Small-strain dynamic properties of sand-EPS bead mixtures

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ABSTRACT: Soil modified with Expanded Polystyrene beads results in lightweight mixtures used in many geotechnical applications. Investigating the dynamic behavior of such mixture may enhance its applications. This paper presents a laboratory characterization program using sand mixed with EPS particulates. The host sand was modified with up to 2.5% EPS beads by weight, which corresponds to approximately 70% EPS by volume. The paper focuses on the small strain dynamic properties of these composite mixtures at increasing percentages of beads and different confining pressures using Resonant Column tests. Results indicate that for each 0.5% increase in the beads content there is an average reduction of 12% in dry unit weight. The small strain dynamic properties show decreased shear stiffness with increasing EPS beads content and less influenced material damping with increasing the beads content. Overall, the laboratory evaluation of these sand-EPS bead mixtures resulted in properties that are within the range of engineering use and could be considered as an alternative construction material in various geotechnical applications.

Keywords: Lightweight fill, Sand-EPS bead mixtures, Dynamic properties, Small shear strains

1 INTRODUCTION

EPS geofoam blocks have been widely used in many geotechnical applications due to their advantageous physical and mechanical characteristics. They have been used as lightweight fill, compressible inclusion, and thermal insulator. However, using large blocks of geofoam poses a problem in some situations where transportation of prefabricated blocks in large volumes is un-economical. In addition, blocks are difficult to use in filling irregular volumes. Thus, soils mixed with geofoam beads may be a viable alternative in overcoming these deficiencies.

Cemented soil-EPS bead mixtures have also been used in various geotechnical applications. In Japan, these mixtures have been widely used in huge quantities in different projects as harbors and ports (Miki, 1996; Okumura, 2000). The first application was in 1988 in Japan; the modified mixture was used as a backfilling material for a pipeline of 359.3 m in length (Yamada et al., 1989). A quantity of 84,610 m^3 of this modified soil has been used in seawall and ground improvement of Tokyo international airport. In addition, the mixture was used in a quay wall in port of Yokohama, and in banking on rear of an embankment at Hachiohe city to reduce earth pressure (Miki, 1996; Okumura, 2000). In 2001, the mixture was utilized for the first time in China to stabilize an embankment for the Zhangzhou Shaon Expressway project (Ma, 2001). In addition, soil modified with EPS beads can be used as a desiccation crack controller and swell-shrink modifier of expansive soils (Illuri, 2007). It was noted from the previous studies and applications that water is important in providing workability required in forming Sand-EPS bead mixtures (Zhu et al., 2008). The addition of low stiffness EPS beads into soil mixture leads to reduction in the shear strength of the mixture with increasing the beads content (Zhu et al., 2008; Deng & Xiao, 2010; Rocco and Luna, 2012). However, at low confining pressures ($\sigma_3 < 100$ kPa) no significant reduction in the shear strength was recognized as the beads content increases (Deng & Xiao, 2010).

Available data on the dynamic properties of soil-EPS bead mixtures is very scarce in the literature. Rocco and Luna (2012) investigated the dynamic properties of kaolin-EPS mixtures using Resonant Column testing. The kaolin and EPS particulates were mixed with different ratios of (i.e. 0.0, 0.5, 1.0 & 1.5% by weight). They concluded that increasing the beads content leads to reducing the small strain shear stiffness (G_{max}) of the kaolinite mixture, about 30% to 34% reduction in G_{max} when adding EPS beads of 1.5% by weight, which is a significant reduction in the maximum shear stiffness. On the other hand, increasing the beads content has no significant influence on the small-strain damping ratio (D_{min}). The main advantage of adding EPS beads to soil was interpreted from the normalized degradation curves of the shear modulus, as for mixtures with increasing EPS beads content, the maximum shear stiffness was maintained to higher strain levels compared to pure kaolin specimens.

Due to the limited published data on the effect of modifying sand by adding EPS beads on the small strain dynamic properties, this paper presents this investigation which includes determining the influence of both the beads content and the confining pressure on the small strain dynamic properties using Resonant Column (RC) tests.

2 MATERIAL PROPERTIES

The sand used in this research is medium sand having a uniform gradation and classified as poorly graded sand (SP) according to the Unified Soil Classification System. Very small proportion of fines content that does not exceed 0.6% was found within the host sand. The specific gravity (G_s), maximum and minimum void ratios (e_{max} & e_{min}) were determined according to the ASTM D4253 and D4254 to be 2.65, 0.7 and 0.39, respectively.

White spherical EPS beads sizing between 1-3 mm were used in this study. The specific gravity and the unit weight of the beads were determined using a modified method similar to that used for fine aggregates (ASTM C128; Deng and Xiao, 2010). A one-liter hydrometer was filled with beads until it was apparently occupied without any compaction applied on the beads, only soft tilting effort was applied. The net weight of the beads that fill the hydrometer was measured and the unit weight was calculated by dividing the net weight by the standard volume of the hydrometer. The unit weight was calculated to be 0.19 kN/m^3. For the specific gravity, a piece of gauze was used to cover the opening of the hydrometer, and then de-aired water was added through the gauze until the total weight of the hydrometer remained constant. The absolute volume occupied by the beads can be calculated and the specific gravity was estimated to be 0.029. For the grain size distribution of the host sand as well as that of the used EPS beads (see Figure 1).

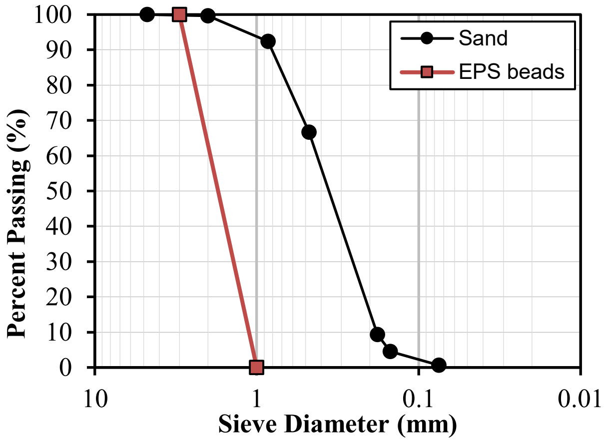

Figure 1. Grain size distribution curves of the host sand and EPS beads.

3 EXPERIMENTAL PROGRAM

To elaborate the influence of EPS geofoam beads on the unit weight of the mixture, standard proctor tests were conducted according to ASTM D698. The effect of EPS beads content was studied by testing the host sand and mixtures with varying beads content of 0.5%, 1.0%, 1.5% and 2.5% by weight (η), which corresponds to up to 70% by volume (see Table 1). Resonant Column (RC) apparatus was used to investigate the small strain dynamic properties of the different modified sand mixtures at three different confining pressures of 50, 100, and 200 kPa, to cover the range of stresses that may be encountered in the prospective geotechnical applications.

To assure the homogeneity of sand-EPS bead mixtures, sand was blended thoroughly with the determined proportion of beads and adding water is a necessity. All specimens were prepared at 10% water content and 95% relative compaction, as relative density cannot be estimated for the wet mixtures. Specimens were prepared in five sequential layers according to the method of under-compaction proposed by Ladd (1978). Resonant Column specimens were 50 mm in diameter and 90 mm in height with height to diameter ratio approximately equals 2:1. Finally, two stages have been executed to achieve the targeted full saturation; flushing and back pressure saturation. Figure 2 presents a sand-EPS bead mixture, with 1.5% beads content by weight, prepared in the RC apparatus.

Table 1. Proportions of beads by weight and the corresponding proportion by volume.

% Beads by weight (η)	% Beads by volume
0.5	31.9
1	48.5
1.5	58.6
2.5	70.5

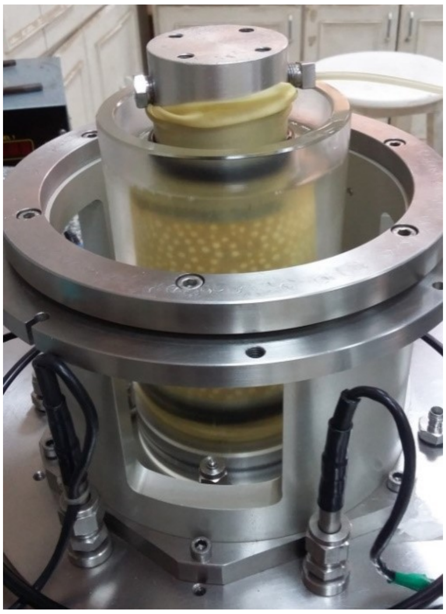

Figure 2. Tested specimen in the RC apparatus (η = 1.5%).

4 RESULTS

Standard Proctor compaction tests were conducted to determine the influence of EPS geofoam on reducing the mixtures dry unit weight. While RC tests gave the advantage of determining the small strain dynamic properties of the host sand and the modified sand mixtures.

4.1 *Water content-unit weight relationship*

Compaction curves of pure sand and the sand mixtures show the significant influence of the beads percentage (see Figure 3). The results show that adding EPS beads; having unit weight of nearly 1% of that of ordinary soil, considerably affect the unit weight of the sand-EPS bead mixtures. Approximately an average reduction of 12% in the maximum dry density (γ_{dmax}) was recognized for each 0.5% increase in the beads content. In addition, the compaction curves tend to flatten as the beads content increases. This behavior is expected to be due to the role of geofoam in damping and absorbing the compaction energy. Concerning the optimum moisture content (OMC), no to little influence of beads content on the OMC (Figure 4). It should be noted that adding 1.5% beads by weight or more produces a buoyant lightweight mixture as $\gamma_{dmax} < 9.8$ kN/m^3, which should be considered in design when such mixtures are used.

The relationship between γ_{dmax} and beads content, from Figure 4, follows a second-degree polynomial relationship. Equation 1 can be applied to estimate the maximum dry density of sand-EPS bead mixtures as a function of the maximum dry density of the host sand and the beads content within the soil mixture. The equation shows an excellent match with the experimental results (see Figure 4).

$$\gamma_{dmax_{,\eta\%}} = \gamma_{dmax,s} * (0.057\,\eta^{2} - 0.3754\,\eta + 1) \quad (1)$$

Where; $\gamma_{dmax,\eta\%}$ is the maximum dry density of modified sand mixture having certain η, and $\gamma_{dmax,S}$ is the maximum dry density of pure sand; and η is EPS beads content in percent.

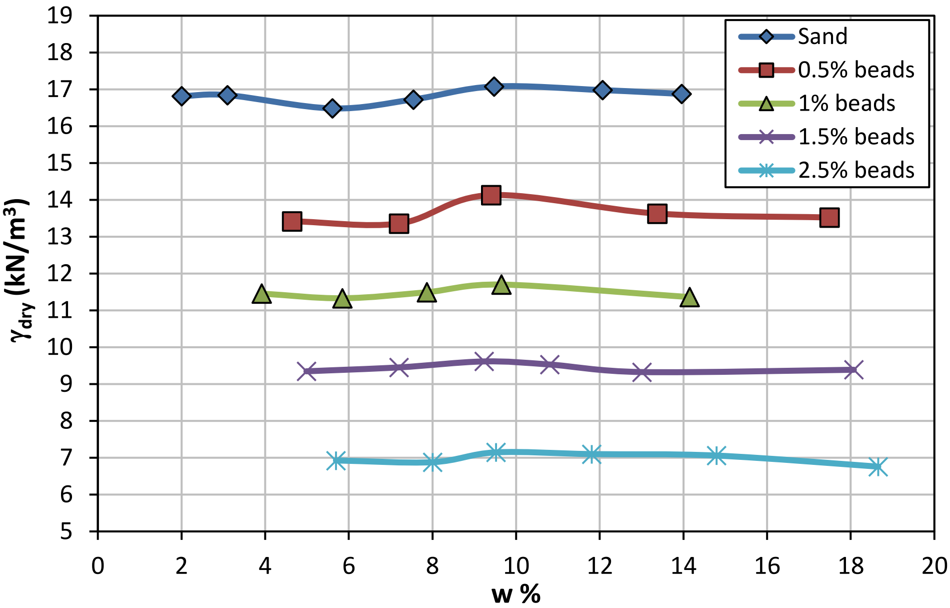

Figure 3. Compaction curves for the tested specimens.

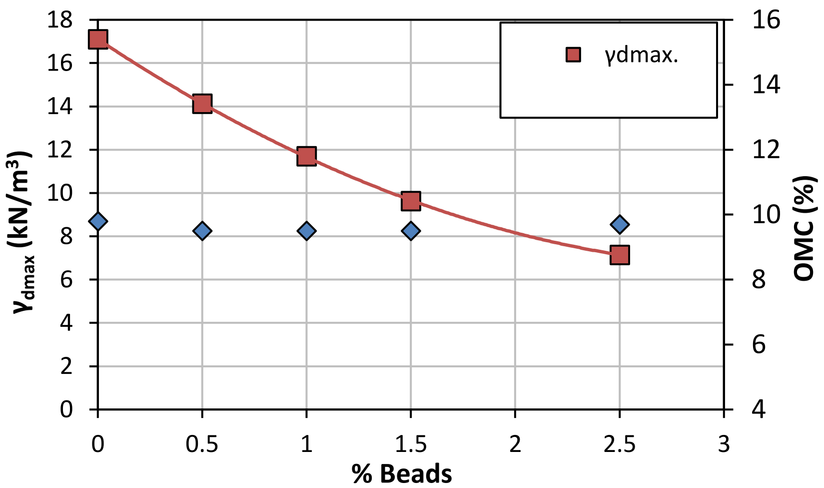

Figure 4. Effect of beads content on dry unit weight and OMC.

4.2 *Resonant column tests*

4.2.1 *Maximum shear modulus*

The maximum shear modulus and minimum damping ratio determined at low strain amplitudes; less than 10^{-3} %, and their reliance on the EPS beads content (η) and the effective confining pressure (σ'_3) were evaluated based on RC test results (ASTM D4015). It should be mentioned that the noise caused by the external vibrations surrounding the apparatus, significantly affect the obtained results at lower strain levels, and no convenient trend for the results was found, accordingly these results were not considered.

The effects of EPS beads content (η) and effective confining pressure (σ'_3) are presented in Figures 5 and 6. The results show the significant effect of EPS beads content on the maximum shear modulus of the modified sand-EPS bead mixtures. For the whole range of the tested confining pressures, significant reduction in G_{max} is recognized with increasing the beads content within the soil mixture. Table 2 summarizes the percentage reduction in G_{max} for the various sand-EPS bead mixtures at different confining pressures. The table shows that the percentage reduction in G_{max} is approximately independent of the applied effective confining pressure. However, it is governed by the beads content as about 60% reduction in the maximum shear modulus of sand is estimated when adding 2.5% beads by weight at σ'_3 of 50 kPa.

Figure 5 also reveals the increase in maximum shear modulus for the different sand mixtures with increasing the applied effective confining pressure. G_{max} increases by about 113% and 76% when increasing the confining pressure from 50 kPa to 200 kPa for pure sand and 2.5% beads content mixture, respectively.

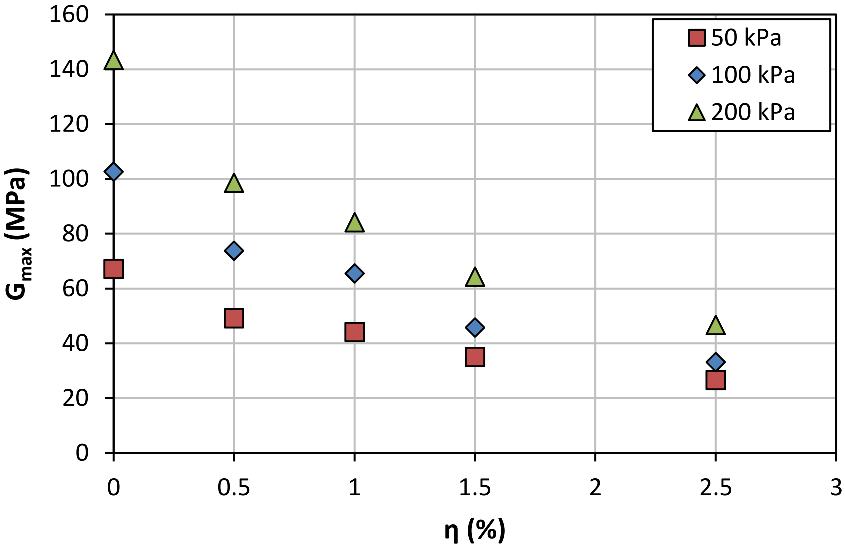

Figure 5. Effect of EPS beads content the maximum shear modulus.

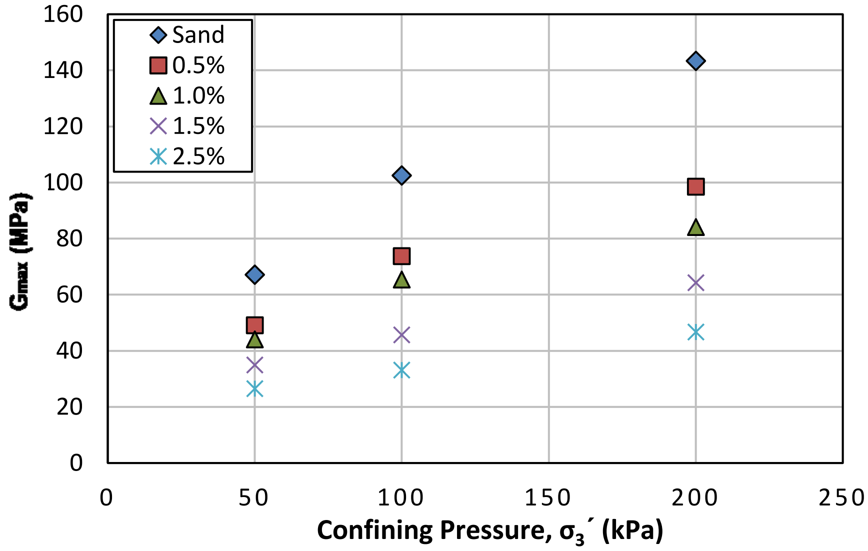

Figure 6. Effect of effective confining pressure on the maximum shear modulus.

This stated reduction in G_{max} may be attributed to the addition of low stiffness EPS geofoam beads to the sand matrix. Besides the fact that G_{max} is a function of the shear wave velocity (V_s) and the soil density ($G_{max} = \rho V_s^2$). From the equation, it is clear that the quadratic V_s have an upper hand over the density (ρ) in its influence on G_{max}. EPS beads have direct influence on both the shear wave velocity and the soil density. Increasing the beads content within the soil mixture increases the void ratio, and as the voids within the soil matrix increase, the shear wave velocity decreases and consequently G_{max} in a similar manner. Also, the role of the super lightweight EPS beads in decreasing the mixtures density is significant. In brief, increasing the void ratio and decreasing the density of soil caused by increasing the beads content, leads to the reduction in G_{max} with increasing the beads content.

On the other hand, increasing the confining pressure causes compression of the air voids as well as the EPS particulates, resulting in a denser and stiffer specimen. In addition, the increase of confinement causes rearrangement of sand particles into a denser structure, which in turn leads to an increase in the bonding and interlocking between the adjacent soil particles within the mixture matrix. All in the same manner lead to an increase in the soil stiffness and thus G_{max}.

Table 2. Percentage reduction in G_{max} of the different sand-EPS bead mixtures.

η (%)	Reduction in G_{max} (%)		
	σ'$_3$ = 50 kPa	σ'$_3$ = 100 kPa	σ'$_3$ = 200 kPa
0.0	0.0	0.0	0.0
0.5	26.9	28.1	31.2
1.0	34.3	36.2	41.3
1.5	47.9	55.4	55.2
2.5	60.5	67.7	67.4

The influence of EPS beads content on the shear wave velocity has been investigated by Rocco and Luna (2012) based on results obtained from Bender Element testing on kaolin-EPS bead mixtures. They have stated a reduction in shear wave velocity with the increase in EPS beads content. On the other hand, shear wave velocity increases with increasing the confining pressure, which matches the results presented in this study. Ishihara (1996) presented various empirical equations that have been concluded from various research studies on different types of sands. The measured maximum shear moduli of the tested sand specimens were compared to those calculated using empirical equations reported in the literature (Figure 7). It can be recognized that the closest calculated results to the measured results are that calculated from the equation proposed by Hardin-Richart (1963) for angular grained crushed quartz and that for Ottawa sand.

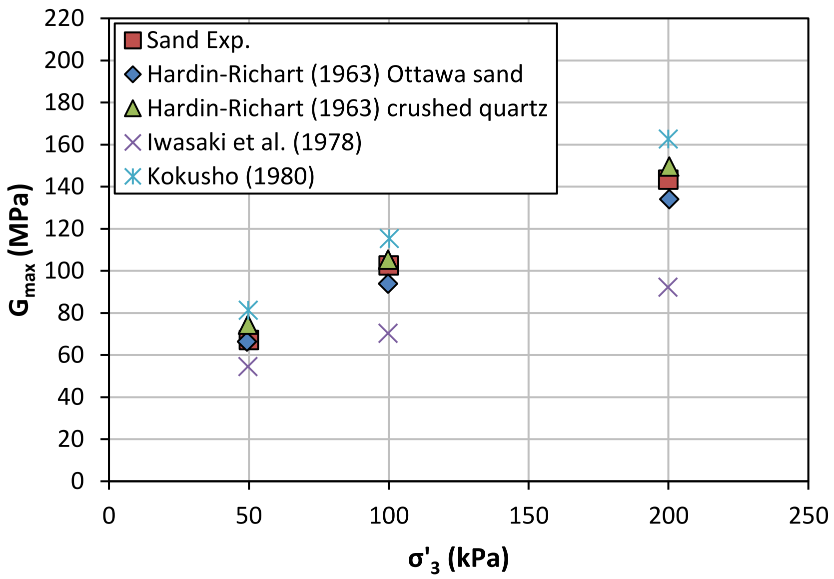

Figure 7. Comparison between the measured and calculated G_{max}.

4.2.2 *Minimum damping ratio*

The minimum damping ratio (D_{min}) quantifies the material damping at small strains (<0.001%). At such small strains, damping ratio has the least value and is strain independent until strains prior to the threshold strain. D_{min} was determined for the different sand-EPS bead mixtures by the RC torsional damping tests at the specified effective confining pressures.

Figures 8 and 9 display the effect of EPS beads content and effective confining pressures on D_{min} of sand specimens modified with EPS beads. The values of D_{min} approximately lies within a range of 0.35 – 0.6% for all the tested specimens. Unlike what was expected, D_{min} shows slight decrease with increasing the beads content within the mixture matrix, except at 200 kPa confining pressure, where no clear trend could be found with increasing the beads content. It was expected that introducing EPS beads to the soil matrix would increase the damping ratio due to its role as a compressible inclusion and its role in increasing the voids in the soil matrix.

The influence of effective confining pressure on the minimum damping ratio appears to follow the same trend as that of beads content. For all specimens, reduction in D_{min} occurs with increasing the applied confining pressure. Specimens with high beads content (η = 2.5%) do not exhibit a clear trend as other soil mixtures and no to very little influence of the confining pressure on its minimum damping ratio can be recognized. Consequently, it could be interpreted that the impact of confining pressure on D_{min} is of less influence as the beads content increases in the mixture. It is suggested that the reduction in D_{min} as the confining pressure increases, is due to the resulted increase in soil stiffness, which in turns leads to less absorption of energy, thus less damping ratio.

In 2012, Rocco et al. stated similar influence of EPS beads on the small-strain damping ratio of slurry consolidated kaolin-EPS bead mixtures. The results of RC tests on kaolin-EPS bead mixtures, showed reduction in D_{min} of the mixtures compared to that of the host kaolin. On the other hand, they stated that the effective confining pressure has no influence on D_{min}, which is contradicting with findings of this study. This contradiction may be attributed to the significant difference in nature and properties of the host soils utilized in both studies.

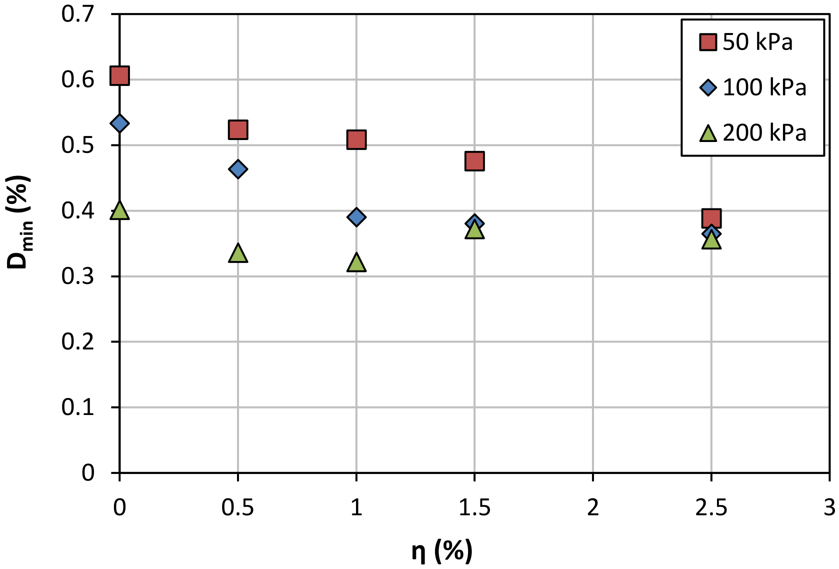

Figure 8. Effect of effective confining pressure on D_{min}.

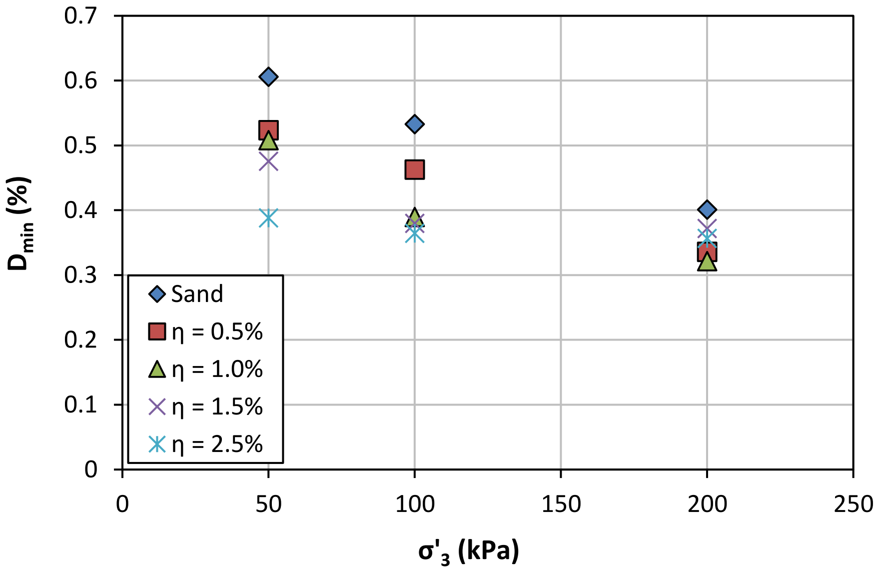

Figure 9. Effect of beads content (η) on D_{min}.

5 CONCLUSIONS

Soil modification with EPS geofoam beads alters the engineering properties of the mixture, including physical, mechanical, and dynamic properties of the mixture. This study targeted investigating the small-strain dynamic properties of modified sand-EPS bead mixtures in the laboratory using the RC device. Based on the results of the laboratory testing, the following conclusions have been reached:

1. Mixing sand with super lightweight material like EPS beads leads to a significant reduction in the determined maximum dry density from standard proctor tests. Approximately, an average of 12% reduction in the maximum dry density (γ_{dmax}) was achieved with each 0.5% increase in the beads

content. On the other hand, the optimum moisture content (OMC) shows no dependency on EPS beads content in all the mixtures.

2. An equation has been proposed to calculate the maximum dry density of sand-EPS bead mixtures as a function of the maximum dry density of the host sand and the beads content.
3. Reduction in maximum shear modulus with increasing beads content within the soil mixture was recognized as the general trend for all the different effective confining pressures at which specimens have been tested.
4. For a specific beads content within the soil mixture, the maximum shear modulus increases with increasing the effective confining pressure. Increasing the confining pressure causes compression of the air voids as well as the EPS particulates, resulting in a denser and stiffer specimen.
5. The measured maximum shear moduli of the tested sand specimens were compared to those calculated using empirical equations reported in the literature and they were very close to the calculated values from the equation proposed by Hardin-Richart (1963) for angular grained crushed quartz and that for Ottawa sand.
6. The values of D_{min} approximately lies within a range of 0.35 – 0.6% for all the tested specimens. D_{min} appears to decrease as the beads content increases. Except at 200 kPa confining pressure, no clear trend could be recognized with increasing the beads content. Similar influence of the effective confining pressure on D_{min} has been reported, as reduction in the values of D_{min} was noted with increasing the applied confining pressure. Eventually, it should be stated that the findings of this study depend on the properties of the materials used and the testing loading conditions.

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