EFFECT OF CONFINING STRESS ON COMPRESSIVE STRENGTH OF EPS GEOFOAM

N. Anasthas[1], D. Negussey[2] and S. Srirajan[1]

ABSTRACT

EPS geofoam has been used in many geotechnical applications for about 30 years in many countries around the world. It has been used for backfilling retaining walls and embankments both with vertical and sloped sides. The behavior of EPS in compression is a function of density, strain rate and sample size. EPS blocks may experience lateral pressures due to soil and or hydrostatic pressure. Confined compressive performance of EPS geofoam should be considered in designing these types of applications. Triaxial tests were performed on cylindrical EPS samples of two different densities. To investigate the effect of confining stress on compressive resistance, tests were performed at different confining stress levels and duration of confinement. Results show that the compressive resistance of EPS geofoam reduces with increasing confining stress. Duration of confinement has no significant effect on compressive strength or Young's modulus of EPS geofoam at low confining stress levels. However, the compressive strength and initial Young's modulus significantly drop at confining stress levels closer to the unconfined compressive strength of the material. The effect of duration of confinement is minimal for durations greater than 3 hours. The initial Young's modulus reduces with increasing confining stress while the post yield modulus slightly increases.

KEY WORDS: compression, EPS geofoam, hydrostatic, modulus, strength, stress-path, triaxial

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BACKGROUND

The use of EPS geofoam is rapidly increasing in the United States and many other countries. Information about the engineering properties of EPS geofoam is essential for design and construction. Compressive resistance and Young's modulus are important engineering properties when considering EPS geofoam as a lightweight soil substitute material. Elragi et al (2000), Duškov (1997) and Eriksson and Trank (1991) among others have shown that the compressive strength of EPS geofoam is a function of density, strain rate, and sample size. Creep deformations can become excessive as working loads approach threshold compressive stress levels. Sun (1997) and Preber et al (1994) noted some reduction in compressive strength with increasing confining stress.

Elragi (2000) performed a series of unconfined compression tests to investigate the effect of sample size, density, and strain rate. Small 50 mm and large 600 mm cubic EPS samples of 15 kg/m^3 density (EPS15) were monotonically compressed at a strain rate of 10% per minute. The compressive resistance for 50 mm cube samples at 1% axial strain was about 35% lower than that of the 600 mm cube samples (Figure 1). However, the compressive resistance at 5% and 10% axial strains for both small and large samples was about the same. Small 50 mm cubic samples of five different densities were monotonically compressed in a strain-controlled mode. The tests were performed at strain rates of 100, 10, 1, 0.1, and 0.01%/min. The following relationships were derived for compressive resistance of EPS materials as a function of strain rate (R in %/min) and density (D in kg/m^3).

Compressive strength at 10% strain $\sigma_{10\%} = 7.3\ R^{0.04}\ D - 35$ **Equation 1**

Compressive strength at 5% strain $\sigma_{5\%} = 6.6\ R^{0.04}\ D - 35$ **Equation 2**

Compressive strength at 1% strain $\sigma_{1\%} = 3.5\ R^{0.01}\ D - 22$ **Equation 3**

Compressive strength of EPS geofoam used in design is only a fraction of compressive strength at 5% strain in order to limit long-term time dependant deformations. If the working stresses within the EPS blocks are kept below the factored stress level, then the time-dependant effects are either negligible or at least within some limit considered acceptable for the given project. Sun (1997), Sheeley (2000), Anasthas (2001) and Srirajan (2001) performed creep tests on 50 mm geofoam cubes. Nominal stress levels representing 30%, 50%, and 70% or 80% of the compressive strength were applied. Results show that creep deformation can be considered negligible for stress levels less than 30% of the compressive strength at 5% strain. If geofoam is exposed to loads greater than 50% of the compressive strength at 5% strain, larger creep deformations occur as was also noted by van Dorp (1988) and Duškov (1997).

Preber et al (1994) performed a series of confined compression tests on EPS geofoam. Samples of 16, 20, 24, and 32 kg/m^3 density were tested at confining stress levels of 0, 21, 41, and 62 kPa. Results indicated that both initial and post-yield modulus increase with density. The rate of increase was lower for post-yield modulus. Compressive resistance increased with density but decreased with confining stress. With increasing confining stress, the initial modulus decreased but post-yield modulus slightly increased. The following stress-strain relationship in terms of density and confining stress was proposed.

$$\sigma = (I + E_p\varepsilon)\left[1 - \exp\left(-C\varepsilon^2 - \frac{E_i\varepsilon}{I}\right)\right]$$ **Equation 4**

$$C = -\frac{E_i}{IX_0} - \frac{1}{X_0^2}\ln\left[1 - \frac{Y_0}{(I + E_pX_0)}\right]$$ **Equation 5**

Where, σ is axial stress and ε is axial strain. C is expressed in terms of initial modulus E_i, post-yield modulus E_p, intersection of axial stress axis and the plastic tangent line I, strain corresponding to the intersection point of elastic tangent and plastic tangent X_0, and Y_0, the stress corresponding to X_0. Preber et al determined these parameters from the stress-strain curves and plotted against confining pressure for each density.

Data provided by Preber el al was used to obtain generalized equations for each parameter as follows:

$$I = (-107 + 910\gamma) + (0.63 - 6.32\gamma)\sigma_3 \qquad \textbf{Equation 6}$$

$$E_i = (-4{,}180 + 39{,}000\gamma) + (-6.2 - 53\gamma)\sigma_3 \qquad \textbf{Equation 7}$$

$$E_p = (85.5 + 638\gamma - 403\gamma^2) + (-3.4 + 28.4\gamma)\sigma_3 \qquad \textbf{Equation 8}$$

$$Y_0 = (-119.4 + 924\gamma) + (0.962 - 7.5\gamma)\sigma_3 \qquad \textbf{Equation 9}$$

X_0 can be determined analytically from E_i, E_p, and I;

$$X_0 = \frac{I}{(E_i - E_p)} \qquad \textbf{Equation 10}$$

Where, σ_3 is confining stress in kPa and γ is density in kN/m^3.

Stress-strain curves obtained using the above equations were found to match with the corresponding curves provided by Preber et al (1994). Confined compressive strength at 5% strain given by this relationship was found to be about 25% lower than the values reported by Sun (1997). Results also indicate that Equation 4 is not valid for densities lower than 16 kg/m^3.

Sun (1997) performed a series of triaxial compression tests to investigate the effect of confining stress on compressive strength of EPS geofoam. Constant strain rate testing was carried out on geofoam samples in a triaxial cell at 0, 34.5, and 68.9 kPa confining stress levels. For each stress level, several tests were performed on samples with densities 14.4, 20.8, and 22.4 kg/m^3. Samples were loaded at a constant strain rate of 10% per minute. Test results showed that both the initial and, to a much less extent, the post yield modulus for EPS geofoam increased with density. The initial modulus decreased with increasing confining pressure while the post yield modulus slightly increased, especially for higher density samples. The compressive strength at 1% and 5% strains also decreased with increasing confining pressure. Compressive strength at 5% strain of a sample of 14.4 kg/m^3 density under zero confinement was approximately 65 kPa. The compressive strength of the same density material at 68.9 kPa confinement was approximately 28 kPa. The reduction of compressive strength is more than 57% as the confining stress increased from zero to 68.9 kPa. Such compressive strength reduction was evident linearly in the density range of 14 – 23 kg/m^3 that was investigated. Table 1 summarizes the findings of the above study. The following equation was derived for compressive strength of EPS geofoam as a function of density (D in kg/m^3) and confining stress (σ_3 in kPa).

Compressive strength at 5% strain $\qquad \sigma_{5\%} = 6.52\ D - 0.62\ \sigma_3 - 26.8 \qquad$ **Equation 11**

The past work on investigating the effect of confining stress on compressive strength of EPS geofoam is very limited compared to the importance and possible implications of the knowledge of compressive strength in field conditions. Further research has been done at the Geofoam Research Center, Syracuse University, to provide improved understanding of compressive strength of EPS geofoam under confinement. The results reported in this paper cover the effect of confinement and duration of confinement on EPS geofoam compression behavior.

TESTING

Tests were performed on samples of 16 and 26 kg/m^3 nominal density at confining stress levels ranging from 0 to 100 kPa with duration of confinement of 0, 3 and 24 hours. The duration of confinement is the period of sustained hydrostatic pre-compression prior to axial loading.

Geofoam cylinders of 16 and 26 kg/m^3 densities were factory cut to a nominal diameter and length of 76 mm and 915 mm, respectively. The long geofoam cylinders were cut to size using a hot wire saw to have an aspect ratio of two. The actual height and the diameter of each sample were measured using a digital caliper and weighed to determine the density. The densities of the samples were found to be between +/- 1.5% of nominal density attributed to the source block.

The experimental setup consisted of a uniaxial compression testing machine (Figure 2), a triaxial cell and accessories, a PC data acquisition system, a displacement transducer (LVDT), a load cell, and a pressure transducer. The load cell and the LVDT were mounted on the testing machine as shown in Figure 2 and connected to the computer through a signal-conditioning box. The pressure transducer was connected to the cell from an air/water interface reservoir and to the computer through the signal-conditioning box.

The cylindrical EPS samples were placed centrally on the base of the triaxial cell and the cell was filled with de-aired water. The sample was held in position by the top cap and loading rod, which was locked to prevent uplift on filling. The pressure line was connected to a bottom port of the cell to apply the appropriate pressure. The triaxial cell was placed on the base plate of the uniaxial compression-testing machine and the assembly was raised to make the loading rod come in contact with the load cell. Confining pressures were applied. The load cell reading and the LVDT readings were zeroed. Load was applied in a strain-controlled mode at a rate of 10% per minute. Load-displacement data were captured by the data acquisition system. The pressure transducer reading was monitored to make sure a constant confining pressure was sustained throughout the test.

RESULTS

The stress-strain curves for triaxial compression tests performed at 10 percent per minute strain rate on cylindrical samples of 16 kg/m^3 nominal density are shown in Figures 3 through 6. The unconfined compression strength at 5% strain is 78 kPa. The curves in Figures 3, 4, and 5 are corrected stress strain curves for test series with 0, 3 and 24 hours duration of confinement. The curves for tests with confining stress levels of 75 and 100 kPa showed initial axial strains of 1% and 9%, respectively, before the uniaxial compression was initiated. Figure 6 shows the trend of compressive strength reduction with increasing confining stress. There is a significant reduction in available compressive strength with increasing confining stress. Figure 6 also shows that the compressive strength is not affected by the duration of confinement when the confining stress levels are lower than the yield strength in unconfined compression. The following equations can be used to determine the compressive strength of EPS16 subjected to confining stress (σ_3 in kPa). These equations are valid for confining stresses less than the yield strength in unconfined compression. It is also evident from the stress strain curves that the initial Young's modulus significantly decreases with increasing confining stress while there is a slight increase in the post-yield modulus.

Compressive strength of EPS16 at 1% strain, $\sigma_{1\%} = -0.42\ \sigma_3 + 45.6$ **Equation 12**

Compressive strength of EPS16 at 5% strain, $\sigma_{5\%} = -0.66\ \sigma_3 + 78.8$ **Equation 13**

Compressive strength of EPS16 at 10% strain, $\sigma_{10\%} = -0.69\ \sigma_3 + 87.4$ **Equation 14**

Similar results obtained from triaxial tests on samples of 26 kg/m^3 nominal density are shown in Figures 7 through 10. Unconfined compressive strength at 5% strain is 155 kPa and the maximum confining stress used in the tests was 100 kPa. Initial axial strains due to hydrostatic pressure were not observed here. The trend of compressive strength and modulus variation with confining stress is similar to those for the lower density samples discussed above. Figure 10 shows the trend in compressive strength reduction with confining stress that can be represented by the following equations. Figure 10 also shows that the duration of confinement did not significantly affect the compressive strength, especially at lower confining stress levels. These equations are valid for confining stresses less than the yield strength of the geofoam in unconfined compression. The equations show that the rate of reduction in strength with confining stress is higher for lower density geofoam.

Compressive strength of EPS26 at 1% strain, $\sigma_{1\%} = -0.29\ \sigma_3 + 92.3$ **Equation 15**

Compressive strength of EPS26 at 5% strain, $\sigma_{5\%} = -0.62\ \sigma_3 + 155.5$ **Equation 16**

Compressive strength of EPS26 at 10% strain, $\sigma_{10\%} = -0.55\ \sigma_3 + 161.4$ **Equation 17**

Figures 11 and 12 present the total stress paths and failure envelopes in p, q space where $p = (\sigma_1 + 2\sigma_3)/3$ and $q = (\sigma_1 - \sigma_3)/2$. The behavior of geofoam with higher confining stress is opposite that of frictional materials like soils, and different from metals. Soils tend to increase strength with confining stress. Yield for metals is unaffected by confining stress levels. Figures 11 and 12 show a phenomenon of a negatively sloped failure envelope for EPS geofoam. Both 5% and 10% strain failure envelopes show similar trend with increasing confinement for samples from both densities. However, the 1% strain criteria envelope for low-density samples shows a mild slope and the envelope is flat for high-density samples.

Figures 13 and 14 present the initial and post-yield modulus values obtained from the triaxial compression tests. The initial and post-yield moduli increased with EPS density. For both densities, there was a significant reduction in initial Young's modulus and a slight increase in post-yield modulus with increasing confining stress. Duration of confinement had significant effect on initial Young's modulus while the post-yield modulus was relatively unaffected. There was a drop in initial Young's modulus with increasing duration of confinement and it increased with increasing confining stress. However, the effect of duration of confinement was minimal after 3 hours. In 24 hours, the drop in initial Young's modulus for confining stress levels above 50% of the unconfined compressive strength was more than 10% of the initial Young's modulus for 0 hour confinement. Figures 15 and 16 present the combination of density and confining stress effects on initial Young's modulus and post-yield modulus. The effect of density and confining stress on modulus is represented as a surface in three-dimensional space. The surfaces in the figures can be characterized by the following equations. The equations express the initial and post-yield modulus as a function of density (D in kg/m^3) and confining stress (σ_3 in kPa).

E_i (MPa) $= 0.0001\ D\sigma_3 + 0.008\ D^2 + 0.152\ D + 0.015 - 0.041\sigma_3 + 0.00006\ \sigma_3^2$ **Equation 18**

E_p (kPa) $= -0.01\ D\sigma_3 - 0.051D^2 + 9.566\ D + 0.966 + 1.812\ \sigma_3 - 0.005\ \sigma_3^2$ **Equation 19**

Figures 17 through 19 present the combination of density and confining stress effects on compressive strength. Compressive strength increases with density and decreases with confining stress and is represented as a surface in three-dimensional space. The surfaces in these figures can be characterized by the following equations. The equations express the compressive strength at 1, 5, and 10 % strains as a function of density (D in kg/m^3) and confining stress (σ_3 in kPa). Results from this study compare favorably with the previous work of Sun (1997). Table 2 compares the actual strength values obtained from the tests to values calculated using Equation 21, Equation 11 reported by Sun (1997) and Equation 4 reported by Preber et al (1994).

$\sigma_{1\%}$ (kPa) = $0.01\ D\sigma_3 + 0.064\ D^2 + 1.84\ D + 0.186 - 0.521\sigma_3 - 0.0002\ \sigma_3^2$ **Equation 20**

$\sigma_{5\%}$ (kPa) = $0.01\ D\sigma_3 + 0.065\ D^2 + 4.144D + 0.418 - 1.085\ \sigma_3 + 0.002\ \sigma_3^2$ **Equation 21**

$\sigma_{10\%}$ (kPa) = $0.009\ D\sigma_3 + 0.078\ D^2 + 4.218\ D + 0.426 - 0.949\ \sigma_3 + 0.001\ \sigma_3^2$ **Equation 22**

CONCLUSIONS

- Compressive strength of EPS geofoam is a function of density, strain rate, sample size, and confining stress. Compressive strength can be expressed as a function of density and confining stress.

- The failure envelope for EPS geofoam is negatively sloping. The failure envelopes for 5% and 10% strains are close and parallel to each other for both lower and higher density EPS. However, the failure envelope for 1% strain for the lower density shows a mild slope while that for the higher density remains flat.

- There is only a slight drop in compressive strength with increasing duration of confinement for lower confining stress levels. The effect of duration of confinement is minimal after 3 hours. When the confining stress is less than 50% of the unconfined compressive strength the drop in compressive strength is less than 5%. However, at higher confining stress levels the compressive strength drops significantly with increasing duration of confinement. The drop in compressive strength in 24 hours for EPS26 at 100 kPa was about 10%.

- Both initial Young's modulus and post-yield modulus of EPS geofoam increase with increasing density. The initial Young's modulus reduces with increasing confining stress while the post-yield modulus slightly increases. Duration of confinement significantly reduces the initial Young's modulus while post-yield modulus is unaffected. The effect of duration of confinement is minimal after 3 hours. Initial Young's modulus drops by more than 10% in 24 hours for confining stress levels above 50% of unconfined compressive strength. Both initial Young's modulus and post-yield modulus can be expressed as a function of density and confining stress.

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Table 1 Summary of Triaxial Compression Test Results (After Sun, 1997)

Sample Density (kg/m^3)	Confining Stress (kPa)	Strength at 5% Strain (kPa)	Strength at 1% Strain (kPa)	Initial Modulus (MPa)	Post-Yield Modulus (kPa)
14.4	0	65.0	27.0	2.65	139.5
14.4	34.5	48.0	19.0	1.85	139.5
14.4	68.9	28.0	14.0	1.50	142.5
20.8	0	112.5	60.0	5.55	210.0
20.8	34.5	82.5	41.0	4.00	210.0
20.8	68.9	69.0	26.0	2.98	225.0
22.4	0	122.0	62.0	6.55	240.0
22.4	34.5	101.5	50.0	4.95	270.0
22.4	68.9	78.5	40.0	3.93	300.0

Table 2 Compressive Strength of EPS Geofoam at 5% Strain

Density (kg/m^3)	Confining Stress (kPa)	Compressive Strength @ 5% Strain (kPa)	
		Actual Result	Predicted by Equation 21
16	0	79.1	83
16	35	55.4	54
16	75	26.2	28
26	0	155.1	152
26	25	135.6	133
26	30	130.2	130
26	50	112.2	117
26	75	109.5	104
26	100	94.3	94

Table 3 Compressive Strength of EPS Geofoam at 5% Strain (Data from Sun, 1997)

Density (kg/m^3)	Confining Stress (kPa)	Compressive Strength @ 5% Strain (kPa)	
		Actual Result	Predicted by Equation 11
14.4	0	65.0	67
14.4	34.5	48.0	46
14.4	68.9	28.0	24
20.8	0	112.5	109
20.8	34.5	82.5	87
20.8	68.9	69.0	66
22.4	0	122.0	119
22.4	34.5	101.5	98
22.4	68.9	78.5	77

Table 4 Compressive Strength of EPS Geofoam at 5% Strain (Data from Preber et al, 1994)

Density (kg/m^3)	Confining Stress (kPa)	Compressive Strength @ 5% Strain (kPa)	
		Actual Result	Predicted by Equation 4
20	0	75	81
24	20	72	101
32	41	142	146

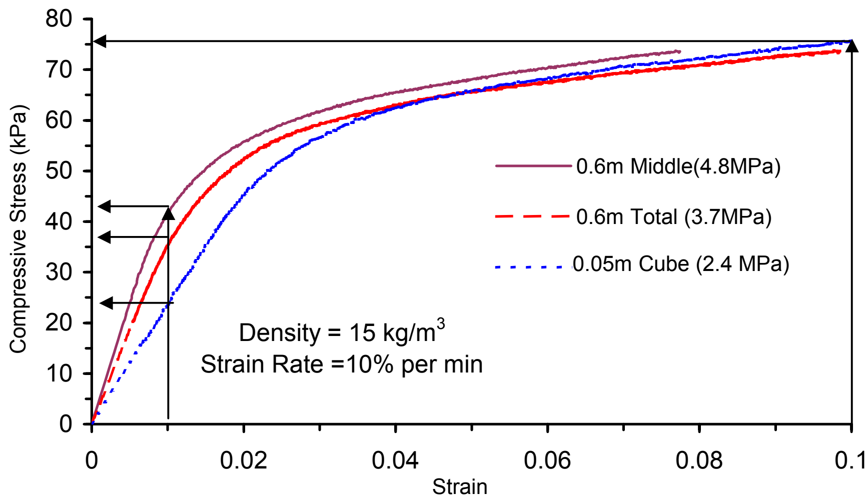

Figure 1. Effect of Sample Size on Compressive Strength (After Elragi, 2000)

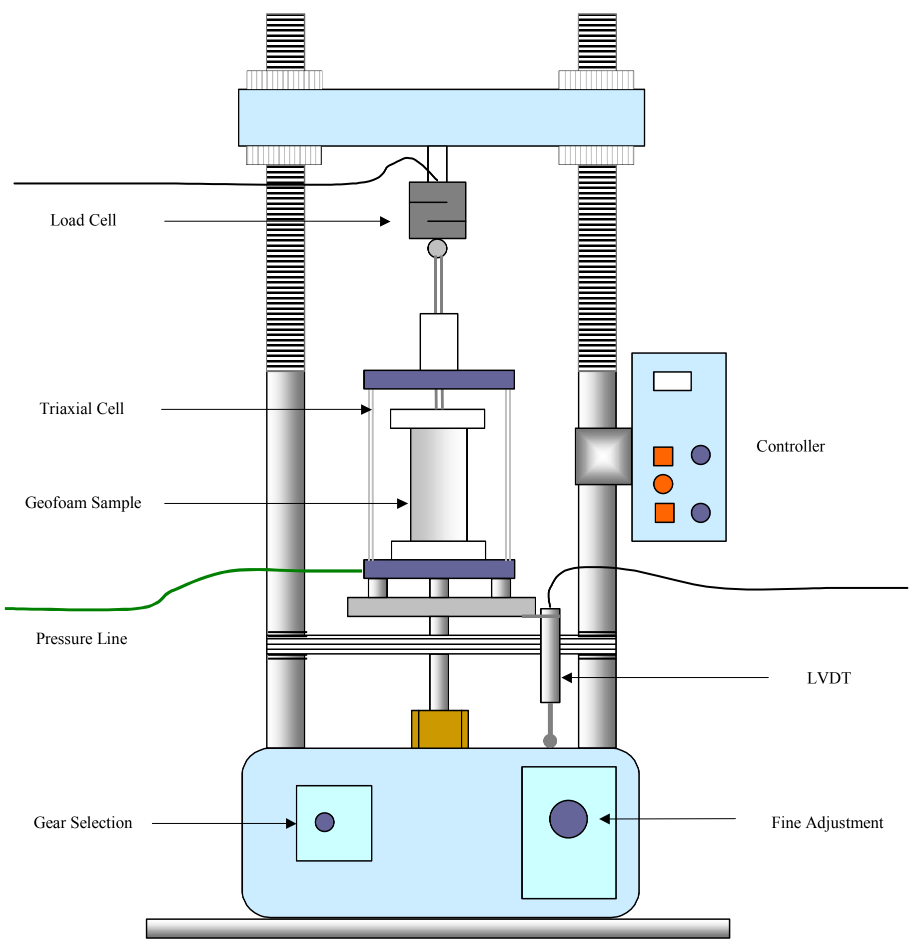

Figure 2. Diagram of Triaxial Test Setup

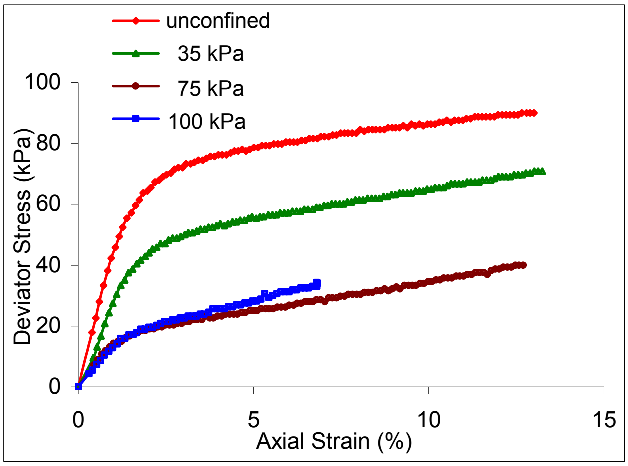

Figure 3. Stress-Strain Curves for EPS16 (Duration of Confinement = 0 hr.)

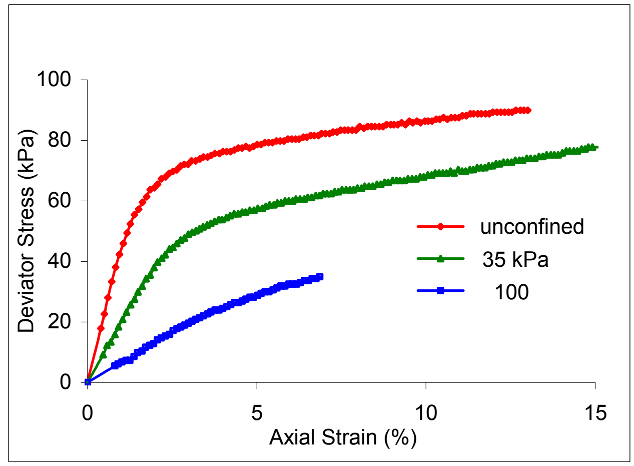

Figure 4. Stress-Strain Curves for EPS16 (Duration of Confinement = 3 hrs.)

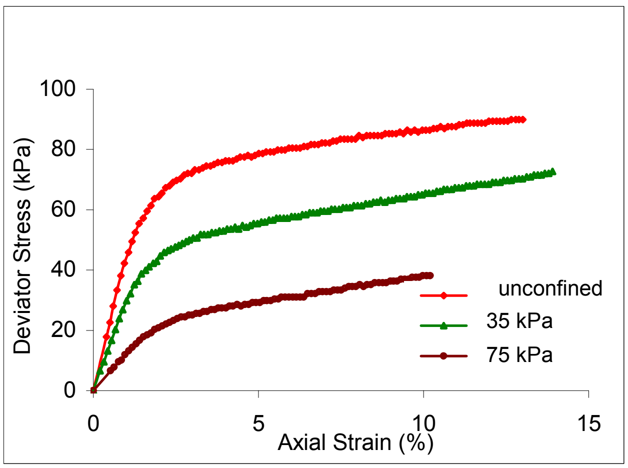

Figure 5. Stress-Strain Curves for EPS16 (Duration of Confinement = 24 hrs.)

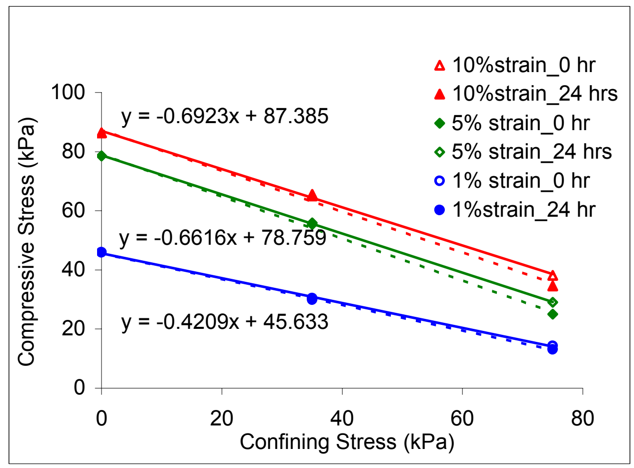

Figure 6. Strength of EPS16 with Confining Stress and Duration of Confinement

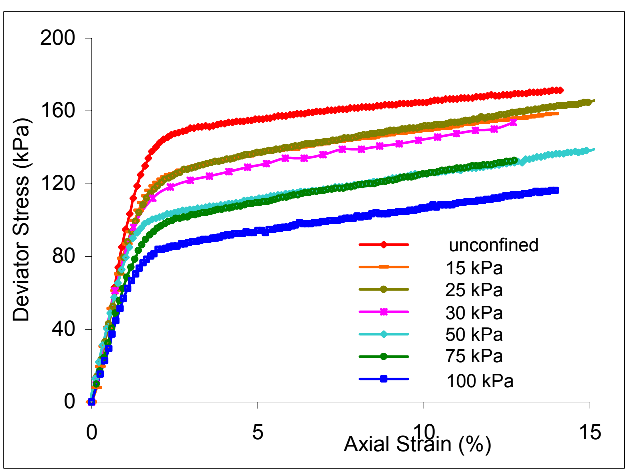

Figure 7. Stress-Strain Curves for EPS26 (Duration of Confinement = 0 hr.)

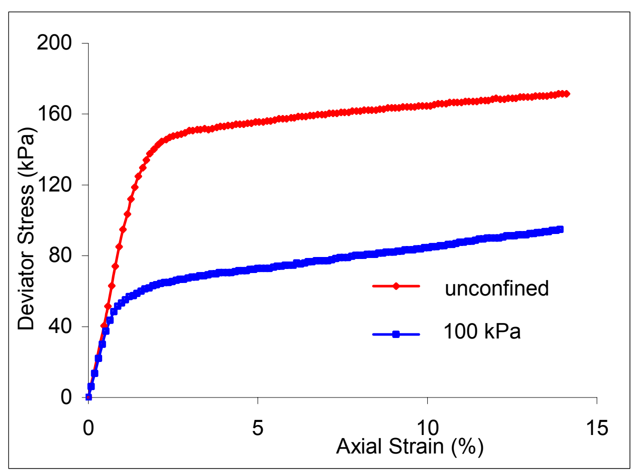

Figure 8. Stress-Strain Curves for EPS26 (Duration of Confinement = 3 hrs.)

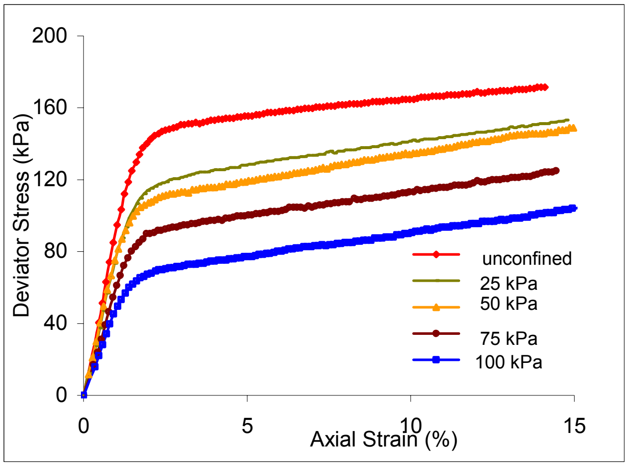

Figure 9. Stress-Strain Curves for EPS26 (Duration of Confinement = 24 hrs.)

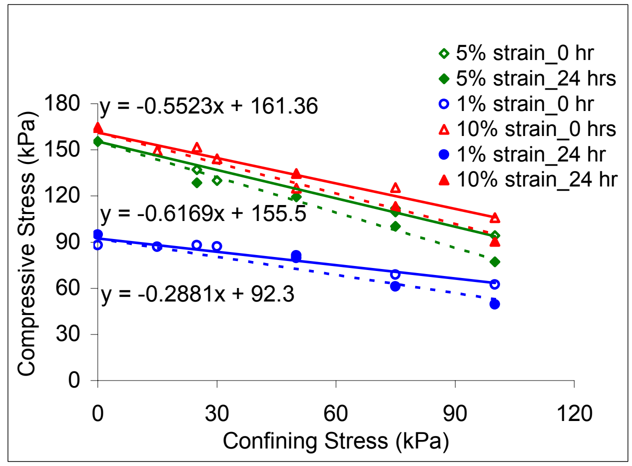

Figure 10. Strength of EPS26 with Confining Stress and duration of confinement

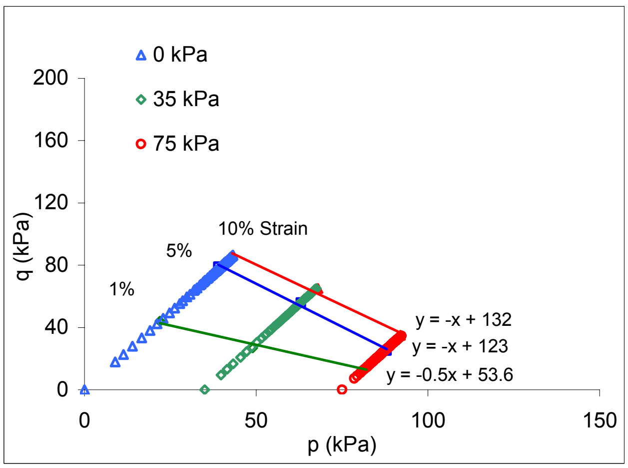

Figure 11. Stress Path for EPS16 During Triaxial Compression

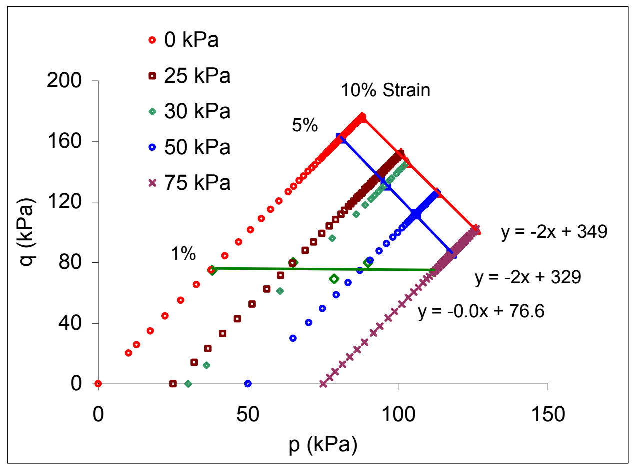

Figure 12. Stress Path for EPS26 During Triaxial Compression

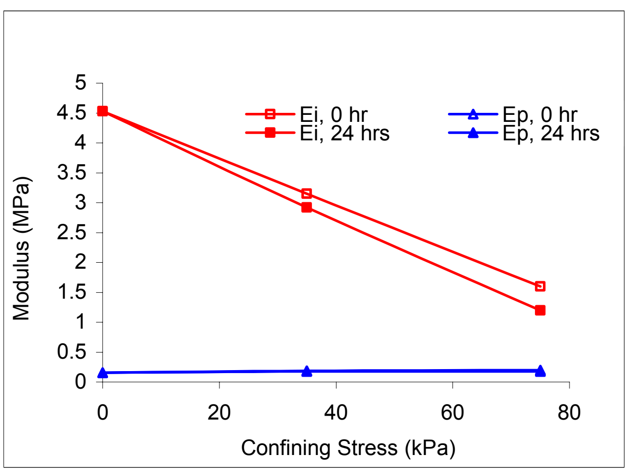

Figure 13. Modulus of EPS16 with Confining Stress (Duration of Confinement = 0 and 24 hrs.)

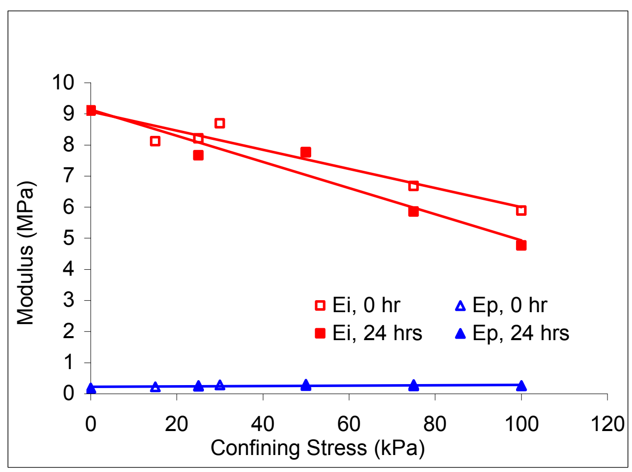

Figure 14. Modulus of EPS26 with Confining Stress (Duration of Confinement =0 and 24 hrs.)

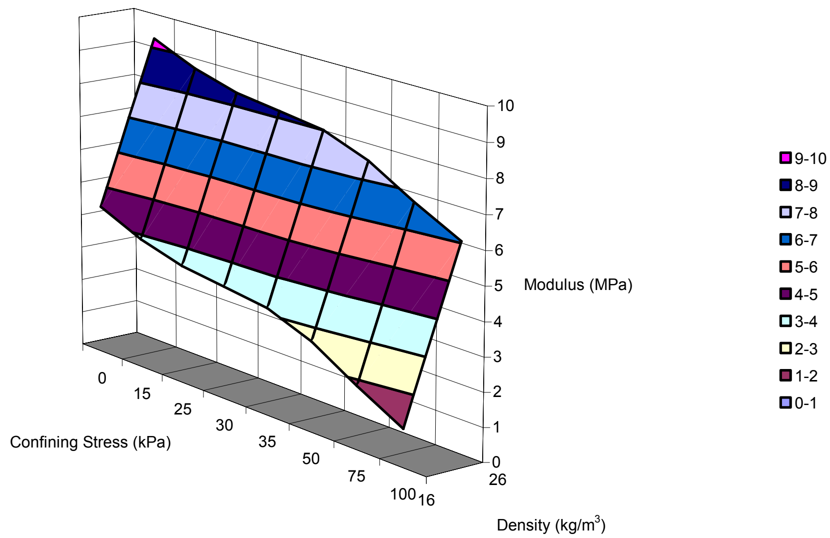

Figure 15 Initial Young's Modulus

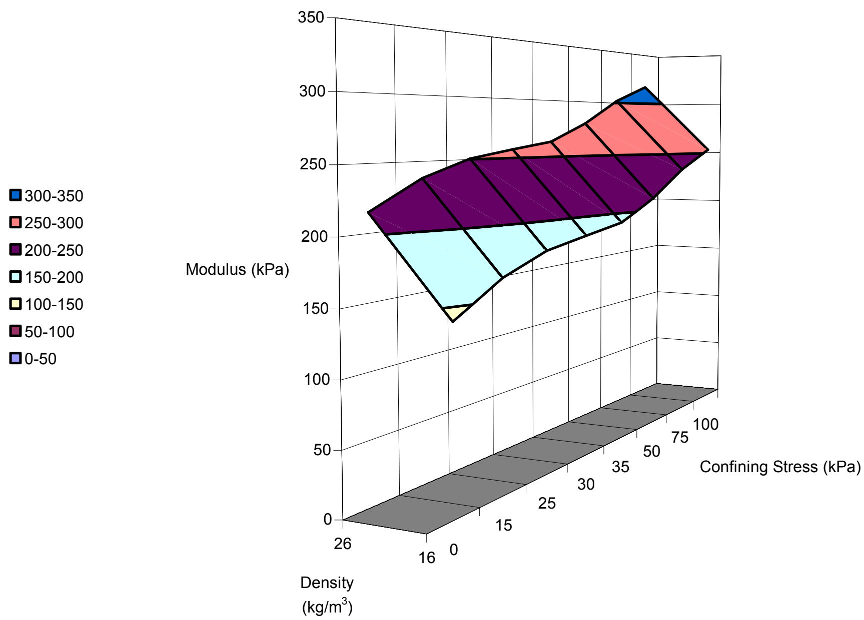

Figure 16. Post-Yield Modulus

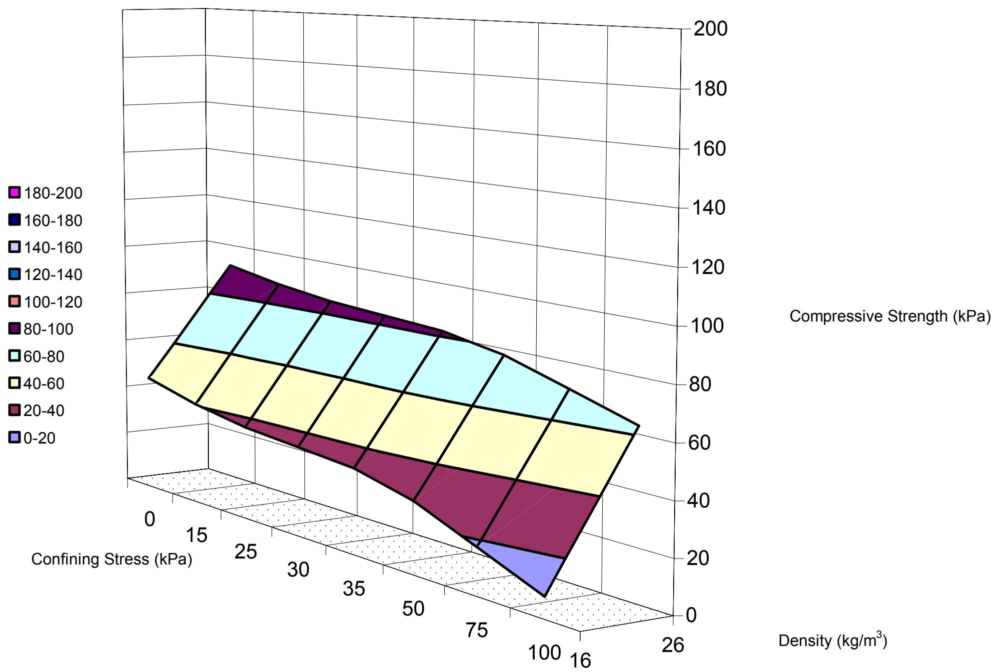

Figure 17. Compressive Strength at 1% Axial Strain

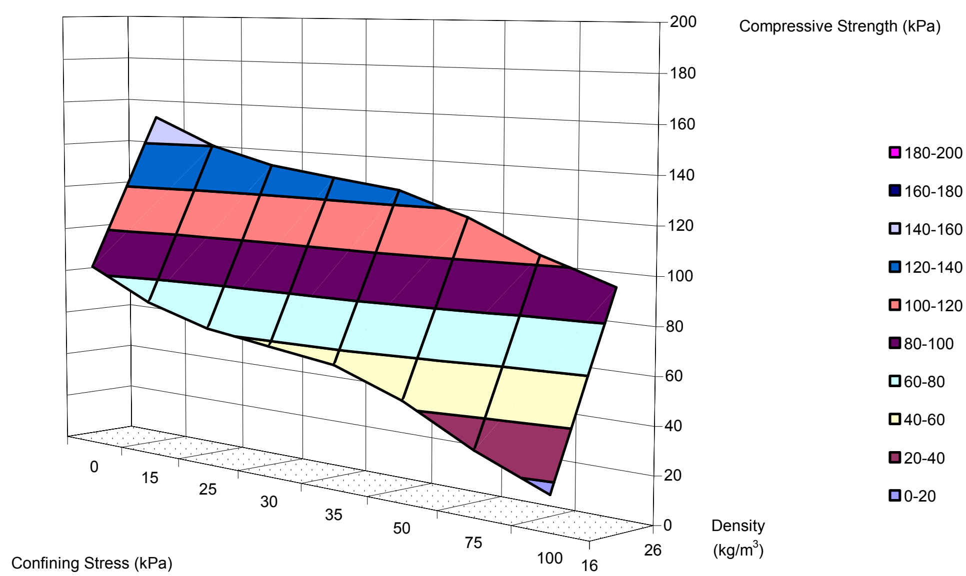

Figure 18. Compressive Strength at 5% Axial Strain

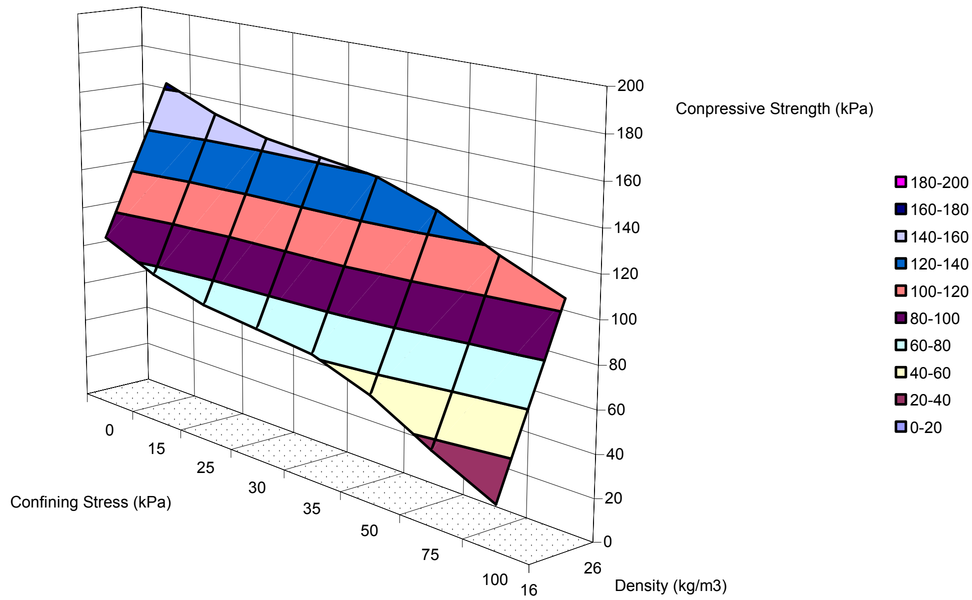

Figure 19. Compressive Strength at 10% Axial Strain