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DYNAMIC MODULUS AND DAMPING RATIO OF EPS COMPOSITE SOIL UNDER SMALL STRAIN CONDITION

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Key words: EPS composite soil, Resonant column tests, Small strain, Dynamic shear modulus, Damping ratio.

Abstract: *Dynamic shear modulus and damping ratio are important parameters to evaluate mechanical properties of soils. Expanded polystyrene (EPS) composite soil is mixed with EPS beads, cement, soil and water, which is usually used as a filling material in Road Engineering, Civil Engineering and so on. A series of resonant column tests were carried out to study the effect of EPS beads content, cement content and confining pressure on the dynamic modulus and damping ratio of EPS composite soil under small strain condition. Testing results show that the effect of cement content on the dynamic shear modulus is the most significant followed by EPS beads content, while the confining pressure has a slight effect. The initial shear modulus of EPS composite soil increases linearly with the confining pressure, while EPS beads impact on the initial shear modulus associated with cement content. The normalized shear modulus of EPS composite soil is less affect by EPS beads, while it is significantly influenced by cement content and confining pressure. The attenuation characteristic of normalized shear modulus for EPS composite soil can be well fitted by Davidenkov model. The damping ratio of EPS composite soil increases with cement content, while confining pressure has a slight effect on the damping ratio. The influence of EPS beads content on the damping ratio is more complicated due to the uncertainty of weak interface between EPS beads and soil particle. This study can provide references for the design and application of EPS composite soil in practical engineering.*

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1 INTRODUCTION

EPS composite soil is a mixture that is usually mixed with EPS (expanded polystyrene) beads, soil, cement and water. Since it was proposed in the 1960s, EPS composite soil has attracted more attention. Owing to its high-strength, light-weight, and controllable deformation, EPS composite soil has been widely used in practice such as soft soil treatment, embankments and bridge abutments, expressways, and underground pipelines [1-3]. Over the past twenty years, numerous tests have been conducted on EPS composite soil to study its physical and mechanical characteristics including unconfined compression tests, uniaxial compression tests, direct shear tests, and triaxial compression tests [4-7]. The mixing ratio and its influence on the strength, deformation and failure modes for EPS composite soil were investigated and discussed [8, 9].

When used on land, in the coast, or underwater, EPS composite soil is likely to undertake dynamic loadings such as seismic loading, traffic loading, and wave loading. Therefore, the dynamic characteristics of EPS composite soil are also a concern for engineering. Some experimental studies have been conducted to study dynamic characteristics of EPS composite soil like dynamic stress–strain relationship and dynamic strength. Cyclic triaxial shear tests are the most commonly used methods. Minegishi et al. concluded that the deformation and strength of EPS composite soil under cyclic loadings are mainly determined by the confining pressure [10]. Li and Miao conducted cyclic triaxial tests on EPS composite soil and discovered that the resilient modulus increased with an increase in the confining pressure and cement content, while the damping ratio slightly changed [11]. However, numerous engineering and experimental studies show that soils are mostly in a small strain condition [12]. Few experiments have been conducted to study the dynamic deformation and strength of EPS composite soil under small strain condition.

In this paper, a series of resonant column tests were carried out to study the effect of EPS bead content, cement content and confining pressure on the dynamic modulus and damping ratio of EPS composite soil under small strain condition.

2 EXPERIMENTAL PROGRAM

2.1 Experimental materials

EPS composite soil was mixed by EPS beads, soil, cement and water with different mixing ratios. The soil used in this study was muddy and silty clay which was taken from Yangzi Jiang River. Physical and mechanical properties of the mucky and silty clay are shown in Table 1. The round EPS beads are 2-3 mm in diameter. The unit weight and the bulk unit weight for EPS composite soil were 0.237 kN/m^3 and 0.159 kN/m^3, respectively. Portland cement (P.O 32.5) was used as a binding material.

Water content (%)	Wet unit weight (kN/m^3)	Dry unit weight (kN/m^3)	Saturation degree (%)	Void ratio	Relative density	Liquid limit (%)	Plastic limit (%)
48.1	16.8	1.13	96	1.373	2.74	39.2	22.6

Table1: Physical and mechanical properties of mucky silty clay

2.2 Specimen preparation

The cylindrical specimen of EPS composite soil used in this study is 50 mm in diameter and 100 mm in height.

The specimen preparation process mainly includes the followings: 1) The soil was oven-dried and crushed into powder with a rubber hammer; 2) According to the mixing ratio, the dried soil, Portland cement and water were weighed and stirred to form a slurry; 3) The desired amount of EPS beads were added into the slurry and fully stirred again until a uniform mixture was formed; 4) The mixture was placed into a three-section mould with a inner diameter of 50 mm and height of 100 mm; and 5) The specimen was cured for 7 days with a constant temperature of 20±2°C and relative humidity at 100%.

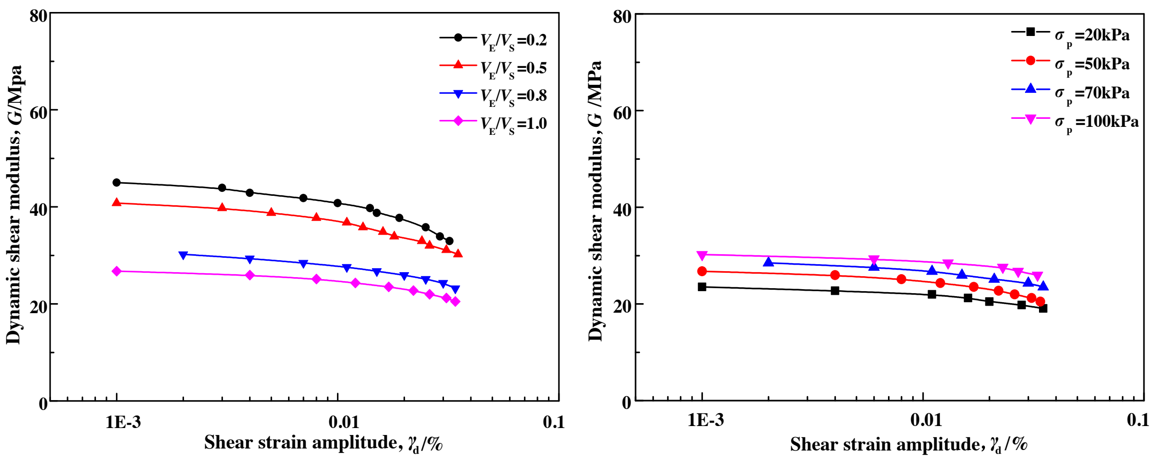
2.3 Test scheme and procedure

This experiment mainly discusses two factors, which affect dynamic characteristics of EPS composite soil, that is, mixing ratio and confining pressure. The mixing ratios include cement content and EPS beads content. Cement content (m_c/m_s) that is the mass ratio of cement to dried soil considered 6%, 8% and 10%. EPS beads content (V_E/V_S) that is the volume ratio of EPS beads to the mixture considered 0, 20%, 50%, 70% and 100%. The confining pressures considered 20kPa, 50kPa, 70kPa and 100kPa. The water content for all specimens was 60%, which was denoted as the mass ratio of water to dried soil. Experiments were carried out on the resonant column apparatus, TSH-100, manufactured by GCTS.

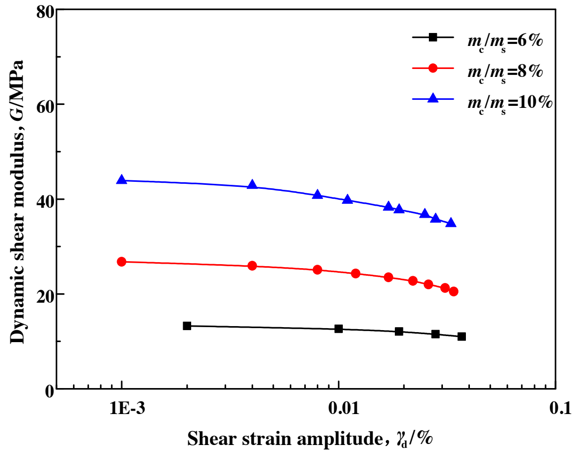
3 EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Characteristics of dynamic shear modulus

Sixty sets of data were obtained from the resonant column test for EPS composite soil with various mixing ratios and confining pressures. The relationship between dynamic shear modulus and shear strain amplitude of EPS composite soil is shown in Figure 1. It can be demonstrated that under small strain condition (smaller than 10^{-3}) the effect of cement content on the dynamic shear modulus is the most significant followed by EPS beads content, and the confining pressure is the least.



(a) m_c/m_s=8%, σ_p=50kPa (b) m_c/m_s=8%, V_E/V_S=1.0



(c) σ_p=50kPa ,V_E/V_S =1.0

Figure 1: Relation between dynamic shear modulus and shear strain amplitude for EPS composite soil

3.1.1 Initial shear modulus

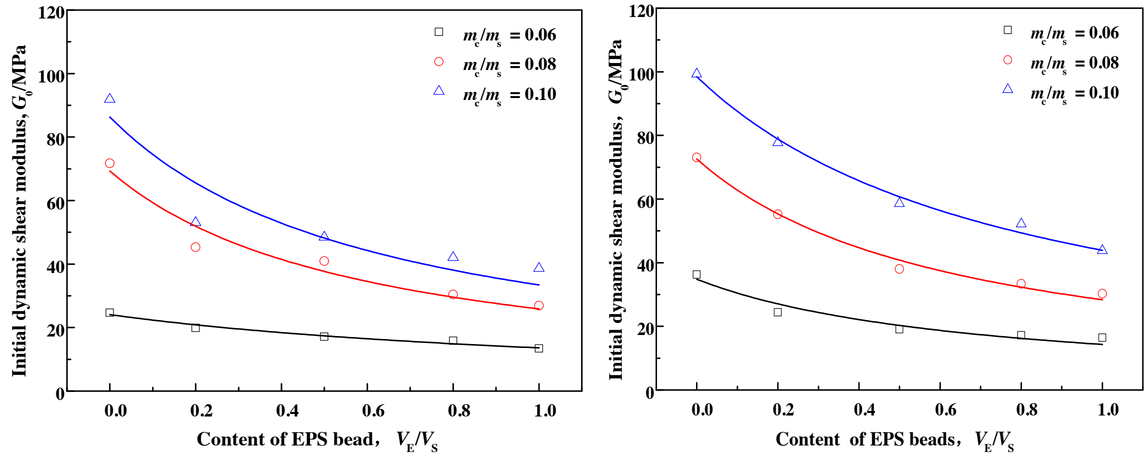
A hyperbolic model proposed by Hardin-Drnevich [13] can be used to describe the dynamic stress-strain skeleton curves of soils, which is expressed as follows:

$$\tau_d = \frac{\gamma_d}{a_t + b_t \gamma_d} \tag{1}$$

$$a_t = 1/G_0 \qquad b_t = G_0/\gamma_r \tag{2}$$

where τ_d is dynamic shear stress, γ_d is shear strain, G_0 is initial dynamic shear modulus, γ_r is reference shear strain, and a_t , b_t are fitting parameters.

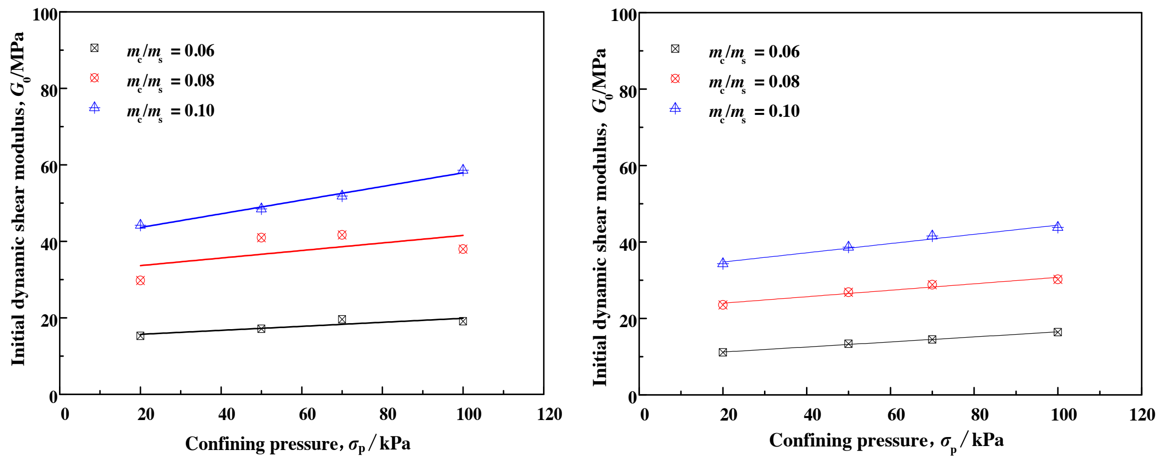
The initial shear modulus of EPS composite soil can be calculated through Eq.s (1) and (2). Figure 2 shows the effect of EPS beads on the initial dynamic shear modulus of EPS composite soil under small strain condition. V_E/V_S=0 indicates that EPS bead is not included in composite soil, namely cemented soil. It can be seen from the figure that the initial dynamic shear modulus decreases gradually with the increase of EPS beads content when the confining pressure and cement content are constant. However, when cement content is smaller, the change of the initial dynamic shear modulus of EPS composite soil is not obvious with the increase of EPS beads content. The reason is that the product of hydration wrapped around the soil skeleton to form a cemented medium, which has a quite greater strength than the soil skeleton. More cemented medium produced with the increase of cement content contributed more strength to EPS composite soil. As the cement content was reduced, the hydration reaction was inadequate and the strength of composite soil was controlled by EPS beads. So the strength of composite soil was smaller since the strength of EPS beads in the elastic stage was much smaller than that of cemented medium. When the confining pressure and cement content were constant, more EPS beads resulted in smaller initial shear modulus which was induced by the lower strength of EPS beads.



(a) σ_p=50kPa (b) σ_p=100kPa

Figure 2: Effect of EPS beads content on the initial dynamic shear modulus for EPS composite soil

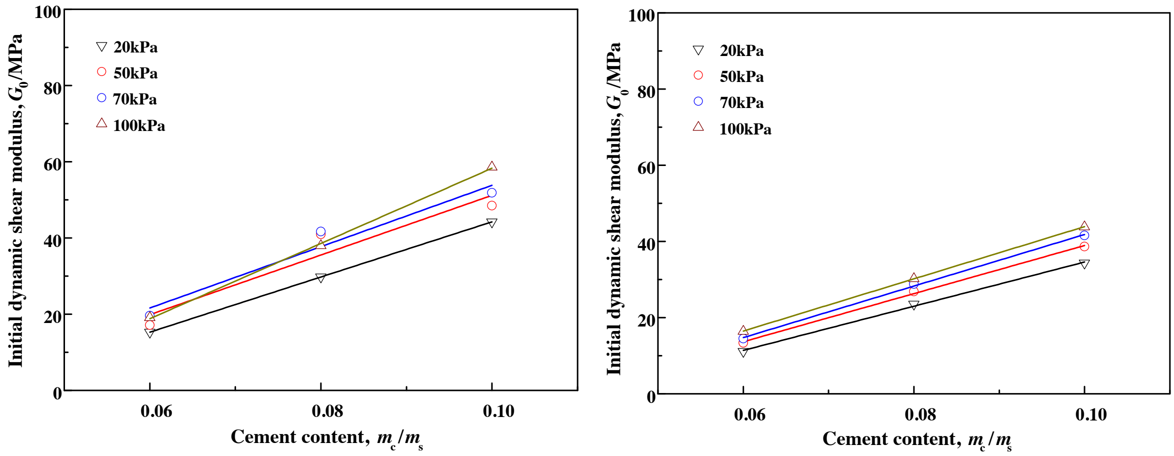
Figure 3 shows the relationship between confining pressure and initial shear modulus in the case that EPS beads content are 50% and 100%. It can be obtained that the initial dynamic shear modulus of EPS composite soil is increased approximately linearly with the confining pressure.



(a) V_E/V_S=50% (b) V_E/V_S=100%

Figure 3: Effect of confining pressure on the initial dynamic shear modulus for EPS composite soil

The influence of cement content on the initial shear modulus is shown in Figure 4. It is apparent from the figure that the initial shear modulus of EPS composite soil increased with the increase of cement content, which is approximately a linear change when other conditions keep the same. The cementation action ensures a higher stability of the soil skeleton. By comparing the effect of cement content and confining pressure, we can draw a conclusion that the effect of cement content on the shear modulus of EPS composite soil is greater than that of confining pressure.



(a) V_E/V_S=0.5 (b) V_E/V_S=1.0

Figure 4: The influence of cement content on initial dynamic shear modulus

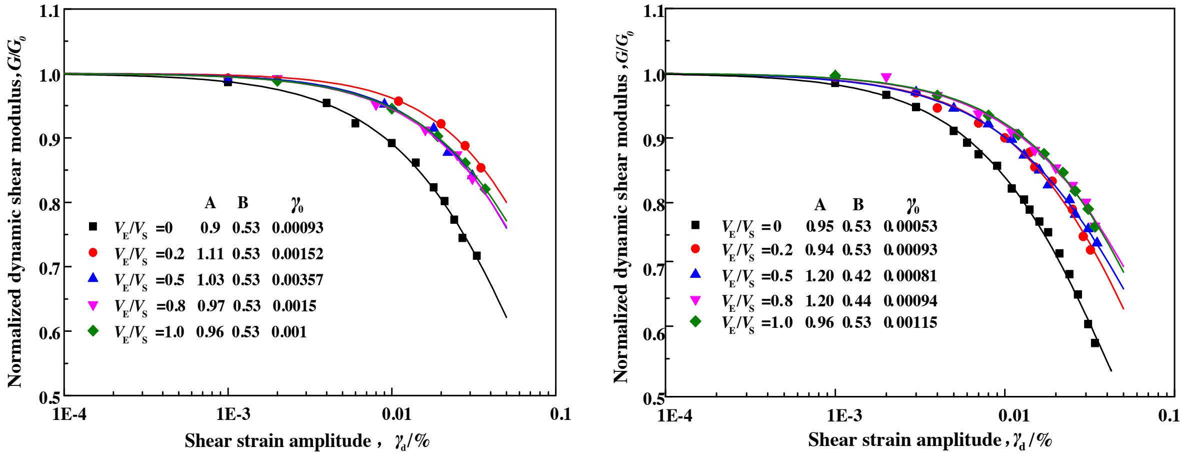
3.1.2 Attenuation characteristics of normalized dynamic shear modulus

Combined the existing attenuation formula with the experimental data, Martin-Davidenkov model [14] is used to fit the normalized curve of dynamic shear modulus. Martin-Davidenkov model is expressed as follows:

$$\frac{G}{G_0} = 1 - \left[\frac{\left(\gamma / \gamma_0 \right)^{2B}}{1 + \left(\gamma / \gamma_0 \right)^{2B}} \right]^{A} \tag{3}$$

where G is dynamic shear modulus; G_0 is initial shear modulus; γ is shear strain; A, B and γ_0 are fitting parameters related with soil properties. The value of parameter A ranged from 0.85 to 1.20, and B ranged from 0.38 to 0.53. It will be demonstrated that Martin-Davidenkov model can well fit the attenuation characteristics of normalized shear modulus for EPS composite soil.

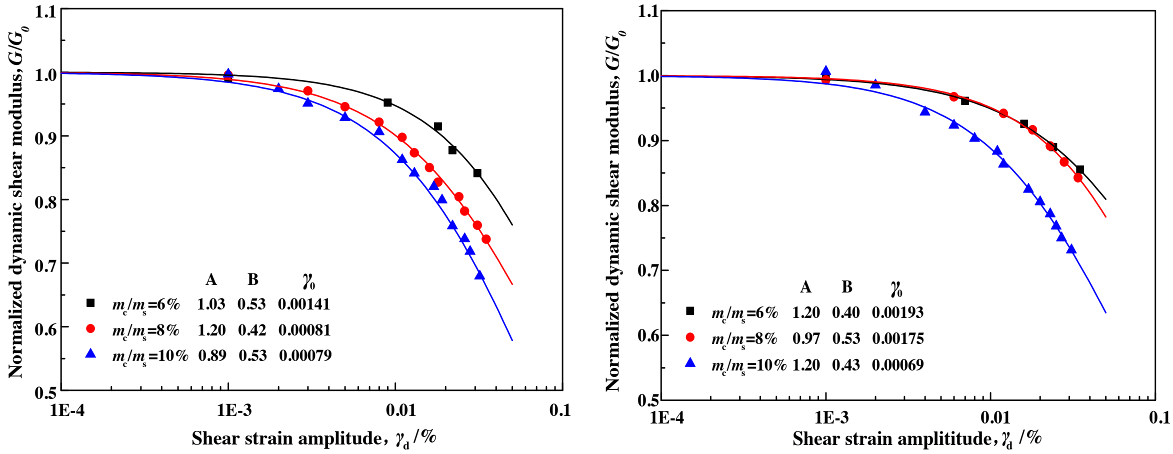
Figure 5 shows the normalized dynamic shear modulus of EPS composite soil changing with EPS beads under the confining pressure of 50 kPa. When the cement content is lower, the normalized curve with different EPS beads contents (excluding V_E/V_s=0) concentrated in a narrow range. However, there is a large difference in the normalized curve between cemented soil (V_E/V_s=0) and EPS composite soil. This is because when V_E/V_s=0 the strength of composite soil originated from the cemented medium formed by the cement around the soil particle. When the cement content was smaller, the cemented strength was easily to be destroyed as the shear strain increased, thus leading to a quick attenuation in the shear modulus. When adding the EPS beads, the cement would be wrapped around EPS beads and soil particle. Owing to their good elastic performance, EPS beads could delay the damage of the cemented strength. With lower cement content, the surface of EPS beads could not be fully wrapped by the cement resulting in that the variation of dynamic shear modulus was not obvious.



(a) m_c/m_s=6% (b) m_c/m_s=8%

Figure 5: Effect of EPS beads content on normalized dynamic shear modulus (σ_p=50kPa)

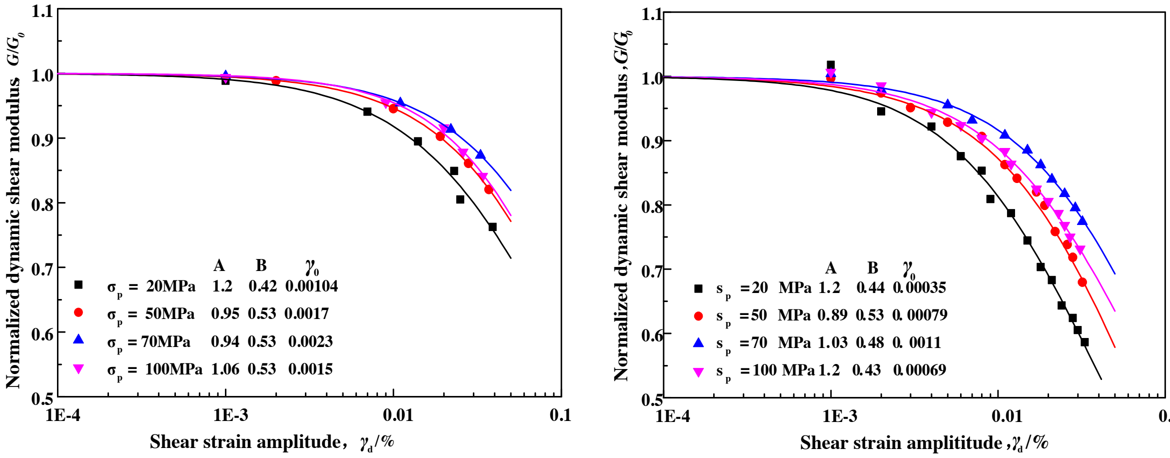
The attenuation curve of normalized dynamic shear modulus for EPS composite soil with different cement contents is shown in Figure 6. What can be seen is that the larger cement content leads to a sharper attenuation.



(a) σ_p=50kPa (b) σ_p=100kPa

Figure6: The influence of cement content on normalized dynamic shear modulus (V_E/V_s=50%)

Figure 7 shows the fitting curve of normalized dynamic shear modulus for EPS composite soil under different confining pressures when EPS beads content is 50%. The figure demonstrates that the normalized curve varies more gently with the increase of confining pressure. The larger friction resistance among EPS composite soil induced by the increasing confining pressure slows down the sliding of soil particle. So the attenuation of dynamic shear modulus tends to slow down. It also can be found that the normalized curves have a certain difference under different confining pressures, which indicates the confining pressure has some impact on the normalized shear modulus of EPS composite soil.



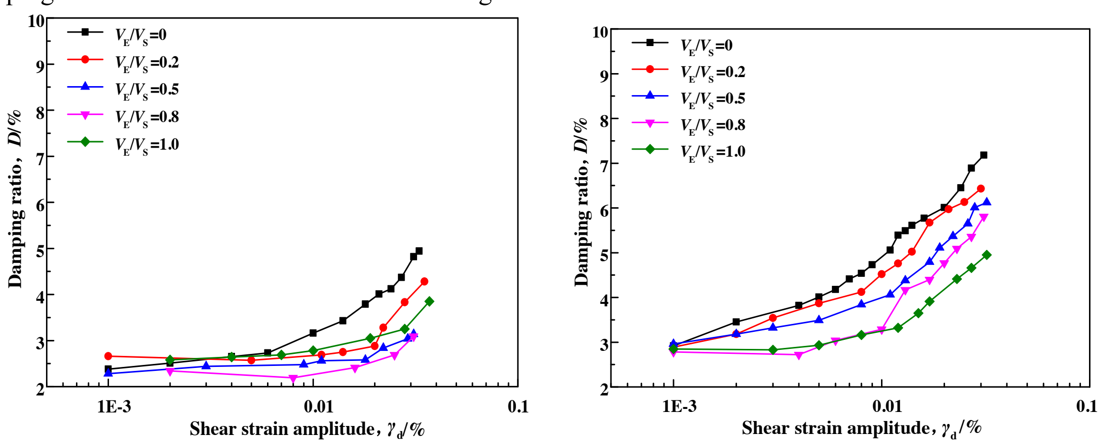
（a） m_c/m_s=6%　　（b） m_c/m_s=10%

Figure7: Effect of confining pressure on normalized dynamic shear modulus (V_E/V_S=50%) for EPS composite soil

3.2 Characteristics of damping ratio

The damping ratio reflects the loss of energy caused by the internal resistance of soils under dynamic loads [15]. The damping ratio of EPS composite soil increases with shear strain under dynamic loads. The influences of EPS beads content, cement content and confining pressure on damping ratio are discussed in small strain stage.

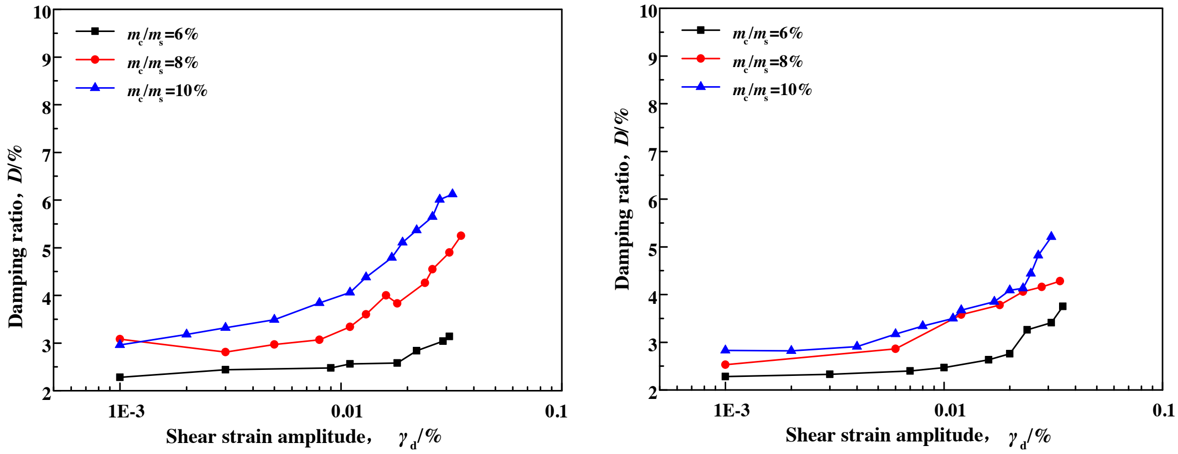
The influences of EPS beads content and cement content on damping ratio under small strain condition are shown in Figure 8 and Figure 9, respectively. Limited by the accuracy of testing instrument, the confining pressure at the lower level is difficult to keep stable, which results in the discreteness of testing data. It is found that the influence of EPS beads on damping ratio is more complex. Due to the interface between soil particle and EPS beads belongs to weak plane of cementation under small strain, while the damping ratio is related to the strength of cement and the number of weak cementation surface. Soil particle and EPS beads are connected by the weak cementation action and the damping ratio is related to the cementation strength and the number of weak cementation interface.



（a） m_c/m_s=6%　　（b） m_c/m_s=10%

Figure 8: Influence of EPS content on damping ratio (σ_p=50kPa)

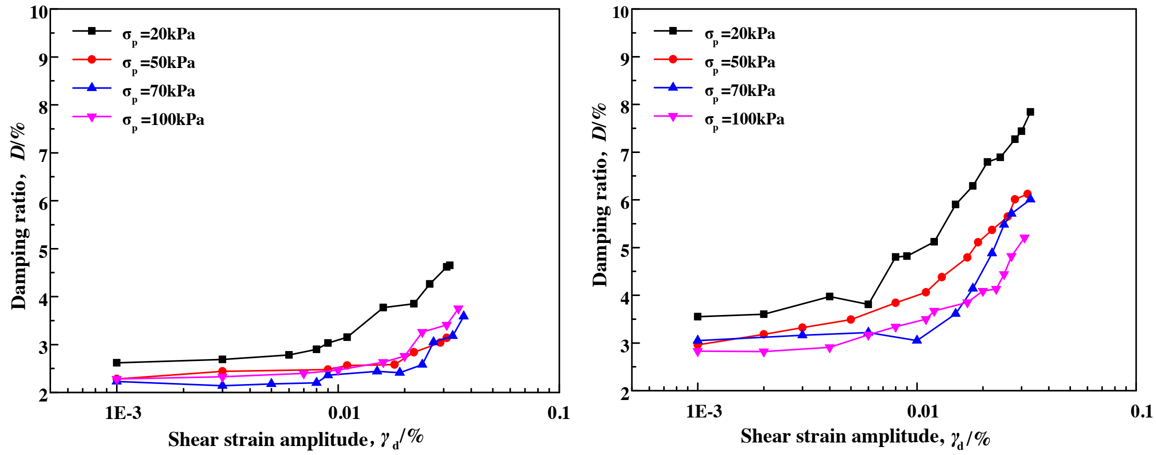
It is worth noting that the increase of cement content led to the increase of damping ratio under small strain condition. This conclusion is inconsistent with that from general understanding. In small strain stage, soil skeleton was not damaged and structural damping played a significant role. Large cement content results in great cementation strength. It is necessary to overcome the large hysteretic damping force when the same shear strain occurs, which led to large damping ratio.



（a） σ_p=50kPa （b） σ_p=100kPa

Figure 9: Influence of cement content on damping ratio (V_E/V_S=50%)

Figure 10 shows the effect of the confining pressure on damping ratio of EPS composite soil under small strain condition. As shown in the figure, the damping ratio roughly increases with the decrease of confining pressure. The reason is the contact between EPS beads and soil particle becomes denser with the increase of confining pressure. This leads to a decrease in the energy dissipation for EPS composite soil.



（a） m_c/m_s=6% （c） m_c/m_s=10%

Figure 10: Influence of confining pressure on damping ratio (V_E/V_S=50%)

4 CONCLUSIONS

- The effect of cement content on the dynamic shear modulus is the most significant followed by EPS beads content, while the confining pressure has a slight effect.
- When cement content is smaller, the change of the initial dynamic shear modulus is not obvious with the increase of EPS beads content. Initial shear modulus of EPS composite soil increased approximately linearly with the confining pressure and cement content.
- Confining pressure and cement content have a certain influence on the normalized shear modulus. The normalized curve varies more gently with the increase of EPS beads content. Martin-Davidenkov model can well fit the change of normalized dynamic shear modulus.
- The influence of EPS beads on damping ratio is more complex under small strain condition. The damping ratio of EPS composite soil increases gradually with the increase of cement content and the decrease of confining pressure.

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