EXPERIMENTAL INVESTIGATION OF THE MECHANICAL BEHAVIOR OF EPS GEOFOAM UNDER STATIC AND DYNAMIC/CYCLIC LOADING

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ABSTRACT

The mechanical behavior of Expanded Polystyrene Geofoam (EPS geofoam) under both monotonic and dynamic/cyclic loading conditions was investigated by an extensive laboratory experimental program. Monotonic and cyclic triaxial tests, resonant column tests and wave propagation tests using bender/extender elements were conducted in order to draw conclusions regarding the effect of material density, strain amplitude, confining stress and EPS sample size on the compressive resistance, modulus of elasticity and Poisson's ratio of EPS geofoam. By combining the experimental results of all types of tests, the values of the mechanical parameters are estimated for strain amplitudes ranging from 10^{-6} *to* 10^{-1}*. The effect of material density, strain amplitude and confining stress on the values of dynamic modulus of elasticity and damping ratio was investigated by performing cyclic triaxial tests with local strain measurements, whereas resonant column tests provided data regarding the values of dynamic shear modulus and damping ratio of EPS geofoam under zero confining pressure. For very low strain values (*$\sim 10^{-6}$*) the behavior of EPS geofoam was determined based on the results of bender element tests. The test results indicate that the mechanical behavior of EPS geofoam is linear for strain values lower than* 10^{-4}*, approximately linear for strain values ranging from* 10^{-4} *to* 10^{-3} *and non-linear for strain values greater than* 10^{-3}*. Based on the test results empirical relationships and diagrams are proposed for correlating compressive resistance, elastic moduli, damping ratio and Poisson's ratio of EPS geofoam with material density, mean confining stress,* σ_3*, strain amplitude (in the form of* E/E_o*-*ε_a *curves) and mode of loading (compressional vs. torsional).*

INTRODUCTION

EPS geofoam blocks are widely used in civil engineering projects; among the many different applications, of particular interest is the geotechnical use of the material (a) in the construction of transportation infrastructure, such as lightweight embankments for roads and highways (Horvath 2010, Kalinski and Pentapati 2006, Mathioudakis 2004, Riad and Horvath 2004) and (b) in the construction of earth retaining structures with a compressible inclusion between the backfill and the backface of the wall (Partos and Kazaniwsky 1987, Mc Gown et al.1988, Horvath 1995, 1997, 2004, 2008, 2010 (a, b), Tsukamoto et al. 2002, Pelekis et al. 2000, Hazarika 2001, 2003, Hazarika et al. 2001, Hazarika and Okuzono 2004, Athanasopoulos et al. 2007 (a, b), Trandafir and Ertugrul 2011, Zarnani and Bathurst 2011, Zarnani and Bathurst 2009, Bathurst and Zarnani 2008).

A prerequisite for performing reliable and effective analyses in the above EPS geofoam geotechnical applications is the knowledge and understanding of the mechanical behavior of EPS geofoam under both static and dynamic loading conditions. The need for reliable data regarding the mechanical behavior of EPS geofoam has prompted the performance of many studies for characterizing the material and for describing its behavior. A number of these studies have focused on the experimental investigation of the mechanical properties of the material (e.g. elastic moduli, Poisson's ratio, damping ratio, shearing resistance), whereas other studies aimed at developing constitutive relations for describing its stress-strain-time relations.

The behavior of EPS geofoam under static load conditions has been studied experimentally by performing several types of laboratory tests: monotonic uniaxial tests and triaxial tests, true triaxial tests, direct shear tests and creep tests (Leo et al. 2008, Abdelrahman et al. 2008 (a, b), Atmatzidis et al. 2005, Atmatzidis and Missirlis 2002, Xenaki 2005, Athanasopoulos et al. 2007 (a, b), Ossa and Romo 2009). The above studies aimed mainly at the establishment of the stress-strain curve of the material and its relation to the characteristic structure of EPS geofoam. The experimental results were also utilized for evaluating important parameters such as elastic, plastic and creep strains, elastic moduli, Poisson's ratio, the limit strain for linear behavior and the yield strength of the material. In the early stage of laboratory testing, the specimen deformations during testing were measured by recording the overall change of specimen height and volume. This practice was introducing several errors in the evaluation of material strains and was resulting in material properties dependent on specimen size, which were not representative of the true values corresponding to the full scale applications. Subsequent experimental studies using local specimen strain measurements have provided realistic (and specimen size independent) material properties and helped in establishing the range of strains for the linear, approximately linear and non-linear behavior of EPS geofoam (Xenaki 2005, Athanasopoulos et al. 2007 (a, b), Abdelrahman et al. 2008 (a, b), Leo et al. 2008, Ossa and Romo 2009).

The behavior of EPS geofoam under dynamic/cyclic loading conditions has been investigated in the laboratory by (a) cyclic uniaxial or triaxial testing (Xenaki 2005, Athanasopoulos et al. 2007 (a, b), Athanasopoulos et al. 1999, Trandafir et al. 2011, Ossa and Romo 2011, Trandafir et al. 2010, Ossa and Romo 2008), (b) resonant column testing (Athanasopoulos et al. 1999, Xenaki 2005, Athanasopoulos et al. 2007 (a, b), Ossa and Romo 2011) and (c) bender element testing (Xenaki 2005, Athanasopoulos et al. 2007 (a, b)). The results of the above investigations have provided, relatively consistent, data for the values of dynamic moduli and damping ratios of EPS geofoam for varying values of material density and confining pressure, under low-strain and high-strain cyclic loading conditions. As the experimental data from the laboratory tests mentioned above were becoming gradually available, several investigators proposed empirical correlations and simple or more complex constitutive models for the description of EPS geofoam behavior (Chun et al. 2004, Xenaki 2005, Wong and Leo 2006, Hazarika 2006, Atmatzidis et al. 2005, Ossa and Romo 2008).

In the following sections the results of a laboratory study performed at the University of Patras (which involved monotonic and cyclic triaxial, resonant column and bender element testing) are briefly summarized regarding the behavior of EPS geofoam under static and dynamic/cyclic loading conditions. The effects of material density (ranging from 10kg/m^3 to 30kg/m^3), confining pressure (ranging from 0 to 80kPa) and cyclic strain amplitude (ranging from 10^{-6} to 10^{-2}) on the dynamic moduli, Poisson's ratio and damping ratio were examined and empirical correlations were developed on the basis of experimental results. Whenever possible the proposed relations are compared to previously and more recently test results published by other investigators and conclusions are drawn on their reliability.

LABORATORY TEST PROGRAM

The dynamic properties of EPS geofoam (elastic moduli, damping ratios and Poisson ratio) in the present study were evaluated by conducting four types of tests (Xenaki 2005):

a. Monotonic (uniaxial and triaxial) tests

The tests were conducted in a GDS monotonic/cyclic triaxial testing system with a loading rate ranging from 1%/min to 2.5%/min, Figure 1. The confining pressure in these tests was varied from 0 to 60% of the EPS compressive strength (σ_{c10}). It was found that in this range of loading the rate of volumetric creep of the material becomes negligibly small after 15 min to 30 min following the load application. In these tests the maximum compressive strain was equal to 10%. Also, the reliable measurement of very small material strains was accomplished by using “Hall effect” type local-strain transducers, attached to the mid-height area of the test specimens (Clayton and Khatrush 1989; Clayton et al. 1989) (Fig. 1b).

b. Cyclic triaxial tests

These tests were conducted in the GDS testing system mentioned above, under controlled stress conditions and varying confining pressures and loading amplitudes. The rate of harmonic axial loading was approximately equal to 1%/min. Local strain measuring transducers were also used in these tests.

c. Resonant column tests (torsional)

These tests were conducted, in a “fixed-free” resonant column device, designed and fabricated by the senior author, Figure 2. The shear strains in these tests ranged from 10^{-6} to 10^{-3} whereas the loading frequency ranged from 35Hz to 70Hz (producing loading rates approximately equal to 6%/min). Due to the significant volumetric contraction of the EPS specimens under even small values of confining stress, (which resulted in a contact between magnet and coils) the resonant column testing was only conducted on unconfined specimens.

d. Bender element tests

These tests were conducted in a GDS bender-extender element testing system with wave frequencies ranging from 6.5kHz to 10kHz and vibration amplitude less than 10^{-6} (loading rate equal to 200%/min), Figure 3.

All specimens used in the experimental study were cylindrical with a height to diameter ratio equal to 2 and they were formed from EPS blocks having densities from 12kg/m^3 to 30kg/m^3. The final trimming of the specimens was accomplished by a sand paper, instead of a hot wire, to avoid any thermal disturbance of the surface of the specimens (Atmatzidis et al. 2005).

Figure 1. (a) The triaxial (cyclic/monotonic) loading system used in the laboratory program, (b) the local strain measuring transducers used in the triaxial tests on EPS specimens

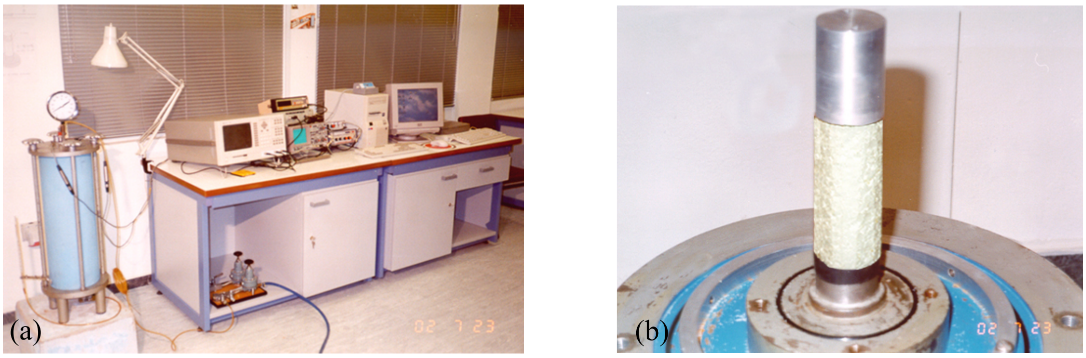

Figure 2. (a) The resonant column system used in the laboratory program, (b) cylindrical EPS specimen mounted to the pedestal of the resonant column device

Figure 3. The bender/extender element system used in the laboratory program (a) the pedestal of the device with the insert element, (b) EPS specimen mounted in the testing system

TEST RESULTS

The test results of the present study are presented in the following three subsections. The results obtained from the axial compression tests are presented first, followed by the small strain and the large strain test results.

1. Compressive Resistance of EPS Geofoam

Based on the results of a large number of uniaxial and triaxial compression tests, the compressive resistance, σ_{c10}, of EPS geofoam was found to depend on material density and isotropic confining pressure, as shown in Figure 4; the value of σ_{c10} (in kPa) can be estimated from Eq. 1 and Eq. 2:

$$\sigma_{c10} = 7.68\rho - 48.3 \tag{1}$$

$$\frac{\sigma_{c10(\sigma_3)}}{\sigma_{c10(\sigma_{3=0})}} = 1.0 - 0.84\frac{\sigma_3}{\sigma_{c10}} \tag{2}$$

where ρ=EPS geofoam density (kg/m^3)

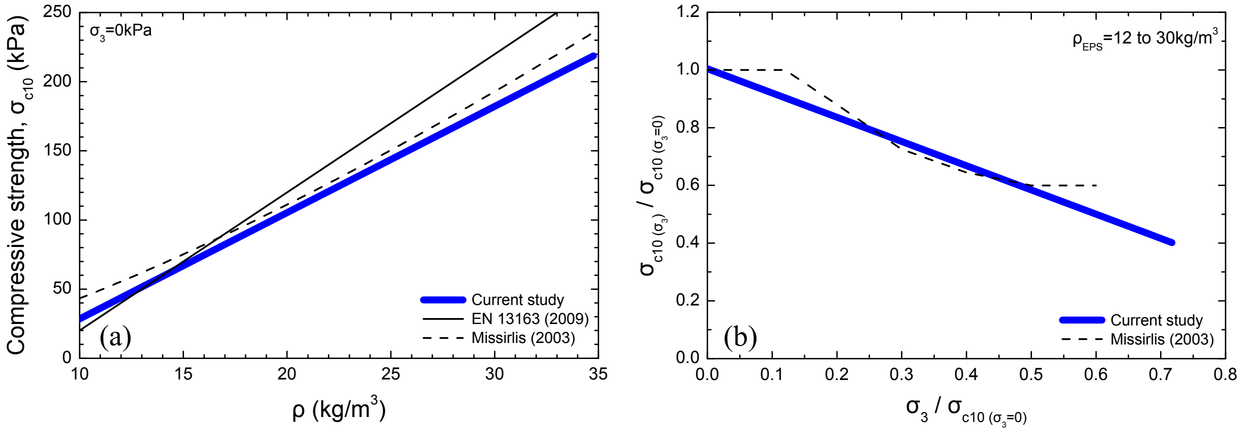

Figure 4. Compressive resistance of EPS geofoam as a function of (a) material density and (b) isotropic confining pressure, and comparison with published results

2. Small Strain Properties of EPS Geofoam

For small strain vibrations the experimental results indicate that the values of elastic moduli (G_o, E_o) of EPS increase with increasing density of material, ρ, and decrease with increasing mean confining pressure, σ_3 (Fig. 5). The low-amplitude value of Poisson ratio, v_o, depends mainly on confining pressure and decreases with increasing values of σ_3 (taking values from 0.30 to -0.05). (Fig. 6). Based on the experimental results, the following empirical equations are proposed for estimating the values of G_o (in MPa) and v_o as a function of material density, ρ:

$$G_{o(\sigma_3=0)} = 0.32\rho - 1.40 \tag{3}$$

$$v_{o(\sigma_3=0)} = 0.22 + 0.0033\rho \tag{4}$$

$$\frac{G_{o(\sigma_3)}}{G_{o(\sigma_{3=0})}} = 1.02 + 0.599\frac{\sigma_3}{\sigma_{c10}} - 1.41\left(\frac{\sigma_3}{\sigma_{c10}}\right)^2 \tag{5}$$

$$v_{0(\sigma_3)} = 0.25 - 0.33\frac{\sigma_3}{\sigma_{c10}} \tag{6}$$

where: ρ=EPS geofoam density (kg/m^3)
σ_{c10}=EPS compressive strength (kPa) from specimens with aspect ratio=2
σ_3=mean confining pressure (kPa)

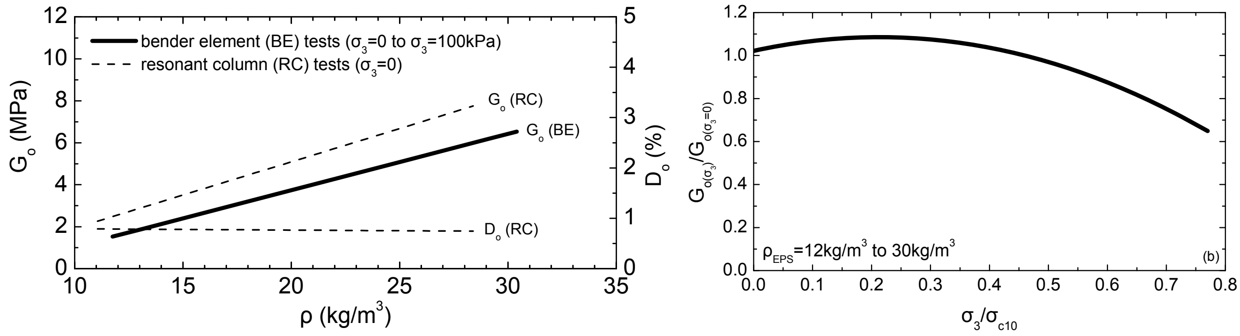

Figure 5. Small strain shear modulus and damping ratio of EPS geofoam as a function of material density and mean confining pressure from resonant column (RC) and bender element (BE) tests

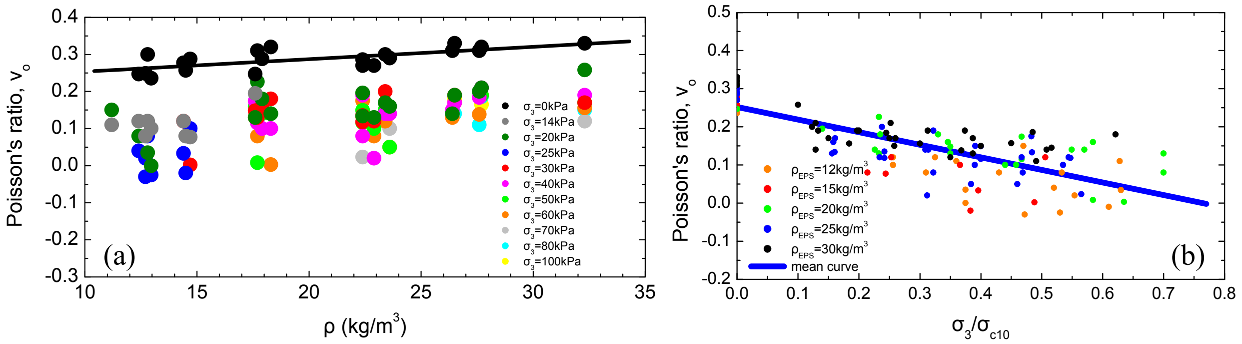

Figure 6. Small strain Poisson's ratio of EPS geofoam as a function of material density and confining pressure from bender element (BE) tests

The experimental results also indicate that the low-amplitude damping ratio, D_0, of EPS (for both the hydrostatic and deviatoric components of loading) takes low values and does not depend on material density. The value of D_0 increases somewhat with confining pressure and a mean value of D_o=1.70% is suggested for all small strain vibration applications.

3. Large Strain Properties of EPS Geofoam

For large strain vibrations the dynamic properties of EPS geofoam, in addition to material density and confining pressure, depend also on strain amplitude. More specifically, for increasing values of strain the elastic moduli decrease, the damping ratio increases whereas the Poisson ratio decreases markedly and may take negative values (Fig. 7, 8). A very interesting finding is that the EPS modulus of elasticity, E, in the range of intermediate to large strains (10^{-4} to 10^{-2}) also depends on the type of loading (monotonic vs. cyclic). More specifically, as shown in the diagram of Figure 9, in the above mentioned strain range, the moduli obtained from cyclic loading are approximately 20% higher compared to the values from monotonic (i.e. static) loading. This behavior shows a remarkable similarity to the behavior of soils (Lo Presti et al. 1997; Pradhan and Ueno 1998).

The modulus degradation curve of EPS geofoam was found to depend –although not significantly –on the material density, confining pressure and type of loading. As a first approximation these effects may be neglected and a unique relation (Eq. 7) is proposed for practical applications (depicted as an equivalent G/G_0-γ_c curve in Figure 6a):

$$\frac{E}{E_o} = \frac{1}{1+\frac{\varepsilon_c}{0.01}} \qquad (7)$$

Values of Poisson's ratio, v, -estimated from the measured axial and radial deformations of specimens- were obtained mainly from the monotonic triaxial tests, assuming an equivalent-linear material behavior. It was found that the value of v decreases with increasing confining pressure and axial strain whereas it is insensitive to the value of EPS density. Test results for three values of ρ are summarized in the diagrams of Figure 8, which indicate that for large strains and high confining pressures Poisson's ratio may take negative values (up to -0.30). This indicates that under such conditions, the EPS behaves as an "auxetic" material (Stavroulakis 2004). Values of EPS Poisson's ratio for practical applications may be obtained from the diagrams of Figure 8 by linear interpolation between the limit values of σ_3 shown in the graphs.

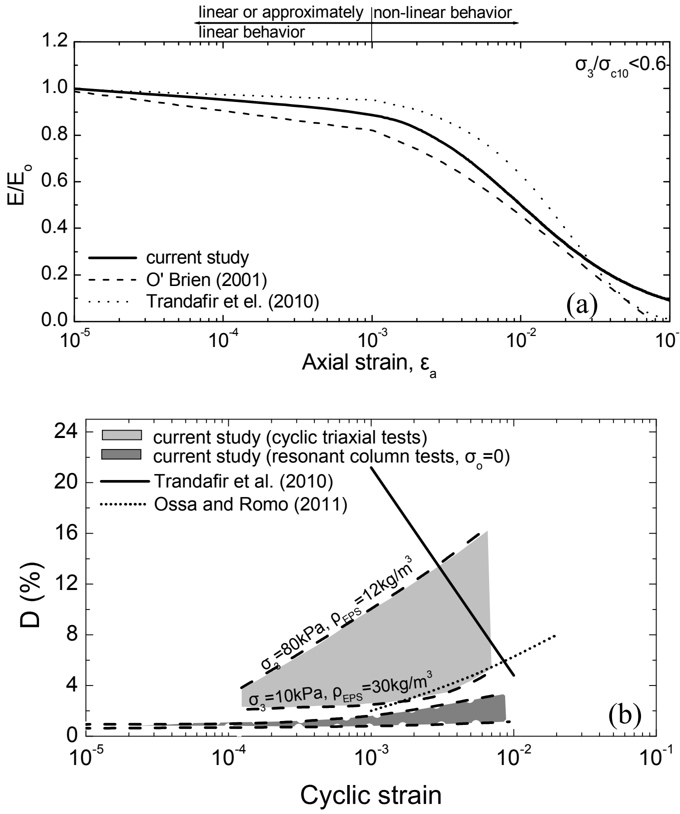

Figure 7. Normalized modulus/damping ratio vs. cyclic strain relations derived in the present study and comparison with published results

Finally, according to the test results, the damping ratio value of EPS is increased for large strains and furthermore it increases with increasing confining pressure and decreasing material density (Fig. 7b). However, the most important effect seems to be associated with the type of loading, with damping ratio values for compressive loading being about 4 times the corresponding values for shear loading. For practical applications involving large strains it is suggested to use the values of D≈3% and D≈14% for the deviatoric and hydrostatic component of loading, respectively.

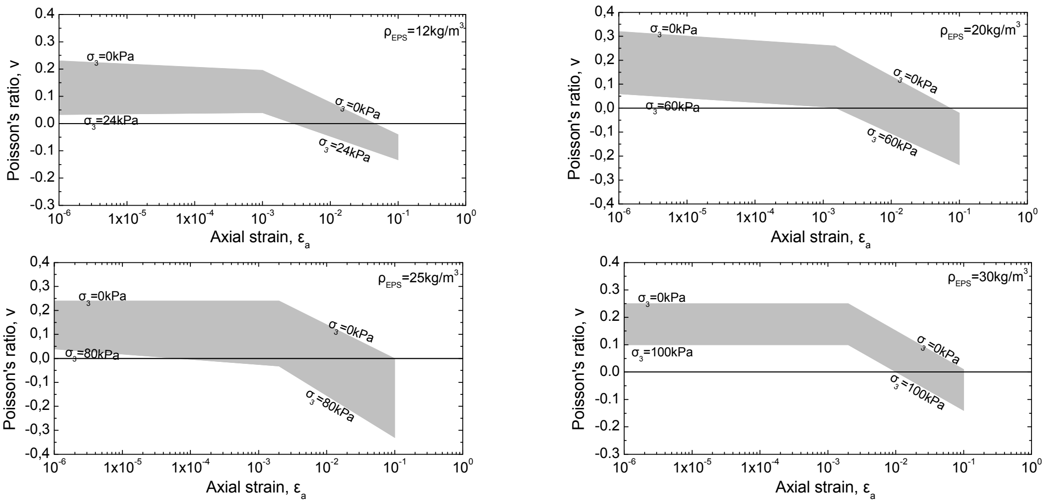

Figure 8. Poisson's ratio of EPS geofoam as a function of strain amplitude, confining pressure and material density (a synthesis of bender element and triaxial tests of the present study)

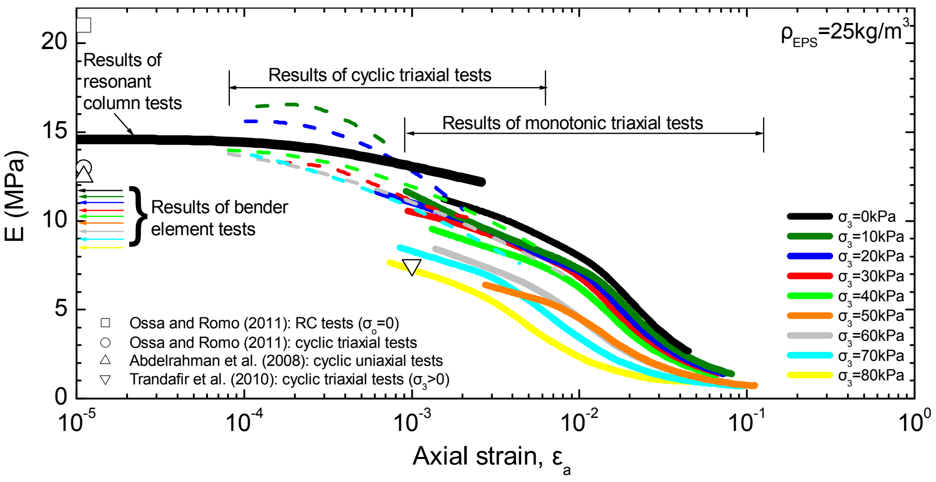

Figure 9. A synthesis of test results (for EPS geofoam elastic modulus) and comparison with published results for ρ_{EPS}=25kg/m^3

DISCUSSION

The results of the laboratory testing of the present study indicate that for stains less than 10^{-4} (0.01%) (small strains) the mechanical behavior of EPS geofoam is linear (i.e. independent of strain magnitude), whereas for strains ranging from 10^{-4} to 10^{-3} the behavior is approximately linear (i.e. the deviation from the linear behavior is less than 10%). For strains greater than 10^{-3} (0.1%) (large strains) the behavior is non-linear and the dependence of dynamic properties on strain should be taken into account.

It is worth mentioning that the relations for estimating the E_{EPS} and the ratio E/E_o-ε_α proposed in the present study have been found to be in excellent agreement (Athanasopoulos and Xenaki 2008) with results of field measurements in full scale structures (reported by Negussey 2007) as well as with measurements performed in shaking table physical model testing (reported by Zarnani and Bathurst 2007). The relations proposed for estimating the Poisson's ratio are, also, in fair agreement with published results (being somewhat overpredictive in the case of small strains) (Abdelrahman et al. 2008b). In the case of damping ratio, the relations proposed in the present study are in agreement with the experimental results of Ossa and Romo (2011); hoewever contradicting results have been recently published by Trandafir et al. (2010).

Finally, of great interest is the finding that the dynamic properties of EPS geofoam are dependent on the mode of loading (compressive vs. distorsional).

CONCLUSIONS

The static and dynamic properties of EPS geofoam (compressive resistance, elastic moduli, damping ratio and Poisson's ratio) depend mainly on material density, mean confining pressure and amplitude of deformation. Empirical relations are proposed for estimating values of these properties. A comparison with other published data shows, in general, a satisfactory agreement, with the exception of some recent findings on the damping ratio vs. strain relationship. Further research on the subject is necessary to shed light into this aspect of energy dissipation behavior.

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