica (Si) and aluminum (Al) atoms.

In this study, the EPS beads were classified into three categories based on their density: small EPS, medium EPS, and large EPS. The small EPS had a density of 14.9 g/L, while the medium EPS and large EPS had densities of 27.6 g/L and 32.7 g/L, respectively. Figure 1 shows the approximate size of the EPS beads in each category.

To create the soil samples, the three main substances, bentonite, EPS beads, and OPC, were mixed. The composition of the mixture included 2% EPS beads, distilled water with an amount of 1.5 times the bentonite liquid limit (105%), and bentonite soil for the remainder. The percentage of each component was based on the weight of the bentonite soil. The mixture was then blended with 25% cement. Table 2 presents an example of one sample mixture, noting that only one size of EPS beads was used in this step.

TABLE 2. Mixture Composition for One Sample

Composition of Bentonite-EPS Beads-Cement Mixture		
Bentonite	: 50 g	
Distilled Water	: 78.75 g	(1.5 × liquid limit or 1.5 × 105%)
EPS Beads	: 1 g	(2% weight of bentonite)
Cement	: 12.5 g	(25% weight of bentonite)

The samples for the UCT test were prepared as follows. The mold was first coated with grease to facilitate the extrusion of the soil sample upon reaching the curing time. Secondly, due to due to the highly fluid nature of the EPS beads-bentonite-cement mixture, the mold was glued to a ceramic to prevent any leakage. The bentonite clay powder was then poured into a bowl followed by the addition of distilled water in accordance with the ratios presented in Table 2. While the soil-water mixture was being mixed into a homogeneous slurry, the EPS beads were slowly added to the slurry, with the mixing continuing until the beads were uniformly distributed within the slurry. The cement was then added and mixed until a homogenous mixture was obtained. The mixture was then poured into three molds that were designed for unconfined compression tests (UCT) with a diameter of 3.8 cm and a height of 7.6 cm. The three molds corresponded to three different curing times, i.e., 7, 14, dan 28 days. Subsequently, UCT tests were performed to obtain the stress-strain response of the sample. The stress-strain curve was later used to determine the unconfined compression strength (q_u) and the modulus of elasticity at a 50% stress level (E_{50}). The sample preparation and UCT test were replicated on samples with different EPS beads sizes. The same procedure was also performed on samples with no EPS beads (bentonite-cement mixture). Figure 2 illustrates the sample preparation steps in this study. Table 3 summarizes the experimental plan of this study.

(a) (b) (c) (d) (e)

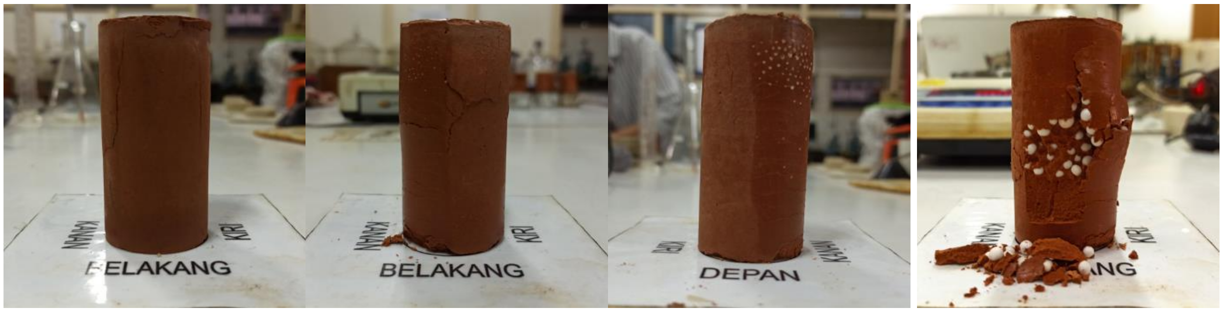
FIGURE 2. Sequential sample preparation: (a) smearing the mold with grease, (b) gluing mold to the ceramic, (c) mixing the materials, (d) adding cement, and (e) molding the samples.

TABLE 3. Experimental plan

Variations	Values	Purposes
Size of EPS beads	Small EPS, medium EPS, and large EPS	To investigate the effects of the size of EPS beads on q_u and E_{50} values of the EPS beads-bentonite-cement mixture.
Curing time	7 days, 14 days, and 28 days	To investigate the effects of sample curing time on q_u and E_{50} values of the EPS beads-bentonite-cement mixture.

RESULTS AND DISCUSSIONS

Figures 3, 4, and 5 display the conditions of the soil samples without EPS, and with small, medium, and large EPS beads after 7, 14, and 28 days of curing time, following the UCT test. Figure 6 illustrates the stress-strain curves of the samples with small, medium, and large EPS beads and without EPS beads after 7, 14, and 28 days of curing time. The results demonstrate that both curing time and EPS beads size significantly impacted the stress-strain behavior of the samples. In general, a longer curing time resulted in more ductile samples. As presented in Fig. 6(c) where the curing time was the longest, the samples exhibited elastic deformation characterized by the linear stress-strain relationship until they reached the yield stress point. As the strain increased, the stress-strain curve showed plastic deformation and reached the ultimate stress point, also known as the unconfined compression strength (qu). No further increase in stress was observed beyond this point. Notably, this behavior was more pronounced in the samples cured for 28 days. For shorter curing times, such as 7 and 14 days, the stress-strain curves exhibited a strain-softening response after the ultimate stress point, following the elastic region.



(a) (b) (c) (d)

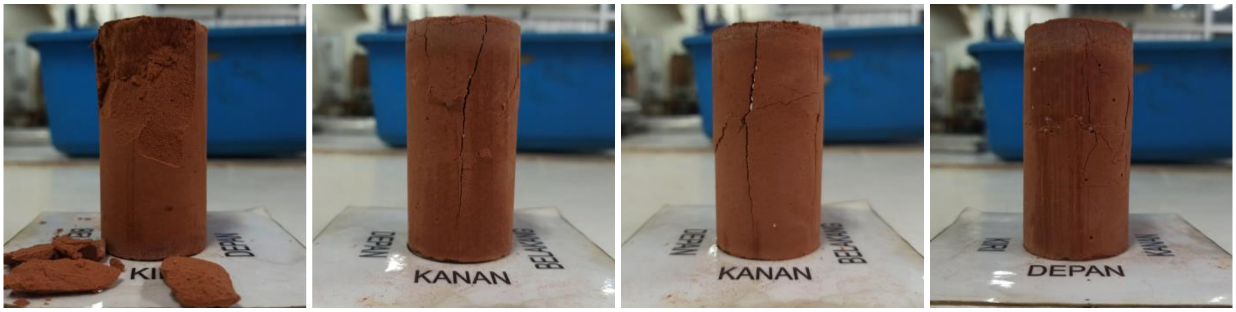
FIGURE 3. Samples condition after UCT test for samples with 7 days of curing time and (a) without EPS, (b) small EPS, (c) medium EPS, and (d) large EPS

(a) (b) (c) (d)

FIGURE 4. Samples condition after UCT test for samples with 14 days of curing time and (a) without EPS, (b) small EPS, (c) medium EPS, and (d) large EPS

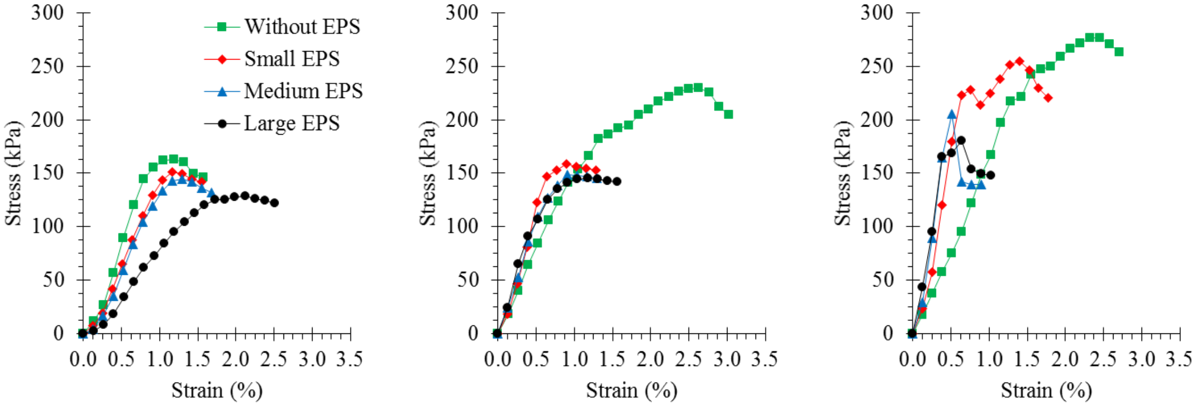
Additionally, the results from Fig. 6(b) and (c) demonstrate that the addition of EPS beads to the soil-cement mixture led to an increase in stresses at a smaller strain level (i.e., less than 1%). However, at higher strain levels, the samples without EPS beads had a higher stress for the same strain level compared to the samples with EPS beads.

This indicates that the bentonite-EPS beads-cement mixture was able to support higher stresses under small strain conditions, providing a potential advantage. Nevertheless, the samples with EPS beads exhibited a lower qu value than the samples without EPS beads, with larger EPS bead sizes leading to even lower qu values. This observation suggests that the shear strength of the samples with EPS beads was lower.



(a) (b) (c) (d)

FIGURE 5. Samples condition after UCT test for samples with 28 days of curing time and (a) without EPS, (b) small EPS, (c) medium EPS, and (d) large EPS



(a) (b) (c)

FIGURE 6. Stress-strain curves for samples with small, medium, large, and without EPS beads for curing time (a) 7 days, (b) 14 days, and (c) 28 days

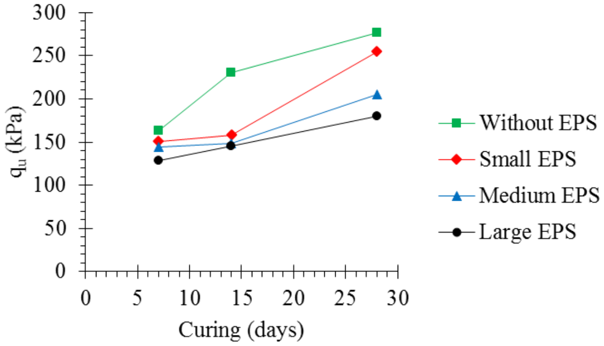


FIGURE 7. Relationship of q_u with curing time

Figure 7 depicts the relationship between the unconfined compression strength (qu) and curing time, as well as EPS bead size. Longer curing time and smaller EPS bead size promoted higher qu values for samples with and without EPS beads. This behavior can be attributed to the process of cement hydration, which contributes to the hardening of the soil samples. The qu value decreases with increasing EPS bead size because shearing resistance decreases with decreasing soil-cement particle contact area. It is worth noting that 98% of the EPS beads' composition is air, and the rest is the raw material (by mass) [7]. As a result, the EPS beads do not contribute to increasing shearing resistance since air shear resistance is negligible.

The addition of EPS beads not only affected the qu value but also the stiffness of the bentonite-EPS beads-cement mixture, which was measured by the magnitude of E50 in this study. Figure 8 illustrates the change in E50 value for various curing times and EPS bead sizes. The results demonstrate that the samples without EPS beads had a relatively constant E50 value of about 16.2 MPa for different curing times. Meanwhile, for samples with EPS beads of different sizes, the stiffness of the soil-cement mixture increased with increasing curing time. Furthermore, for the same curing time, the E50 values of samples with 14 and 28 days of curing time were larger than the E50 value for samples without EPS beads. A similar observation was also made in [6]. The E50 value of the samples with EPS beads for a curing time of 28 days was 1.98 to 2.27 times higher than the E50 value of the samples without EPS beads. Moreover, the size of the EPS beads did not significantly affect the E50 value of the samples for the same curing time in this study. This indicates another benefit of adding EPS beads to the soil-cement mixture, regardless of the size of the EPS beads. EPS beads could increase the stiffness of the soil-cement mixture, resulting in smaller deformation compared to the mixture without EPS beads under the same stress level.

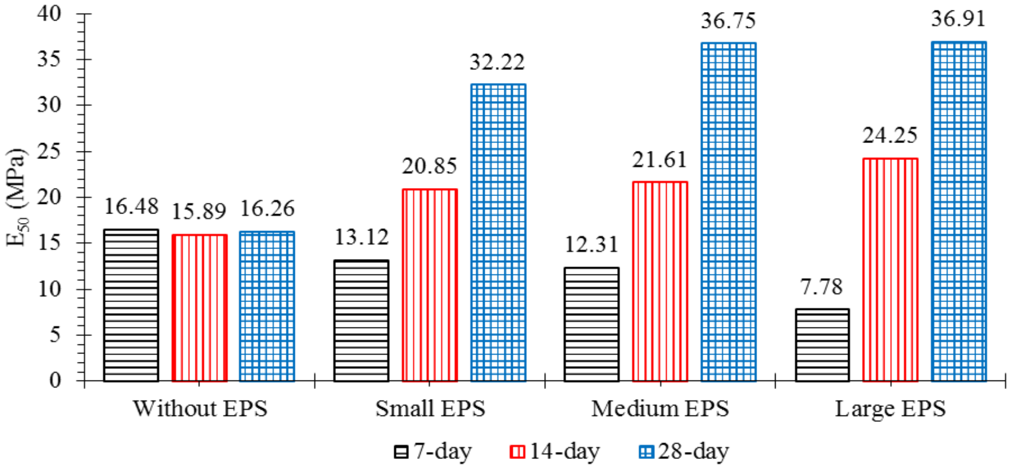


FIGURE 8. Relationship between E_{50} and curing time and size of EPS beads.

CONCLUSIONS

This paper reports on an experimental study investigating on the effects of adding the small, medium, and large sizes of EPS beads to the unconfined compressive strength and the modulus of elasticity at 50% stress level of the bentonite soil-cement mixture with 7, 14, and 28 days of curing time. The findings suggest that adding EPS beads of different sizes to the soil-cement mixture altered its stress-strain behavior, overall shear strength, and stiffness at different curing times.

The stress-strain behavior of samples with and without EPS beads exhibited a more ductile behavior during the curing period, which became more apparent as the curing time increased. The addition of EPS beads to the soil-cement mixture had both benefits and drawbacks. Firstly, samples with EPS beads exhibited higher stress levels at a low strain (i.e., less than 1%) compared to those without EPS beads, but lower stresses at a high strain. Furthermore, the unconfined compressive strength of the soil-cement mixture decreased as the size of the EPS beads increased, which was attributed to a decrease in the soil-cement contact area and lower shearing resistance. However, the strength of the samples increased with increasing curing time. Secondly, samples with EPS beads, regardless of their size, were stiffer than samples without EPS beads, especially at curing times longer than 14 days, as indicated by the magnitude of the modulus of elasticity at the 50% stress level of the samples. A higher stiffness could benefit in reducing the deformation of EPS beads-cement improved soil. It is also noteworthy that the size of EPS beads did not significantly affect the stiffness of the soil-EPS beads-cement mixture at the same curing time.

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