AN INVESTIGATION OF EPS GEOFOAM BEHAVIOR IN COMPRESSION

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ABSTRACT

Unconfined, constrained (uniaxial), and triaxial compression tests were conducted on EPS geofoam samples with densities ranging from 10kg/m^3 to 35kg/m^3 which were obtained from commercially produced blocks. All tests are interpreted in terms of yield stress, compressive strength (at 10% axial strain) and initial modulus of elasticity values. The results obtained from unconfined compression tests, indicate that sample type (cube or cylinder), aspect ratio (0.5, 1.0, 2.0) and size (100x10^{3}mm^3 to 12000x10^{3}mm^3) have relatively insignificant effects on measured yield stress and compressive strength. Initial modulus of elasticity values are observed to increase significantly with increasing sample volume (up to 100% compared to 50mm cubes). Constrained compression tests indicate that EPS geofoams do not exhibit lateral expansion during compression. Quantified on the basis of triaxial compression tests, Poisson's ratio decreases continuously and attains negative values near the elastic strain limit. At higher stress levels, the behavior of all EPS geofoams tested is definitely contractive. EPS geofoam samples tested in triaxial compression exhibit a "softer" behavior (lower yield stress, compressive strength and modulus of elasticity) compared to similar samples tested in unconfined compression.

KEYWORDS: EPS geofoam, compression, unconfined, constrained, triaxial, volume change, Poisson ratio

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INTRODUCTION

Expanded polystyrene (EPS geofoam) products in the form of blocks or plates are utilized for the construction of a variety of projects as light-weight material or compressible inclusion (i.e. Frydenlund and Aaboe, 1988; Yeh and Gilmore 1992; Horvath, 1995; Beinbrech, 1996; Van Dorp, 1996; Negussey and Sun, 1996; Horvath, 1997; Geotech, 1998; Negussey, 1998). For the design of structures where volumes of EPS geofoam are incorporated, it is necessary to have appropriate information on the behavior of EPS geofoam in compression. Most of the available design parameters are obtained from unconfined compression tests on small-size samples (50mm cubes). The properties used to define the shape of the stress-strain curves obtained from unconfined compression tests are the initial modulus of elasticity, E_i (slope of the initial linear segment of the stress-strain curve), the compressive strength, σ_{c10} (usually defined as the axial stress at 10% axial strain) and the yield stress, σ_y (point of intersection of the initial linear segment and a second linear segment of the stress-strain curve). An objective of numerous past experimental investigations was the establishment of correlations between these properties and the nominal density of EPS geofoam blocks (Magnan and Serratrice, 1989; Eriksson and Trank, 1991; Horvath, 1995; Negussey and Sun, 1996; Duskov, 1997). Rather limited information is available on the effects of testing parameters on properties measured by unconfined compression testing, as well as on the behavior of EPS geofoam in triaxial compression (Duskov, 1997).

Due to the nature of many construction projects, EPS geofoam is expected to function in compression under lateral constrain or in a triaxial stress field. Furthermore, due to the size of the blocks or thick plates used, properties obtained from small-size samples may not be representative of the behavior of EPS geofoam in the field. The information presented herein is part of an extensive experimental investigation of the mechanical properties and behavior of commercially produced EPS geofoam blocks. Scope of this presentation is to offer additional information on the behavior of EPS geofoam in compression and, more specifically, to present results of a parametric study on the behavior in unconfined compression and to compare the behavior in unconfined compression with the behavior in constrained (uniaxial) and triaxial compression.

MATERIALS AND EXPERIMENTAL PROCEDURES

Commercially produced EPS geofoam blocks measuring 2.5m X 1.0m X 0.5m were obtained for the purposes of the investigation reported herein. The blocks had a nominal density of 10, 15, 20, 25, 30 and 35kg/m^3. Three blocks were obtained for each nominal density and each block was cut into three approximately equal-sized parts along the length of the block. Because it is generally expected that EPS geofoam blocks are nonhomogeneous with respect to density (Horvath, 1995), samples were obtained from the central as well as from the end portions of each block. Samples are referred to in this text using the symbol EPS and the nominal density (i.e. EPS 15). The range of density values and the mean density value for all EPS geofoam samples tested are presented in Table 1. It should be mentioned that EPS10 included some recycled material and this may explain some of the observed scatter of the experimental results to be presented. A minimum of five samples was tested for each test parameter combination and average values were obtained for each material property as well as for the stress-strain curve. It should be noted that the shape of the stress-strain curves was corrected at very low strain levels in order to exclude seating problems. All EPS geofoam samples were cut and shaped using hot wires as shown in Figure 1. Also presented in Figure 1 are some photographs from unconfined, constrained (uniaxial) and triaxial compression tests.

Unconfined compression tests were conducted in order to evaluate the effect of sample geometry on the observed behavior of the EPS geofoams. Accordingly, the following series of samples were prepared and tested: (a) 50mm, 100mm and 150mm cubes, (b) 50mm, 100mm, 150mm and 250mm cylinders with aspect ratio equal to 1.0, (c) prisms with 100mm x 100mm cross-section and aspect ratio of 0.5, 1.0 and 2.0, and (d) cylinders with 100mm diameter and aspect ratio of 0.5, 1.0 and 2.0. All tests were conducted at a strain rate of 10%/minute.

Constrained uniaxial compression tests were conducted on cylindrical samples with a diameter of 150mm and an aspect ratio of 1.0. The samples were confined within an aluminum mold and were tested at a strain rate of 10%/minute. Since lateral strains could not be measured, the results of these tests can be compared to results obtained from unconfined compression tests on similar samples only in terms of stress-strain curve shape (yield stress, compressive strength and initial modulus of elasticity values).

Triaxial compression tests were conducted on cylindrical samples with diameter equal to 50mm and aspect ratio equal to 2.0. Testing procedures were similar to those used for testing soils. The samples were confined in a thin membrane and the triaxial testing chamber (cell) was filled with water. Initially, the samples were loaded in hydrostatic compression by applying cell pressure. Three different cell pressures were used for each EPS geofoam, corresponding approximately to 20%, 40% and 60% of the geofoam yield stress. Then the samples were "sheared" by increasing the axial load, at a strain rate of 1%/minute, until a substantial axial deformation (over 30%) was reached. During both loading stages of each test, the air in the voids of the samples was allowed to "drain". The volume change of the sample was recorded continuously during both loading stages in order to have appropriate information for the computation of average lateral strains. Unconfined compression tests were also conducted using samples of the same size and at a strain rate equal to 1%/minute in order to facilitate comparison with results from triaxial testing.

UNCONFINED COMPRESSION

All results obtained from unconfined compression tests on 50mm cubes and on cylinders with diameter and aspect ratio equal to 50mm and 1.0, respectively, are presented in Figure 1. Using a linear correlation as a good first order approximation, it can be observed that samples with cylindrical form are characterized by yield stress, compressive strength and initial modulus of elasticity which have consistently lower values than those obtained for cubic samples. For yield stress and compressive strength these differences are between 7% and 18%. However, the difference is more pronounced (13% to 54%) for the initial modulus of elasticity. Similar observations were made when comparing the results obtained from tests on 100mm and 150mm cubes with results obtained from cylinders with diameter of 100mm and 150mm and aspect ratio equal to 1.0.

Presented in Figure 2a are the results obtained from tests on cylindrical samples with aspect ratio equal to 1.0 and diameter equal to 50mm, 100mm and 150mm. The results obtained from tests on 50mm cylinders are considered as "base-line" or "reference" values, R_{ref}, and the percent deviation from the reference values is computed as: $[(R_i-R_{ref})/R_{ref}]x100$ where R_i is the corresponding value obtained from another test. It can be observed that both yield stress and compressive strength increase with increasing sample size, but, this increase is small and ranges between 0.7% and 7.3% and between 4.1% and 8.8%, respectively, for the two properties. However, a significant increase in the value of the initial modulus of elasticity is observed with increasing sample size. For all nominal densities tested, an increase of sample diameter from 50mm to 100mm and from 50mm to 150mm results in an average increase of the modulus of elasticity by 60% and 95%, respectively. It should be noted that available information suggests that it is not unusual to observe significant differences in measured initial modulus of elasticity between samples obtained from the same product or block (Magnan and Serratrice, 1989; Eriksson and Trank, 1991; Horvath, 1995; Van Dorp, 1996). These differences can be up to ±0.5MPa for low density samples and up to ±1.5MPa for high density samples. If these maximum variations are considered and applied to the average measured values of the initial modulus of elasticity for all nominal densities, it is computed that the percent deviation from reference values should be between ±25% and ±40%. Accordingly, the significant increase in measured initial modulus of elasticity values can be attributed to the effect of sample size.

The results obtained from tests on cylindrical samples with a diameter of 100mm and aspect ratio 0.5, 1.0 and 2.0 are presented in Figure 2b. The results obtained from tests on samples with an aspect ratio equal to 1.0 are considered as reference values in order to compute the percent deviation. A regular trend can not be observed for the variation of yield stress and compressive strength as a function of aspect ratio. For nominal densities between

15kg/m^3 and 30kg/m^3, the computed deviations range between ±10%. However, a distinct trend is observed for the values of the initial modulus of elasticity which increase with increasing sample aspect ratio. A reduction of the aspect ratio from 1.0 to 0.5 yields reductions in the modulus of elasticity by 15% to 62% and an increase of the aspect ratio from 1.0 to 2.0 yields increases of 24% to 90%. These deviations can not be attributed solely to the expected differences between samples of the same product or block and may be due in part to the effect of changes in sample size, associated with changes of the aspect ratio, as well as to the aspect ratio itself.

The foregoing information and observations indicate that, in addition to the anticipated scatter of data due to density deviation from nominal values, the results of unconfined compression tests are affected by the volume as well as by the aspect ratio of the samples tested. In order to provide a comprehensive presentation of the combined effects, of density scatter, sample volume and sample aspect ratio, all available results were plotted, in a rather nonconventional manner, as a function of sample weight (Figure 3). Linear correlations used to fit these data, yielded correlation coefficients, R^2, from 0.961 to 0.990 for yield stress and compressive strength and from 0.840 to 0.924 for initial modulus of elasticity. However, such lines yield a negative intercept on the y-axis, that is, they have a disadvantage in terms of physical interpretation. Furthermore, visual observation of the data indicates a deviation from linearity at the low density range. Accordingly, the power curves ($y=ax^b$) shown in Figure 3 were used to correlate the available data, yielding correlation coefficients between 0.946 and 0.983 for yield stress and compressive strength and between 0.823 and 0.933 for initial modulus of elasticity.

The correlations shown in Figure 3 were used to obtain the “normalized” results shown in Figure 4 by introducing both nominal density and nominal volume of samples. Using property values of 50mm cubes (with 125×10^3mm volume and at nominal densities) as reference values, it can be observed that a decrease of this volume by 20% results in a decrease of yield stress and compressive strength by 5% to 15% and in a decrease of initial modulus of elasticity by 26% to 30%. The effect is more pronounced for low density than for high density geofoam. It can also be observed that increasing the sample volume by up to two orders of magnitude ($125 \times 10^3 mm^3$ to $12272 \times 10^3 mm^3$) the yield stress values increase by 2% to 18%, the compressive strength values increase by 5% to 17% and the initial modulus of elasticity values increase by 49% to 66%. The rate of increase is more pronounced for volume increase of up to one order of magnitude approximately. It can further be observed that testing of short samples (aspect ratio 0.5) or tall samples (aspect ratio 2.0) yields underestimations and overestimations, respectively, of all three material properties. This effect is significant for the initial modulus of elasticity (-47% to –56% and +20% to +102%).

CONSTRAINED (UNIAXIAL) COMPRESSION

Presented in Figure 5 are the average stress-strain curves obtained from constrained (uniaxial) compression tests and from unconfined compression tests on cylinders with diameter and aspect ratio equal to 150mm and 1.0, respectively. Summarized in Table 2, are the results obtained for yield stress, compressive strength and initial modulus of elasticity. It can be observed that there are no significant differences between the results obtained from the two types of tests. With the exception of EPS 10, the yield stress, compressive strength and initial modulus of elasticity values obtained from constrained compression range from 88% to 106%, from 83% to 104% and from 81% to 103%, respectively, of the values obtained from unconfined compression. The larger variations measured for EPS 10 may be attributed to true density effects. These observations indicate that there is a negligible, if any, interaction between the wall of the aluminum mold and the cylindrical surface of the EPS geofoam samples. Accordingly, it can be postulated that the samples tested exhibited negligible or no lateral expansion during application of the axial compressive load. This effect is quantified by measurements made during triaxial compression tests.

TRIAXIAL COMPRESSION

Each triaxial compression test had two loading stages. During the first loading stage, the samples were subjected to hydrostatic compression (similar to the consolidation stage of tests on soil samples) and their volume change was measured. Based on these measurements, Poisson ratio values were computed according to established formulations (Timoshenko and Goodier, 1970) and are presented in Table 3. The required modulus of elasticity values were obtained from unconfined compression (σ_3=0) tests. Similarly, the limit of elastic strains shown in Table 3 was obtained from unconfined (σ_3=0) compression tests. As expected, increasing cell pressures result in increasing computed axial strains. It can be observed that the computed values for Poisson ratio are positive (not exceeding 0.25) when the axial strains are well below the elastic strain limit. As the elastic strain limit is approached, Poisson ratios decrease and attain zero or negative values at approximately the elastic strain limit. Beyond this limit, Poisson ratio values are negative and for most tests range between –0.09 and –0.29. It also appears that EPS geofoams of higher density reach negative Poisson ratio values at lower axial strains than EPS geofoams of lower density.

Typical results depicting the behavior of all samples during the second loading stage of the triaxial compression tests (application of axial load or deviatoric stress) are presented in Figure 6 and confirm the contractive behavior of EPS geofoams at high axial strains (beyond the elastic limit). It can be observed that, regardless of cell pressure, σ_3, (hydrostatic compression), increasing axial strains are associated with continuously decreasing total sample volume (ΔV_{total}). It can further be observed that computed volume change due to axial deformation (ΔV_{axial}) is always smaller than the total volume change. Accordingly, the average lateral strains during this loading stage are definitely contractive. These arguments are qualitative since Poisson ratio values should not be computed for strains higher than the limit of elastic behavior.

The typical stress-strain curves shown in Figure 6 depict the behavior of EPS geofoam samples which have been subjected to hydrostatic compression before the application of increasing deviatoric stress. Under these conditions, it was observed that all samples tested exhibited a “softer” behavior than similar samples tested in unconfined compression (lower yield stress, compressive strength and modulus of elasticity). However, this trend is significantly eliminated if the complete stress history of the samples is considered by adding an initial segment to the stress-strain curves which corresponds to the hydrostatic compression stage of loading (i.e. plotting overall axial stress versus overall axial strain). Presented in Table 4 are results obtained from such stress-strain curves. It can be observed that for initial loading (hydrostatic compression) well within the elastic range of each geofoam sample (15kPa to 25kPa or 8% to 26% of the yield stress), yield stress, compressive strength and modulus of elasticity values have, in most cases, minor differences from those obtained from unconfined compression tests. However, as the initial hydrostatic compression stress increases, these differences become significant, especially for the values of the modulus of elasticity.

SUMMARY

Based on the results of the experimental investigation reported herein, the following conclusion can be advanced:

1. Results obtained from unconfined compression tests can be considered to represent adequately the mechanical behavior of EPS geofoams in applications where the materials are subjected to normal stresses well below their yield stress or even their elastic strain limit. When a more complex stress history is applied, such as that of consolidation under hydrostatic compression followed by shearing due to increased axial load, EPS geofoams may exhibit a significantly “softer” behavior than in unconfined compression.
2. Shape, size and aspect ratio of EPS geofoam samples tested in unconfined compression have relatively insignificant effects on measured yield stress and compressive strength, and testing of 50mm cubes appears to be satisfactory. However, size and aspect ratio have a significant effect on the initial modulus of elasticity which attains higher values (up to 100%) when the sample volume is one order of magnitude larger than the

"conventional" 50mm cube. When results from testing 50mm cubes are used for design purposes, expected strains or deformations may be overestimated by a factor of 2.

3. At low stress levels, characteristic of light-weight fills, the Poisson ratio of EPS geofoams may attain negative values as axial strains increase toward the elastic strain limit. Beyond this limit, EPS geofoams exhibit contractive behavior.

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Table 1. Properties of EPS geofoam blocks

Geofoam	Density (kg/m^3)			
	Nominal	Min. Value	Max. Value	Mean
EPS 10	10	8.87	12.78	9.98
EPS 15	15	13.74	18.74	15.07
EPS 20	20	17.51	23.04	19.90
EPS 25	25	20.39	27.91	24.20
EPS 30	30	25.37	47.88	31.74
EPS 35	35	30.60	45.85	36.39

Table 2. Comparison of results obtained from unconfined and constrained compression tests

Geofoam	Yield stress, σ_y (kPa)		Compressive strength, σ_{c10} (kPa)		Initial modulus of elasticity, E_i (kPa)	
	Unconfined	Constrained	Unconfined	Constrained	Unconfined	Constrained
EPS 10	32.5	27.0	43.0	36.5	1460	1010
EPS 15	66.0	62.0	78.5	77.0	3150	2720
EPS 20	78.0	69.0	94.0	78.0	5040	4770
EPS 25	146.0	155.5	161.5	167.5	7510	6050
EPS 30	162.0	167.5	175.0	180.0	7330	5930
EPS 35	233.0	230.0	256.0	256.0	7510	7760

Table 3. Poisson ratio values from hydrostatic compression stage of triaxial compression tests

Geofoam	Density, ρ (kg/m^3)	Cell Pressure, σ_{is} (kPa)	Axial strain, ε_{is} (%)	Poisson ratio, ν	Elastic Strain limit[1] (%)
EPS 15	14.56	15, 25, 40	0.50, 0.88, 5.11	0.10, 0.00, -0.80	0.81
EPS 20	20.01	15, 25, 50	0.28, 2.86, 2.38	0.05, -0.29, -0.21	0.65
EPS 25	25.27	15, 25, 40	0.14, 0.38, 1.02	0.22, 0.17, -0.09	0.82
EPS 30	29.82	25, 40, 40	0.22 0.42, 0.98	0.25, 0.14, -0.21	0.85
EPS 35	34.23	10, 30, 45	0.12, 0.37, 0.91	0.00, -0.03, -0.17	0.55

[1] Obtained from unconfined compression tests

Table 4. Comparison of results obtained from unconfined and triaxial compression tests

Geofoam	Yield stress, σ_y (kPa)		Compressive strength, σ_{c10} (kPa)		Initial modulus of elasticity, E_i (kPa)		Range of σ_3
	Unconfined	Triaxial	Unconfined	Triaxial	Unconfined	Triaxial	
EPS 15	58.0	55.0-51.4	64.0	70.2-66.0	3536	2380-1960	15-40
EPS 20	76.0	78.0-74.5	83.0	100.0-90.0	3850	3670-2100	15-50
EPS 25	138.0	176.0-133.0	145.0	186.0-158.0	6850	6720-3400	15-40
EPS 30	160.0	169.0-140.0	168.0	151.0-131.0	7910	6780-6590	25-40
EPS 35	198.0	192.0-165.0	212.0	211.0-182.5	10900	10790-10680	15-45

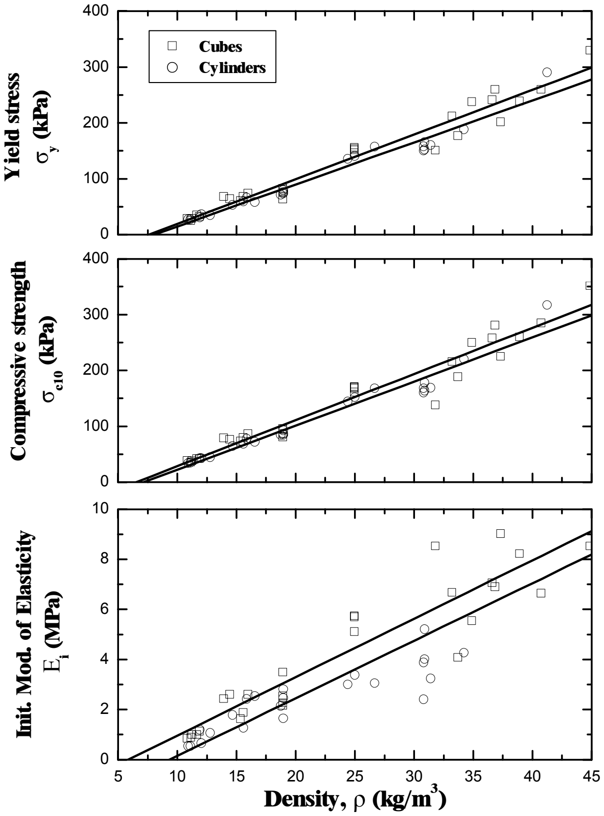

Figure 1. Results from unconfined compression tests on 50 mm cubes and cylinders

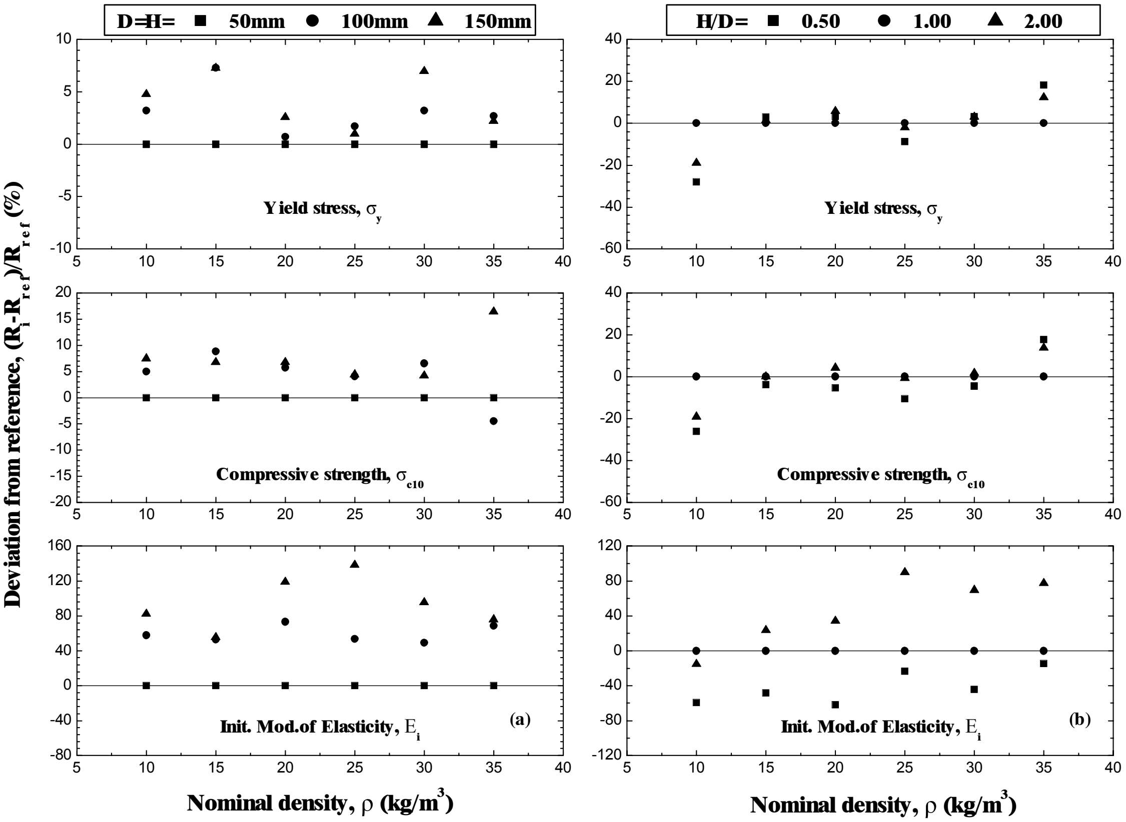

Figure 2. Effect of (a) sample size and (b) sample aspect ratio on unconfined compression test results

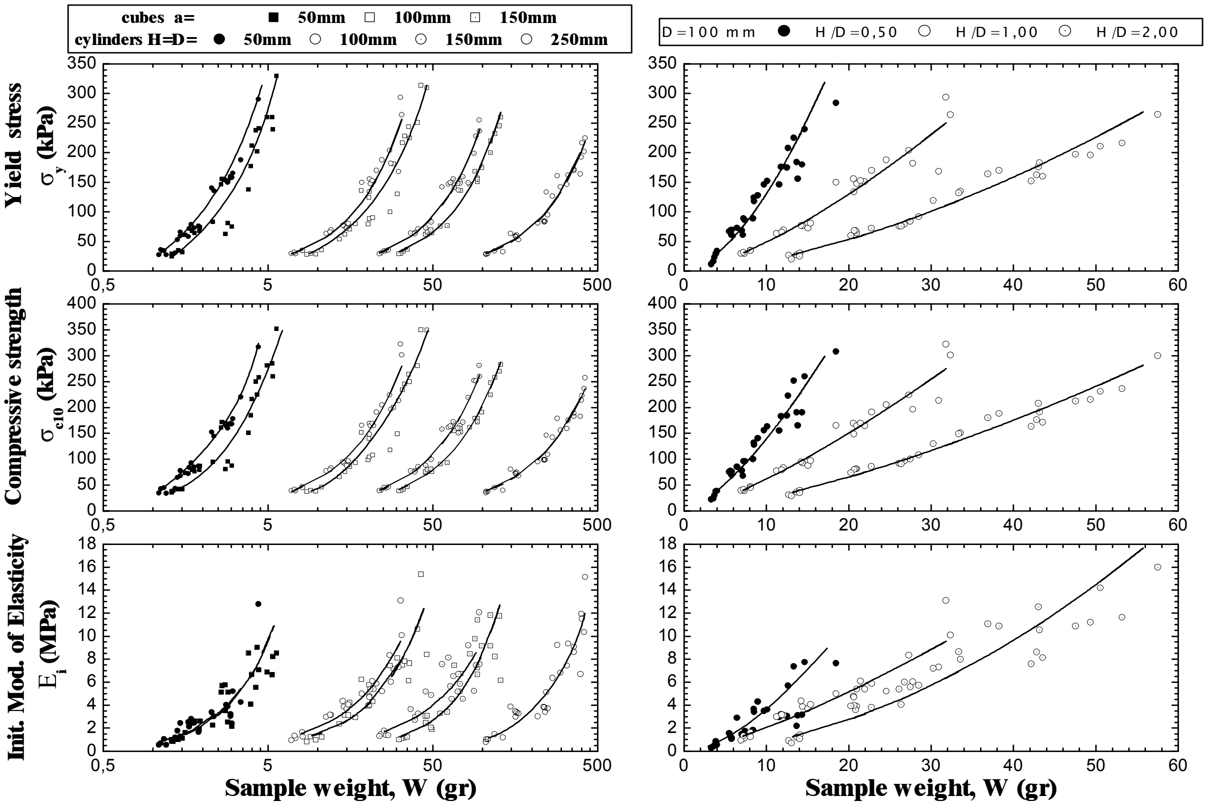

Figure 3. Combined sample density and volume effects on unconfined compression test results

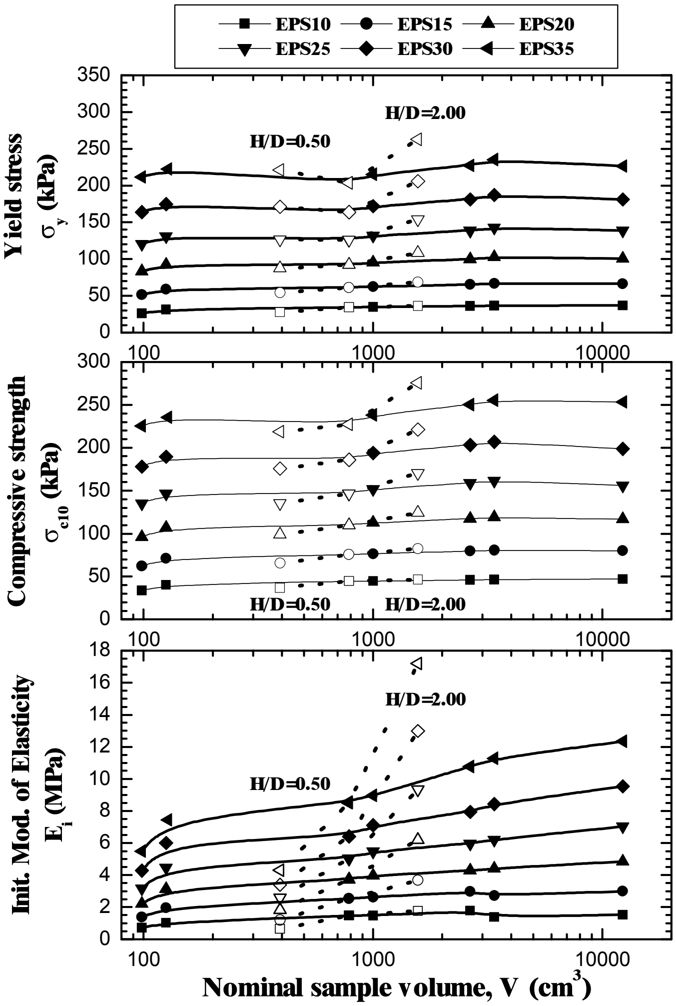

Figure 4. Effect of sample size and aspect ratio on results obtained from unconfined compression tests

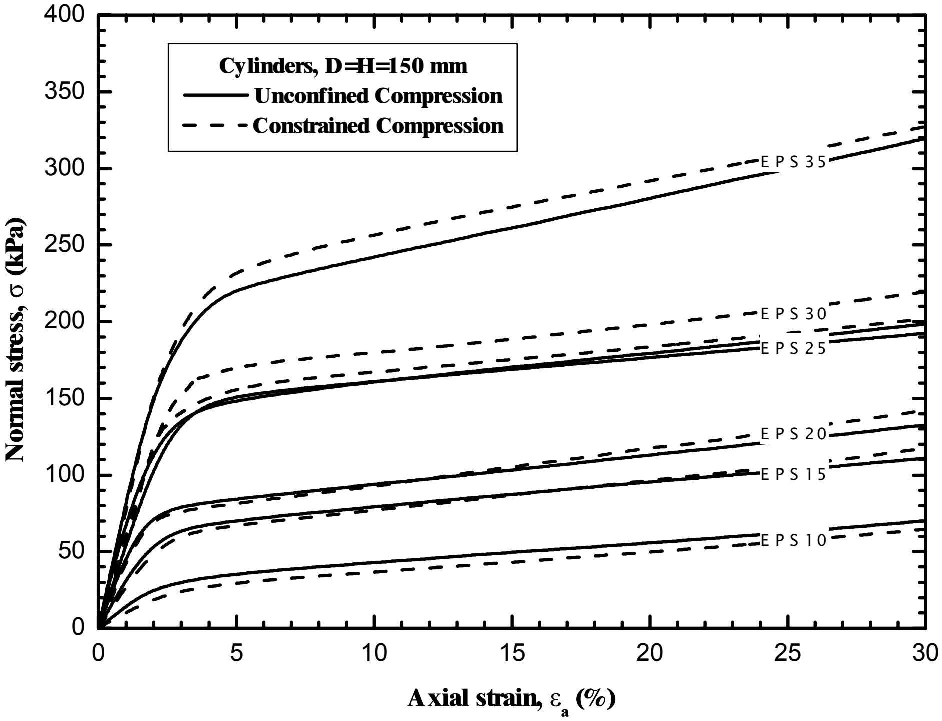

Figure 5. Average stress-strain curves obtained from unconfined and constrained compression tests

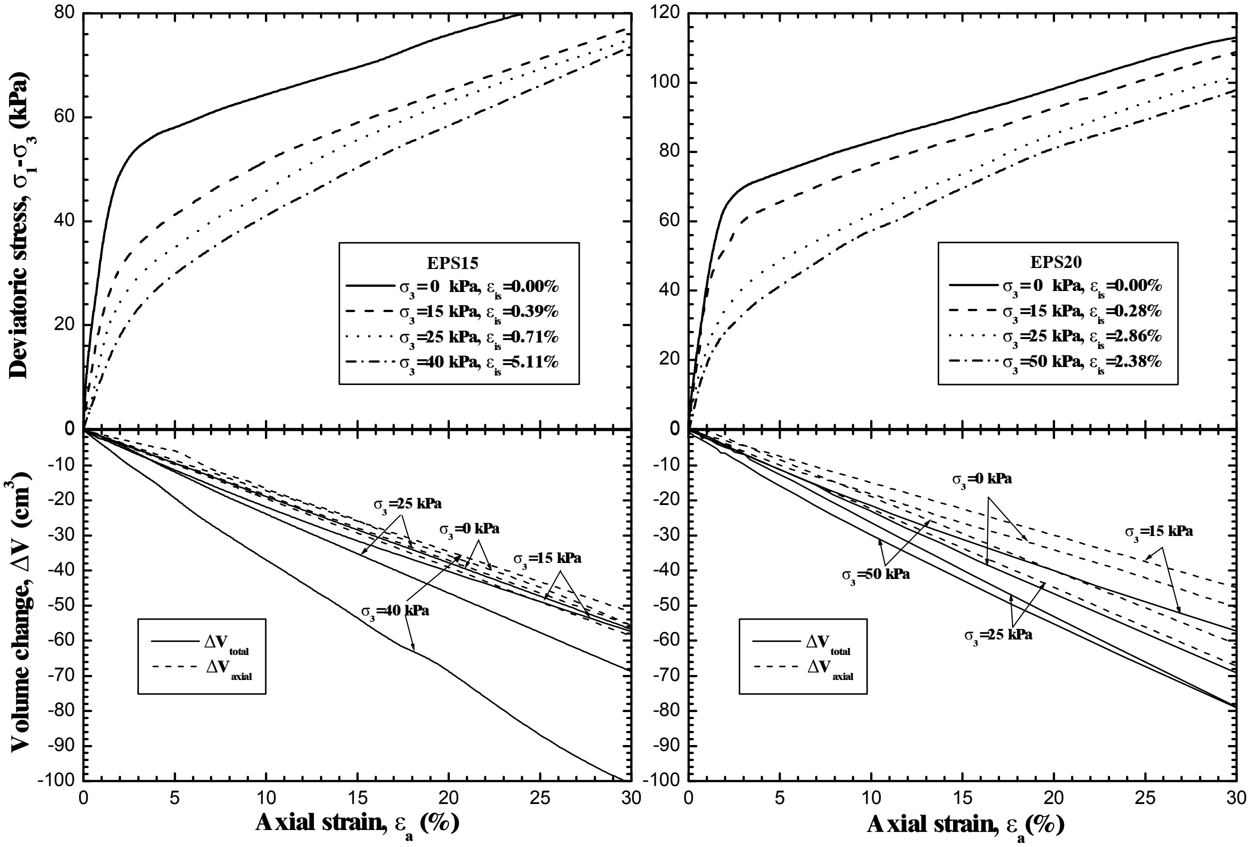

Figure 6. Average stress-strain curves obtained from triaxial and unconfined compression test