Behavior of Expanded Polystyrene Blocks

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An innovative construction material, expanded polystyrene blocks (EPS blocks), has been introduced in geotechnical engineering in recent years. Because of its extremely light weight and ease in handling, it provides an alternative to conventional backfill, embankment earth materials, and lightweight fill. It is anticipated that the use of EPS blocks in the construction industry may result in substantial cost savings. New applications of EPS blocks as structural elements are expected to emerge as engineers learn more about this material. A series of laboratory tests were conducted to determine the mechanical properties of EPS blocks. Included are the results of undrained triaxial tests with volume change measurements for the determination of a constitutive relationship, a repeated loading test, punching shear tests, and a long-term creep test. The test results show several distinctive material characteristics, including a bilinear stress-strain relationship and negative Poisson's ratio that are not common in conventional construction materials. The results of this study can readily be incorporated in detailed analyses of various geotechnical engineering structures constructed with EPS blocks.

The geotechnical engineering and construction industries have been seeking inexpensive, lightweight construction materials for backfill against retaining structures, fill for embankments on soft ground and beneath pavements, and replacement material for slope stabilization. The use of lightweight materials has been considered a technically acceptable and economical solution to many instability and settlement problems related to weak and highly compressible soils.

Super-light expanded polystyrene blocks (EPS blocks) have been used in the road construction industry as a lightweight material for nearly three decades (*1,2*). The literature indicates that the Norwegian Road Research Laboratory has successfully used EPS blocks on more than 100 projects (*1,3,4*). It has been reported that the EPS blocks produce almost no lateral pressure on the bridge abutment walls. EPS blocks have also been used extensively as frost-proofing layers in highways in Europe and North America (*5*).

One of the first projects in which EPS blocks were used in the United States was a bridge near Pickford, Michigan, where a large portion of the abutment fill was replaced with EPS blocks. Another large-scale project in the United States was the 1987 reconstruction of a failed 60-m long section of U.S.-160 near Durango, Colorado (*6*). EPS blocks were selected mainly because the fragile slope could not support any more weight than the highway itself.

Expanded polystyrene has typically been used as insulation and packaging material. Its density is approximately 0.15 to 0.3 kN/m^3, equivalent to $1/60$ to $1/30$ the density of water (*7*). It is therefore extremely light, producing almost no gravity-induced stress, and is easy to handle. It also has extremely low thermal conductivity and can therefore be used as an insulation material in cold regions with frost-susceptible soils. It is stable chemically, and it is not subject to decay. However, it must be protected from petroleum distillates, fire, ultraviolet light, and vandalism. Because of its light weight, the cost of conventional earth work can be dramatically reduced if EPS blocks are used under certain circumstances. Engineering structures constructed with EPS blocks are expected to experience lower stresses than those constructed with conventional materials, resulting in smaller structural sections and thereby substantial cost savings.

DETERMINATION OF MATERIAL BEHAVIOR

A series of laboratory tests was performed on samples cut from EPS blocks for determination of the constitutive relationship, punching shear resistance, material characteristic under a repeated loading, and long-term creep characteristic. The stress-strain relationship was determined from uniaxial compression tests and four sets of undrained triaxial tests on EPS samples of different densities. Each set consisted of four different confining pressures (0, 21, 41, and 62 kPa). The volume change behavior of the EPS samples was also observed during the triaxial tests. The creep behavior of the EPS material was monitored from a sample under an axial load of 24 kPa. The EPS material is identified by its unit weight [i.e., pounds per cubic foot (pcf)], which also represents the product name.

The details of the EPS samples and the stress conditions applied in various laboratory tests are presented in Table 1. The maximum confining pressure applied in undrained triaxial testing was limited to less than 62 kPa because the samples deformed excessively under confining pressures greater than 62 kPa.

Uniaxial Compressive and Undrained Triaxial Tests

Figures 1 through 3 show typical results obtained from the unconfined compression and undrained triaxial tests. The shapes of the stress-strain curves are similar regardless of the material unit weight and confining pressure. The stress-strain relationship is typically bilinear.

The test results indicate that, in general, as the unit weight of the EPS blocks increases, both the initial and plastic moduli increase, with the plastic modulus increasing at a lower rate. The test results also indicate that the material strength increases with unit weight. With increasing confining pressure, the initial modulus decreases but the plastic modulus increases.

Stress-Strain Relationship of EPS Blocks

To establish a detailed stress-strain relationship, four parameters were selected, as shown in Figure 4. These parameters are defined as follows:

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TABLE 1 Summary of Laboratory Tests

Type of Test	Uniaxial Compression	Triaxial Compression	Punch Shear	Creep
Type of Material (pcf)	1,1.25 1.5,2.0	1,1.25 1.5,2.0	1,1.25 1.5,2.0	1.5
Confining Pressure (kPa)		0,21 41,62		
Axial Stress (kPa)				24 71

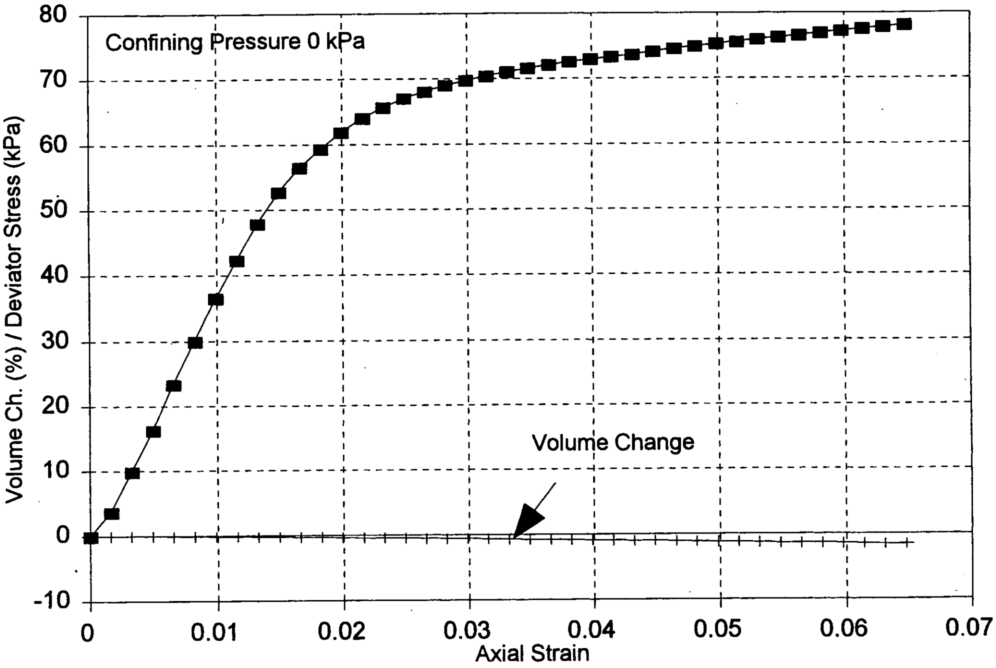

FIGURE 1 Undrained triaxial test on 1.25-pcf EPS.

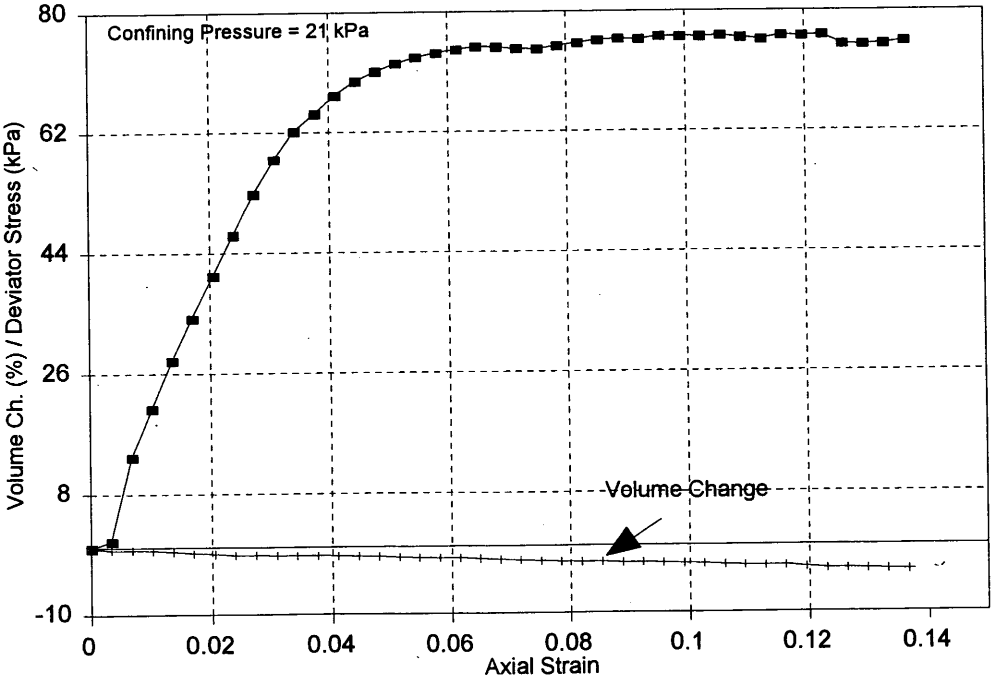

FIGURE 2 Undrained triaxial test on 1.5-pcf EPS.

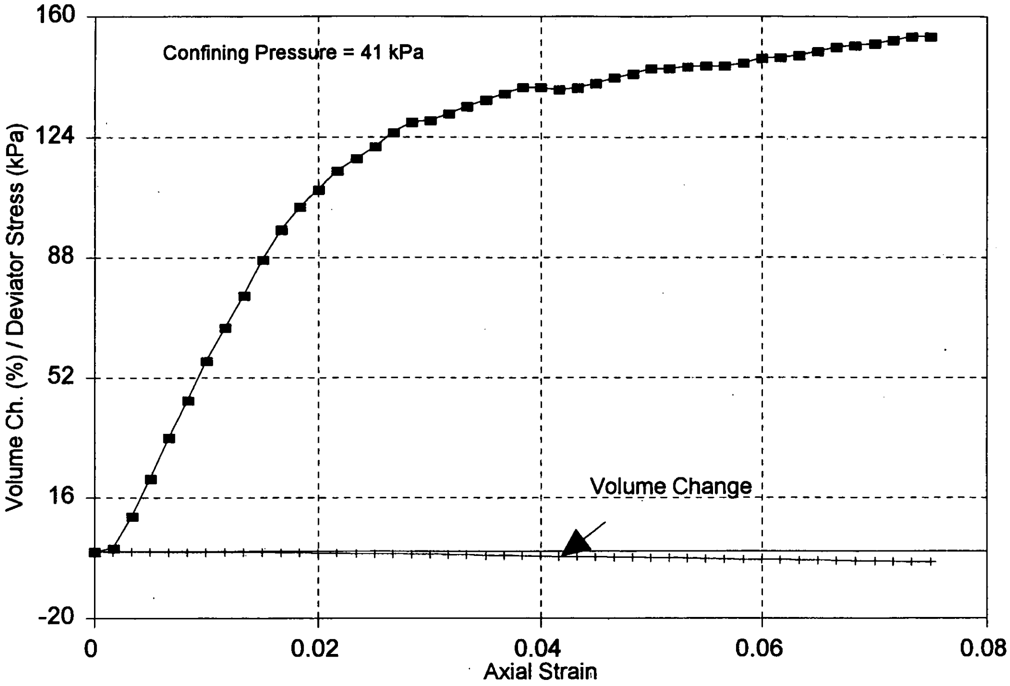

FIGURE 3 Undrained triaxial test on 2.0-pcf EPS.

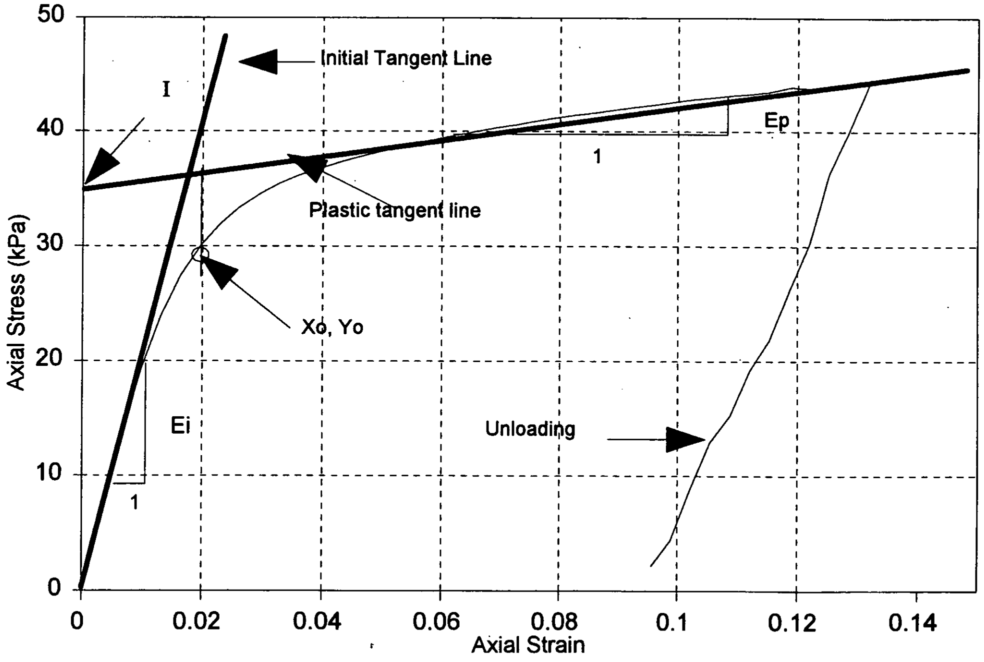

FIGURE 4 Parameters describing constitutive relationship.

E_i = Initial modulus.
E_p = Plastic modulus.
I = Intersection of the axial stress axis and the plastic tangent line.
Y_o = Axial stress value corresponding to strain X_o.

In addition, X_0 is the strain value at the intersection of the initial tangent line and the plastic tangent line. This can be determined analytically from E_i, E_p, and I.

The axial stress-strain relationship of the EPS blocks is proposed to follow

$$\sigma = (I + E_p \epsilon)\left[1 - \exp\left(- C \epsilon^2 - \frac{E_1 \epsilon}{I}\right)\right] \qquad (1)$$

where σ is axial stress and ε is axial strain.

$$C = - \frac{E_i}{I X_o} - \frac{1}{X_o^2} \ln\left[1 - \frac{Y_o}{(I + E_p X_o)}\right]$$

This expression satisfies all the requirements specified previously: the initial modulus, the asymptote defined by the plastic modulus, the yield stress, and the stress-strain data coordinate. This mathematical expression is chosen on the basis of the shape of the observed stress-strain curves.

From this stress-strain expression, the instantaneous tangent modulus of the EPS material can be obtained by differentiating the axial stress with respect to the axial strain. The following steps describe how the four parameters can be evaluated as functions of the EPS material density and the confining pressure.

1. Determine the values of each parameter from the stress-strain curves obtained from the undrained triaxial tests, as shown in Tables 2 through 5.
2. Plot the values of the parameters determined in Step 1 as a function of the confining pressure for each unit weight of the EPS blocks (Figures 5 through 8).
3. Establish the curves corresponding to the highest and the lowest unit weights of the EPS material, representing each parameter. These are shown in Figures 5 through 8 as the limiting curves (solid lines).
4. Interpolate the limiting curves determined in Step 3 for intermediate unit weights of the EPS material (dotted lines).

Though the actual variations of the parameters are somewhat scattered, straight lines have been used in the figures to show the variations. The generalized equations for each parameter are as follows:

$$\begin{aligned} I &= (-107 + 910\gamma) + (0.63 - 6.32\gamma)\sigma_3 \\ E_i &= (-4{,}180 + 39{,}000) + (-6.2 - 53\gamma)\sigma_3 \\ E_p &= (104 + 440\gamma) + (-3.6 + 150\gamma)\sigma_3 \\ Y_o &= (1.4 + 905\gamma) + (-1.1 + 4.5\gamma)\sigma_3 \end{aligned} \qquad (2)$$

where γ is the unit weight of EPS material (kN/m^3) and σ_3 is the confining pressure (kPa).

Poisson's Ratio

Poisson's ratio of the EPS material has been evaluated by measuring the volume change of the EPS samples during the undrained tri-

TABLE 2 ***I* Values from Triaxial Tests (kPa)**

Confining Pressure (kPa)	Type of EPS			
	1.0 pcf	1.25 pcf	1.5pcf	2.0 pcf
0	22.4	68.3	39	165.5
	47.7	61.4	36.9	191.7
21	31.7	49.0	73.8	151.8
	30.3	50.3	72.1	154.4
41	16.2	31.7	58.6	122.7
	17.9	37.9	52.4	124.1
62	10.0	12.4	37.2	100.0
	15.2	21.4	31.7	82.7

TABLE 3 ***E_i* Values from Triaxial Tests (kPa)**

Confining Pressure (kPa)	Type of EPS			
	1.0 pcf	1.25 pcf	1.5pcf	2.0 pcf
0	1536	4073	3505	6791
	4183*	4036	2176	9464
21	2234	3335	4597	7388
	4313*	3418	1970	7968
41	2955*	2501	4867	7335
	2555*	7661	5910	6895
62	1207	2758	4413	6015
	660	2236	4186	7454

*Unused data in regression analysis

TABLE 4 ***E_p* Values from Triaxial Tests (kPa)**

Confining Pressure (kPa)	Type of EPS			
	1.0 pcf	1.25 pcf	1.5pcf	2.0 pcf
0	297*	212	556	422*
	195	284	509	253
21	169	246	164	362
	168	207	42	181*
41	254	189	138	517
	241	286	241	431
62	261	302	207	506
	207	260	280	716

*Unused data in regression analysis

TABLE 5 ***Y_o* Values from Triaxial Tests (kPa)**

Confining Pressure (kPa)	Type of EPS			
	1.0 pcf	1.25 pcf	1.5pcf	2.0 pcf
0	20.8	56.9	35.2	157.2
	36.9	57.2	42.1	180.6
21	28.4	43.4	65.5	144.8
	20.0	45.9	64.5	153.1
41	12.4	26.9	50.3	118.6
	15.2	23.8	49.0	113.8
62	9.3	9.0	28.6	88.3
	10.7	15.2	27.6	79.3

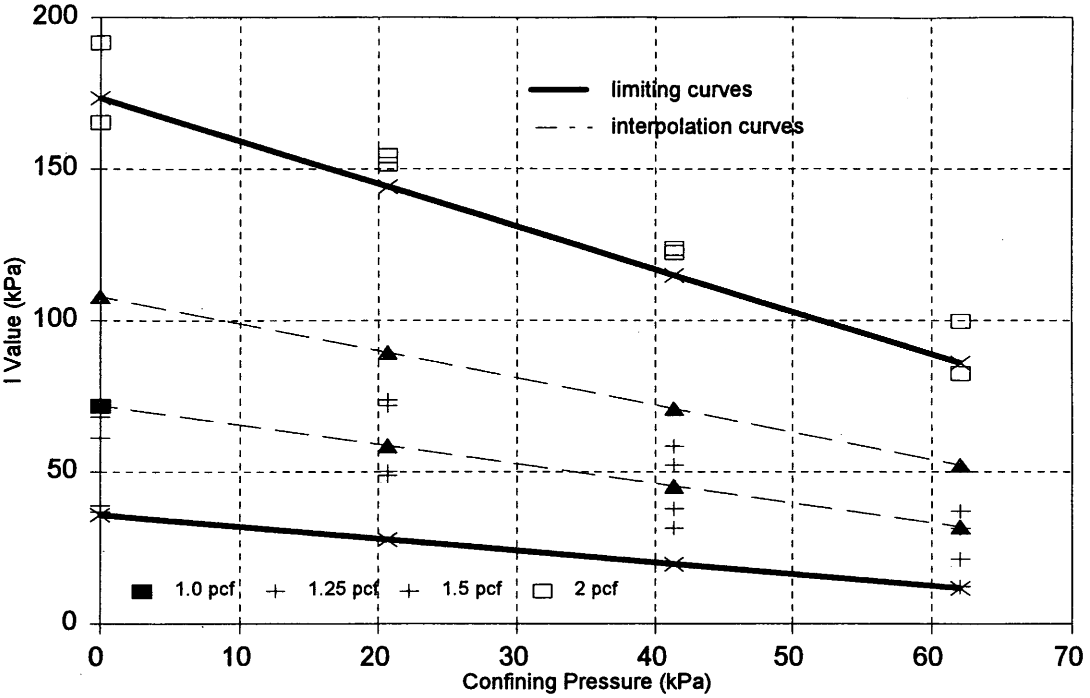

FIGURE 5 Variation of *I* value.

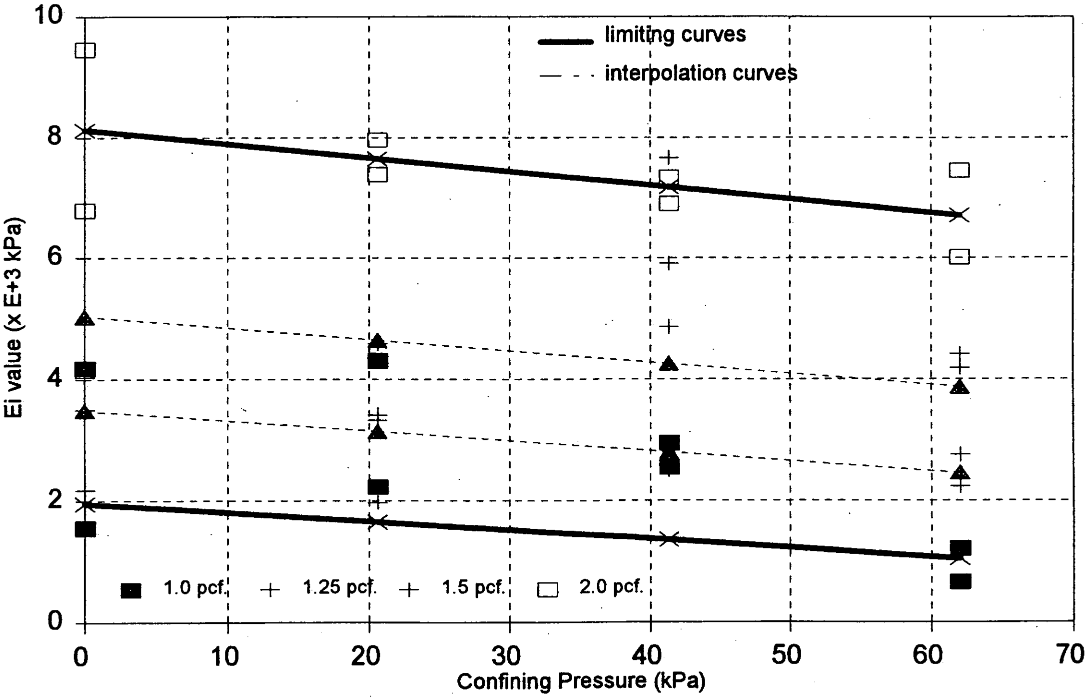

FIGURE 6 Variation of E_i value.

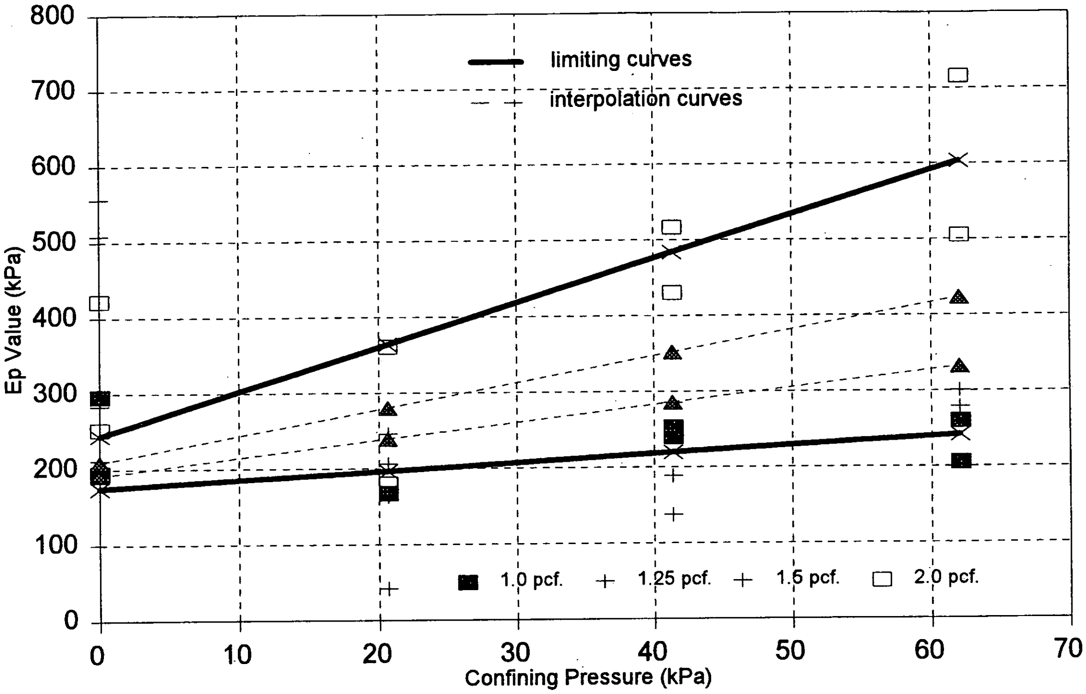

FIGURE 7 Variation of E_p value.

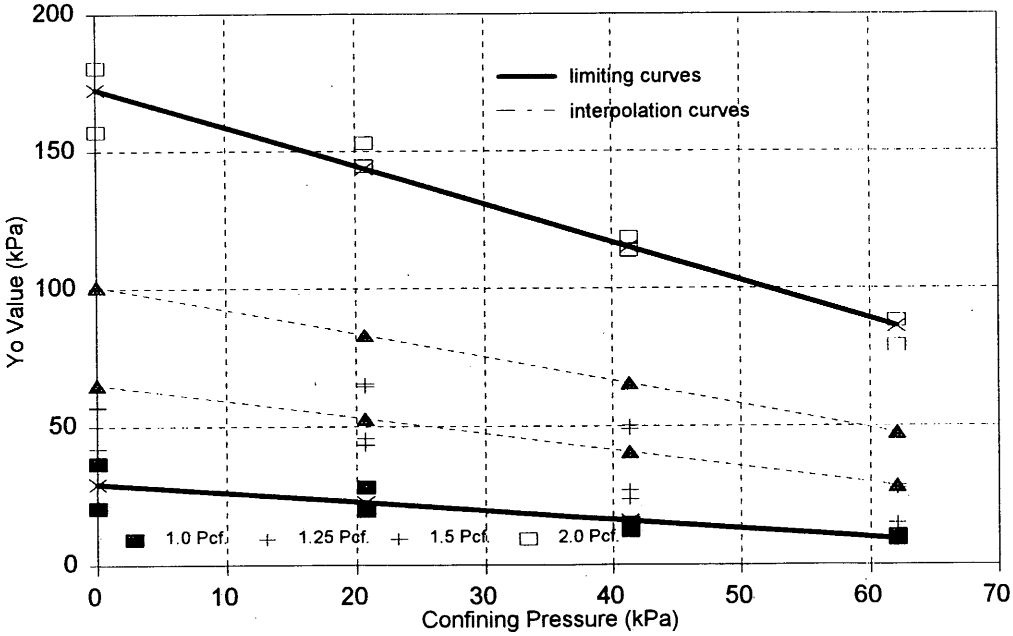

FIGURE 8 Variation of Y_o value.

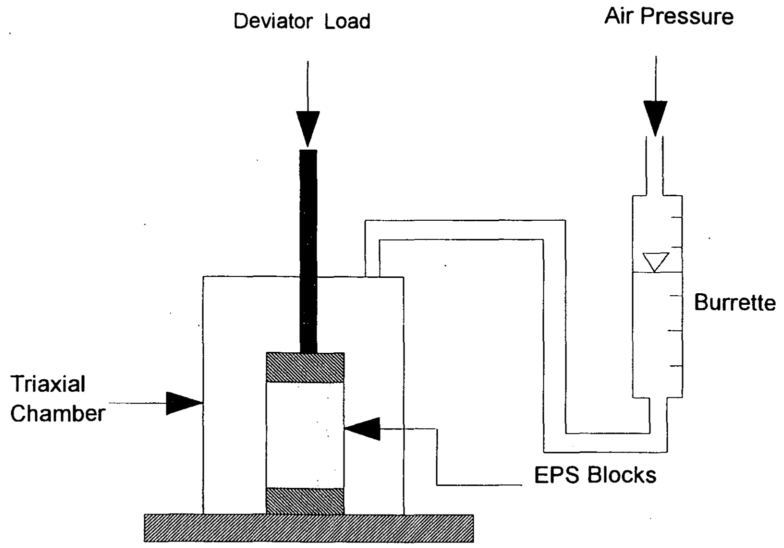

FIGURE 9 Schematics of undrained triaxial test on EPS blocks.

axial tests. The samples were separated from the surrounding chamber water by a thin rubber membrane. The volume change of the EPS samples was determined by measuring the amount of water flowing into or out of the triaxial chamber during the test. The test setup is shown in Figure 9.

The Poisson's ratios were calculated at the intersection of two tangent lines of the stress-strain curves and at large stress values as shown in Tables 6 and 7. The procedure of computing the Poisson's ratio from the measured volume change follows.

TABLE 6 Poisson's Ratio at Intersection

Confining Pressure (kPa)	Type of EPS			
	1.0 pcf	1.25 pcf	1.5pcf	2.0 pcf
0	.175 .332	.301 .295	.142 .163	.381 .380
21	-.440	-.110	.075 -.270	.250 .005
41	-.420 -.330	-.250 -.420	.052 -.142	.170 .240
62	-.750 -.610	-.420 -.285	-.149 -.029	.037 .065

TABLE 7 Poisson's Ratio at Failure

Confining Pressure (kPa)	Type of EPS			
	1.0 pcf	1.25 pcf	1.5pcf	2.0 pcf
0	.131 .199	.204 .231	.107 .115	.256 .240
21	-.237	-.102	-.091 -.182	.010 -.051
41	-.110 -.182	-.238 -.206	-.140 -.187	-.342 -.004
62	-.440 -.336	-.366 -.248	-.239 -.239	-.081 -.132

Poisson's ratio is defined by Desai and Siriwardane (*8*) and Gere and Timoshenko (*9*) as

$$\text{Poisson's ratio} = -\frac{\text{lateral strain}}{\text{axial strain}} = \frac{H\,\Delta R}{R\,\Delta H} \qquad (3)$$

The total volume of the original sample is the same as that of the deformed sample plus the change in volume of water, as shown in Figure 10:

$$\begin{aligned}\text{Total volume} &= V_w + \frac{\pi R^2}{4} H \\ &= V_w + \Delta V_w + \frac{(R + \Delta R)^2}{4}(H - \Delta H) \qquad (4)\end{aligned}$$

By combining Equations 3 and 4 and neglecting the second-order terms, one obtains

$$\text{Poisson's ratio} = \frac{\pi R^2\,\Delta H - 4\Delta V_w}{2\,\pi R^2\,\Delta H} \qquad (5)$$

As can be seen in Figures 11and 12, Poisson's ratio starts with approximately 0.2 at zero confining pressure. It decreases as the confining pressure increases and finally falls below zero as the confining pressure increases further. The figures indicate that this observation is more or less the same for both cases, that is, Poisson's

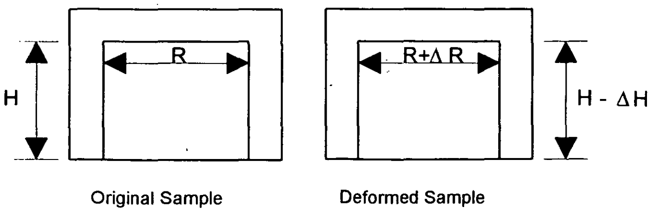

FIGURE 10 Simplified deformation under triaxial condition.

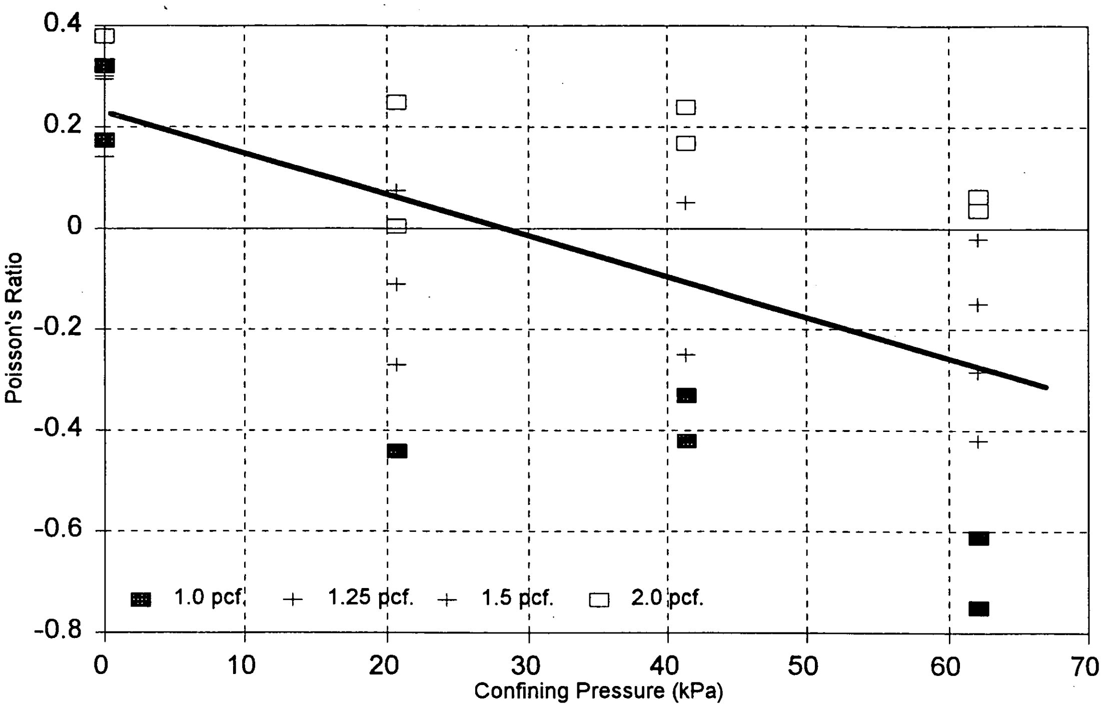

FIGURE 11 Poisson's ratio at intersection.

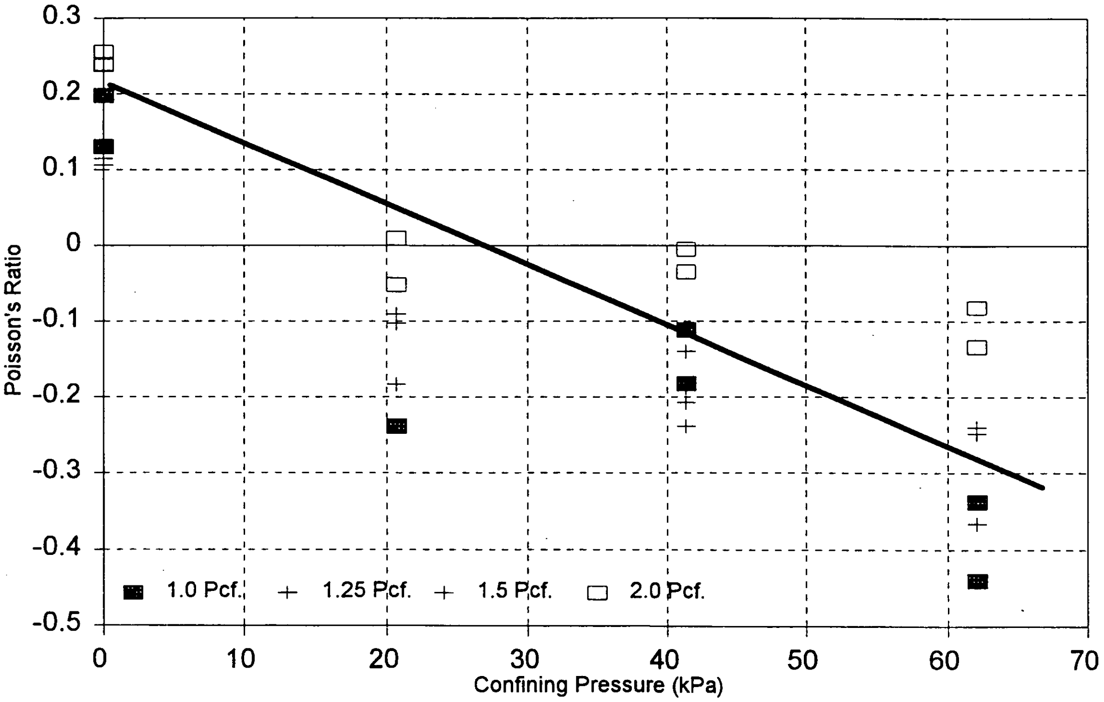

FIGURE 12 Poisson's ratio at failure.

ratio at the intersection point and at failure, although the samples with lower unit weights tend to exhibit lower Poisson's ratios. On the basis of the limited data obtained, the volume change behavior of the EPS material can be approximated as

$$\mu = 0.2 - 0.5 \frac{\sigma_3}{62 \text{ kPa}} \qquad \text{for } 0 \leq \sigma_3 \leq 62 \text{ kPa} \qquad (6)$$

where μ is Poisson's ratio and σ_3 is confining pressure (kPa).

It is noted that the past observations of reduced lateral earth pressures acting on retaining walls when the EPS blocks were used as backfills can be explained from the negative values of the Poisson's ratio. If Poisson's ratio indeed becomes negative, parts of the sides of the EPS blocks that have been in contact with the retaining walls may cave inward as the stress increases, resulting in partial separation from the retaining wall. Full-scale field instrumentation study is needed to verify this postulation.

Punching Shear Tests

In many geotechnically engineered structures, shear stresses combine with normal stresses, developing especially at and near the edges of the structures. Hence this combined stress condition needs to be simulated in laboratory testing. The punching shear test is one possible method of simulating this condition, since it produces both shear and normal stresses simultaneously. Figures 13 and 14 show the results of two typical punching shear tests. The stress-strain relationship curves are nonlinear. The punching shear strength increases rapidly at small strain, but its increasing ratio reduces gradually as the shear strain increases.

The punching shear strength of the EPS material increases about 300 percent from 1- to 1.25-pcf EPS material. However, the percent increase in punching shear strength decreases as the unit weight increases further. The maximum punching shear strengths are approximately 83, 275, 410, and 550 kPa for EPS samples of 1, 1.25, 1.5, and 2 pcf, respectively.

Repeated Loading Test

EPS blocks have been used frequently beneath pavement as either a frost-proofing layer or a load-bearing subgrade layer. For this reason, a simple repeated loading test was conducted on a 1.5-pcf EPS sample under a repeating axial stress of 72 kPa in a one-dimensional consolidometer.

The test results show that virtually zero permanent, nonrecoverable axial strain remains after 300 cycles of axial stress application, indicating that the resilient modulus of the EPS material is almost identical to the elastic modulus. This indicates that the EPS blocks can perform well under the repeated loading condition as long as the maximum stresses are less than its yield strength. However, testing for a higher number of load cycles may be necessary to confirm this behavior.

Creep Test

Figure 15 shows the results of a creep test on a 1.5-pcf EPS sample under a constant axial stress of 24 kPa. Through extrapolation, one can estimate the creep strain rate of less than 0.6 percent a year, indicating the relative insensitivity of the EPS material to creep.

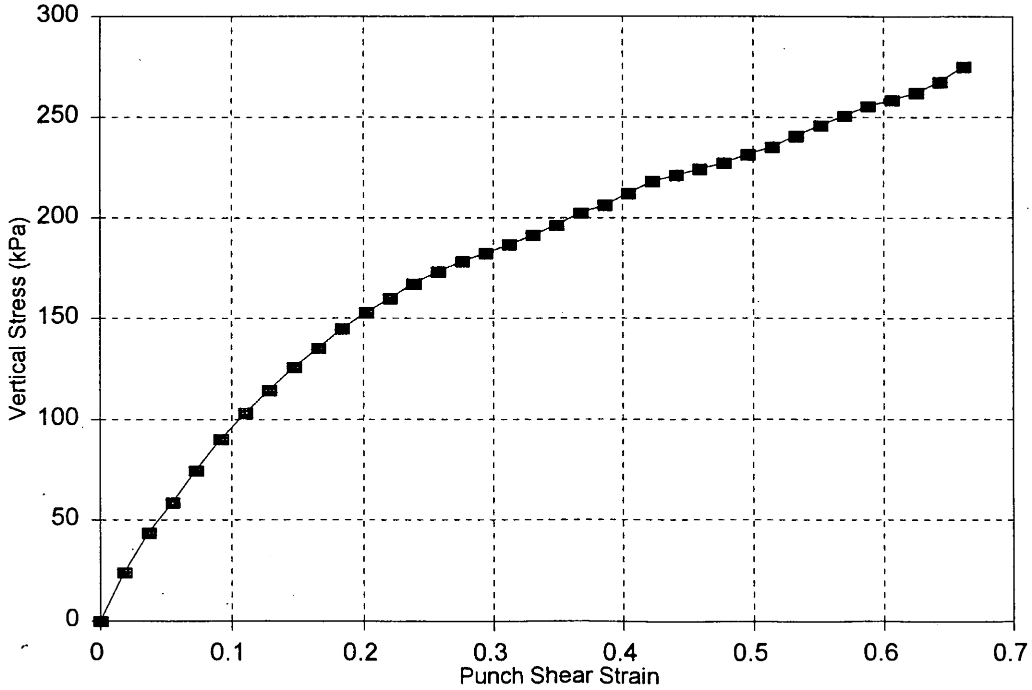

FIGURE 13 Punch shear test on 1.25-pcf EPS.

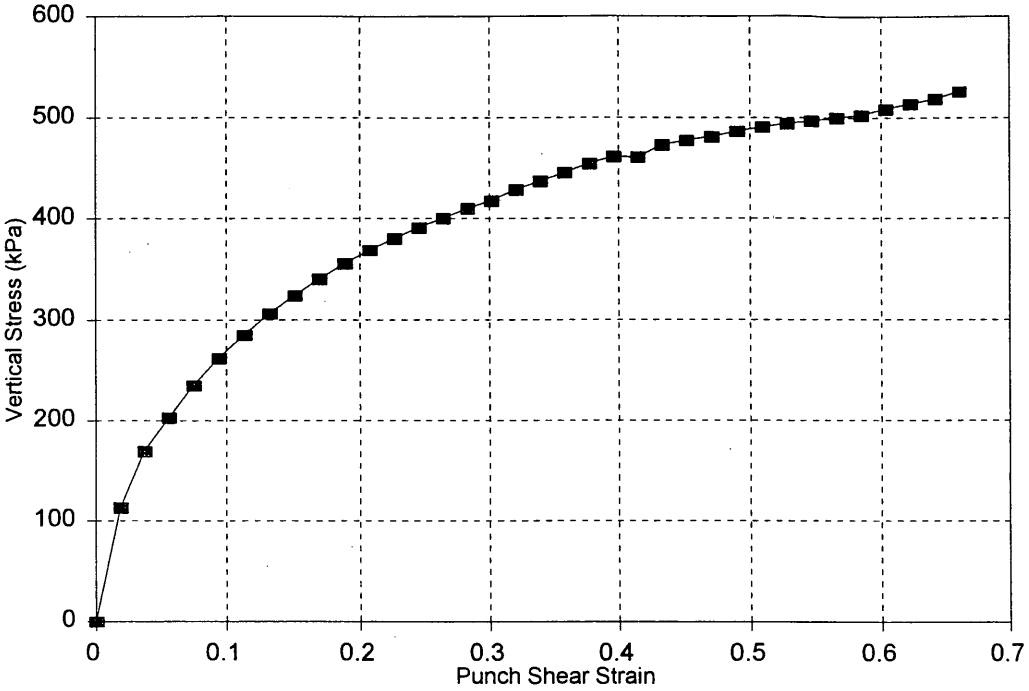

FIGURE 14 Punch shear test on 2.0-pcf EPS.

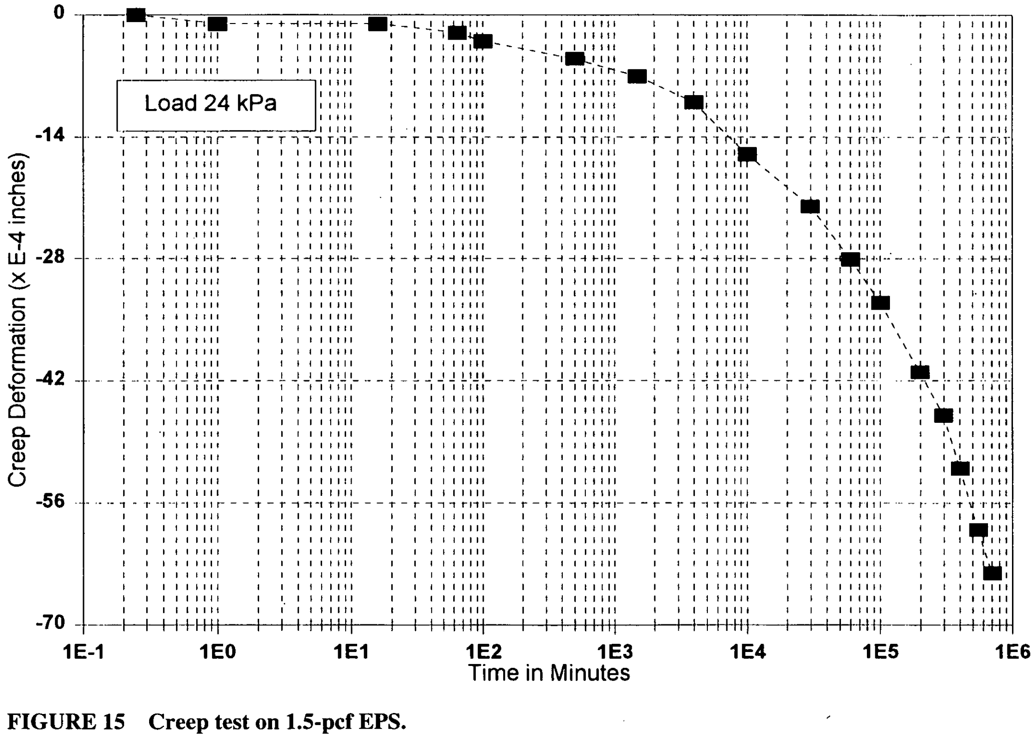

FIGURE 15 Creep test on 1.5-pcf EPS.

CONCLUSION

Various laboratory tests on EPS samples have been conducted to characterize behavior under constant and repeated loading conditions. Although there is some scatter in the test data, a general distinctive behavior of the EPS material has been observed. One possible explanation of the data scatter is sample inhomogeneity created during the manufacturing process. The EPS blocks are produced by a sudden expansion, which usually creates nonuniform material properties, possibly leaving localized dense or loose pockets.

In general, as the unit weight of the EPS material increases, both the initial and plastic moduli increase, with the plastic modulus increasing at a slower rate. The EPS material becomes stronger as the unit weight increases. With an increase in confining pressure, the initial modulus decreases while the plastic modulus increases. Poisson's ratio remains greater than zero at low confining pressures but starts to decrease and eventually drops below zero as the confining pressure further increases.

The EPS blocks have been tested and found reliable under working stress conditions against both creep and repeated stresses.

Straight lines have been used to show Poisson's ratio and the parameters defining the nonlinear stress-strain relationship of the EPS material. This linearization is mainly due to the limited number of data available. Further refinement of the EPS material characterization needs to be made considering wider ranges of stress and strain magnitudes.

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